Julius-Maximilians-Universität Würzburg
Graduate School of Science and Technology

Doctoral thesis / *Dissertation*
for the doctoral degree / *zur Erlangung des Doktorgrads*
Doctor rerum naturalium (Dr. rer. nat.)

Development, Simulation and Evaluation of Mobile Wireless Networks in Industrial Applications

Entwicklung, Simulation und Bewertung von Mobilen Kabellosen Netzwerken in Industriellen Anwendungen

Submitted by / *Vorgelegt von*
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from / aus
Aalen
Würzburg, 2022

Submitted on / *Eingereicht am:* . . . .

Stamp / *Stempel* Graduate School

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2. Reviewer and Examiner / 2. Gutachter und Prüfer: . . . .
3. Examiner / 3. Prüfer: . . . .

Additional Examiners / Weitere Prüfer: . . . .

. . . .

Day of thesis defense / *Tag des Promotionskolloquiums:* . . . .

Abstract

Many industrial automation solutions use wireless communication and rely on the availability and quality of the wireless channel. At the same time the wireless medium is highly congested and guaranteeing the availability of wireless channels is becoming increasingly difficult. In this work we show, that ad-hoc networking solutions can be used to provide new communication channels and improve the performance of mobile automation systems. These ad-hoc networking solutions describe different communication strategies, but avoid relying on network infrastructure by utilizing the Peer-to-Peer (P2P) channel between communicating entities.

This work is a step towards the effective implementation of low-range communication technologies (e.g. Visible Light Communication (VLC), radar communication, mmWave communication) to the industrial application. Implementing infrastructure networks with these technologies is unrealistic, since the low communication range would necessitate a high number of Access Points (APs) to yield full coverage. However, ad-hoc networks do not require any network infrastructure. In this work different ad-hoc networking solutions for the industrial use case are presented and tools and models for their examination are proposed.

The main use case investigated in this work are Automated Guided Vehicles (AGVs) for industrial applications. These mobile devices drive throughout the factory transporting crates, goods or tools or assisting workers. In most implementations they must exchange data with a Central Control Unit (CCU) and between one another. Predicting if a certain communication technology is suitable for an application is very challenging since the applications and the resulting requirements are very heterogeneous.

The proposed models and simulation tools enable the simulation of the complex interaction of mobile robotic clients and a wireless communication network. The goal is to predict the characteristics of a networked AGV fleet.

The proposed tools were used to implement, test and examine different ad-hoc networking solutions for industrial applications using AGVs. These communication solutions handle time-critical and delay-tolerant communication. Additionally a control method for the AGVs is proposed, which optimizes the communication and in turn increases the transport performance of the AGV fleet. Therefore, this work provides not only tools for the further research of industrial ad-hoc system, but also first implementations of ad-hoc systems which address many of the most pressing issues in industrial applications.

Zusammenfassung

Viele industrielle Automatisierungslösungen verwenden drahtlose Kommunikationssysteme und sind daher auf die Verfügbarkeit und Qualität des drahtlosen Kanals angewiesen. Gleichzeitig ist das drahtlose Medium stark belastet und die Gewährleistung der Verfügbarkeit der drahtlosen Kanäle wird zunehmends herrausfordernder. In dieser Arbeit wird gezeigt, dass Ad-hoc-Netzwerklösungen genutzt werden können, um neue Kommunikationskanäle bereitzustellen und die Leistung von mobilen Automatisierungssystemen zu verbessern. Diese Ad-hoc-Netzwerklösungen können unterschiedliche Kommunikationsstrategien bezeichnen. In all diesen Strategien wird der Peer-to-Peer (P2P)-Kanal zwischen zwei kommunizierenden Systemen verwendet statt Netzwerk-Infrastruktur.

Diese Arbeit ist ein Schritt hin zur effektiven Implementierung von Kommunikationstechnologien mit geringer Reichweite (z.B. Visible Light Communication (VLC), Radarkommunikation, mmWave-Kommunikation) in der industriellen Anwendung. Die Implementierung von Infrastrukturnetzen mit diesen Technologien ist unrealistisch, da die geringe Kommunikationsreichweite eine hohe Anzahl von Access Points (APs) erfordern würde um eine flächendeckende Bereitstellung von Kommunikationskanälen zu gewährleisten. Ad-hoc-Netzwerke hingegen benötigen keine Netzwerkinfrastruktur. In dieser Arbeit werden verschiedene Ad-hoc-Netzwerklösungen für den industriellen Anwendungsfall vorgestellt und Werkzeuge und Modelle für deren Untersuchung vorgeschlagen.

Der Hauptanwendungsfall, der in dieser Arbeit untersucht wird, sind Fahrerlose TransportSysteme (FTS) (fortführend als Automated Guided Vehicles (AGVs)) für industrielle Anwendungen. Diese FTS fahren durch die Produktionsanlage um Kisten, Waren oder Werkzeuge zu transportieren oder um Mitarbeitern zu assistieren. In den meisten Implementierungen müssen sie Daten mit einer Central Control Unit (CCU) und untereinander austauschen. Die Vorhersage, ob eine bestimmte Kommunikationstechnologie für eine Anwendung geeignet ist, ist sehr anspruchsvoll, da sowohl Anwendungen als auch Anforderungen sehr heterogen sind.

Die präsentierten Modelle und Simulationswerkzeuge ermöglichen die Simulation der komplexen Interaktion von mobilen Robotern und drahtlosen Kommunikationsnetzwerken. Das Ziel ist die Vorhersage der Eigenschaften einer vernetzten FTS-Flotte.

Mit den vorgestellten Werkzeugen wurden verschiedene Ad-hoc-Netzwerklösungen für industrielle Anwendungen mit FTS implementiert, getestet und untersucht. Diese Kommunikationssysteme übertragen zeitkritische und verzögerungstolerante Nachrichten. Zusätzlich wird eine Steuerungsmethode für die FTS vorgeschlagen, die die Kommunikation optimiert und damit einhergehend die Transportleistung der FTS-Flotte erhöht. Dieses Werk führt also nicht nur neue Werkzeuge ein um die Entwicklung industrieller Ad-hoc Systeme zu ermöglichen, sondern schlägt auch einige Systeme für die kritischsten Kommunikationsprobleme industrieller Anwendungen vor.

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List of Abbreviations

5G	5th Generation
AFM	Attenuation-Factor-Model
AGV	Automated Guided Vehicle
AODV	Ad hoc On-Demand Distance Vector
AP	Access Point
BS	Base Station
BER	Bit Error Rate
CCU	Central Control Unit
CR	Cloud Robotics
CDF	Cumulative Distribution Function
DoF	Degrees of Freedom
DTN	Delay Tolerant Network
DSDV	Destination-Sequenced Distance-Vector
D2D	Device-to-Device
DSR	Dynamic Source Routing
ER	Epidemic Routing
FBNM	Flooding-based Network Monitoring
FANET	Flying Ad-hoc NETwork
HTTP	HyperText Transfer Protocol
LoS	Line-of-Sight
LTE	Long Term Evolution
MTU	Maximum Transmission Unit
MAC	Medium Access Control
MQTT	Message Queuing Telemetry Transport
MANET	Mobile Ad-hoc NETwork

MSN	Mobile Sensor Network
NTP	Network Time Protocol
NEP	Nodal Encounter Pattern
OSI	Open Systems Interconnection
OLSR	Optimized Link-State Routing
PDR	Packet-Delivery-Ratio
PER	Packet Error Rate
P2P	Peer-to-Peer
PDP	Power-Delay-Profile
PDF	Probability Density Function
PLC	Programmable Logic Controller
QoS	Quality of Service
RF	Radio Frequency
RWPM	Random Way-Point Model
RTAD	Real-Time Alarm Dissemination
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
ROS	Robot Operating System
RTT	Round-Trip-Time
RLT	Route Life Time
SINR	Signal-to-Interference-and-Noise-Ratio
SNR	Signal-to-Noise-Ratio
SLAM	Simultaneous Localization and Mapping
SBC	Single Board Computer
SDN	Software-Defined Network
SaW	Spray-and-Wait

SDWSN	Software-Defined Wireless Sensor Network
TORA	Temporally-Ordered Routing Algorithm
TSN	Time Sensitive Network
TCP/IP	Transmission Control Protocol/Internet Protocol
URLLC	Ultra-Reliability and Low Latency Communication
UDP	User Datagram Protocol
VANET	Vehicular Ad-hoc NETwork
VR	Virtual Reality
VLC	Visible Light Communication
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WRP	Wireless Routing Protocol
WSN	Wireless Sensor Network
ZRP	Zone Routing Protocol

1 Introduction

The last industrial revolution led to wide-spread robotic automation on the factory floor. The logistics on the shop floor (first-mile / intralogistics) were one target for this automation. Automated Guided Vehicles (AGVs) are used to move materials, tools and work pieces through the production facility. With the trend towards Industry 4.0 the tasks of these automated transportation systems are increasing in complexity [1] (e.g. handling single work pieces to machines, collaborating with workers or fleet self-organization). This new generation of AGVs, mobile assistance systems or mobile logistic assistant (further generalized as mobile robots) requires new technologies to fulfill tasks like collaborating with humans or other AGVs. The wireless communication of the mobile robots is the focus of this work.

The goal of this work is to deliver steps towards the inclusion of ad-hoc communication technologies to the factory floor. Ad-hoc communication solutions have the distinct advantage, that they do not rely on network infrastructure. This contrasts the more common infrastructure networks. Due to the defined goal, the following aspects of the mobile robot communication are being focused on:

1. The influence of the wireless communication on the mobile robot performance not in terms of throughput or latency, but utilizing metrics more relevant to the mobile robotics application, like the completed transportation tasks per hour
2. The ability to model and simulate the complex interaction between mobile robot, industrial environment and wireless communication
3. The inclusion of Mobile Ad-hoc NETworks (MANETs) and Delay Tolerant Networks (DTNs) to the factory floor for communication between mobile robots
4. Utilization of mobile robot movement for network coverage optimization

Hence, there are two main sections. Section 4 describing new metrics to evaluate robot communication and methods for the modeling, simulation and evaluation of these metrics. In section 5 three different ad-hoc communication systems are applied to the industrial use case. They are being designed and evaluated using the methods and metrics described in section 4.

This work contributes to different fields of research. Firstly, it contributes new methods, ideas and communication strategies to the field of industrial automation. New analysis tools for the industrial application are contributed to the research field of MANETs. And new modelling and simulation capabilities for industrial applications are contributed to the field of network simulation.

Due to the wide range of contributions of this work, some limitations in the scope were necessary. Whenever possible, the physical layer of the communication, is abstracted in the given descriptions. This leads to independence of the presented results from the utilized communication technology but also prohibits optimization on the physical network layer. Security is also quite important in the context of industrial communication, but security concerns could not be explicitly included in this work. Security features might be included in the abstracted physical layer of the presented solutions but these features inclusion can impact the performance of the presented methods and systems. Future work will explore further topics, that are relevant to this subject. For example: routing-layer security in mobile ad-hoc networks, Time Sensitive Networks (TSNs) for industrial applications, fleet control for AGVs, etc. The mentioned topics and other subjects are briefly mentioned in the following work, but their in-depth examination are subjects for future work.

1.1 Motivation

In the last decade the industrial environment began to change. The fourth industrial revolution, Industry 4.0, emphasises flexible production facilities [1, 2] and efficiently interconnected processes. The inclusion of cutting edge technologies, especially enhanced communication capability, enables these trends. Facilitating mobility within the factory is a key factor in enabling the pursued flexibility. The necessity of communication and inclusion of mobility requires the effective utilization of wireless communication technologies.

Today a wide spectrum of communication technologies are available when designing an industrial system. These include the IEEE 802.11 standards (often referred to as Wireless Fidelity (WiFi) or Wireless Local Area Network (WLAN)), Bluetooth, ZigBee, cellular network (Long Term Evolution (LTE) and very recently 5th Generation (5G)) and proprietary communication solutions like radar or VLC [2]. In todays factory almost exclusively networks with a cellular-like topology are used. These networks utilize specialised networking hardware (APs or Base Stations (BSs)) to enable communication between clients. However many of the present communication technologies also enable ad-hoc topologies and/or P2P communication. With the exception of Wireless Sensor Network (WSN) these topologies are rarely utilized by the industry. Using these topologies to enable or improve mobile wireless communication is a central motivating factor for this work.

Some important networking trends are also influencing the shape of the factory of the future. The previously mentioned WSNs for example enable many predictive maintenance applications. TSNs enable networked control system for factory automation [3]. And Software-Defined Networks (SDNs), e.g. Software-Defined Wireless Sensor Networks (SDWSNs) [4] enable the virtualization of communication systems and a more fine-grained and intelligent control over the network.

The vision is, that the ad-hoc communication does not replace infrastructure networks, but expands upon them. In future factories multiple communication technologies will be present and balance each others weaknesses. At the same time the workload regarding network setup and management will be reduced by automated systems. The flexibility and the multi-modal communication will enable new use cases and applications like Virtual Reality (VR),Cloud Robotics (CR) and more.

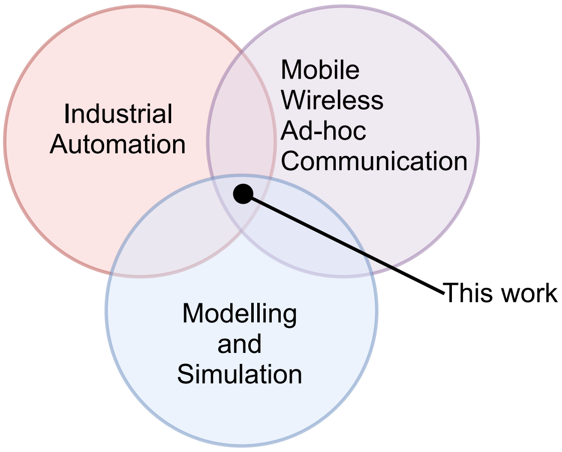


Figure 1: The three main research fields of this work.

1.2 Contributions and Limitations

The three research fields most relevant to this work are summarized in Figure 1. A more detailed description follows:

Industrial Automation
The field of industrial automation focuses on the possibility to automate industrial processes. The field includes the application of the presented research. This work contributes new methods to control communicating mobile robots in the context of industrial automation and new methods of communication for these mobile robots. Additionally new methods and tools regarding the examination and simulation of these industrial processes are presented. The impact of the wireless communication on control systems of industrial mobile robots is an additional focus of this work.

Mobile Wireless Ad-hoc Communication
The research regarding mobile wireless ad-hoc networks currently trends towards the application of specialized networks to specific use-cases (e.g. underwater networks or Vehicular Ad-hoc NETworks (VANETs)). In this work the specific application of mobile industrial networks is examined. New communication methods as well as modelling and simulation tools for this application are introduced by this work.

Modelling and Simulation
There were previous efforts to combine the simulation and modelling of communication systems and robotic systems. In contrast to these previous efforts, this work focuses on the application of communicating mobile robots used for transportation tasks. Additionally new methods and models for the simulation of the industrial environment are presented.

From all of these fields different research questions are addressed in this work. The presented work started from the question: *How can mobile robots in industrial applica-*

tions effectively utilize ad-hoc networking technologies? From this very general question, more precise research questions were formulated. The two questions: *What metrics can represent the impact of communication technologies on the effectiveness of mobile robots? And which methods are suitable to simulate/estimate/predict the effects of the communication technology?* These question mostly concern the methodology of this work and describe the tools and methods used to answer other research questions. These other question concern the effective utilization of ad-hoc communication by the mobile robots. An often requested feature for industrial communication is real-time data exchange. Therefore a presented question was, *if ad-hoc networks can provide a real-time channel for inter-robot communication ?* Secondly, applications with a low number of mobile robots were of concern. Accordingly, the presented research question is: *How can ad-hoc communication enable communication is a sparse robotic network?* This question is especially relevant if low-range communication is investigated. Lastly, the application of communicating mobile robots does not only provide specific challenges but also offer specific opportunities. Therefore an examined research question was: *How can the mobility of the clients be controlled to optimize the coverage of the network in a factory environment?*

The contributions of this work are answers to the research questions and observations that were made while conducting this research. The most central contributions of this work are listed below:

- A number of methods and models are introduced to characterize and model industrial ad-hoc networks. This includes a novel simulation tool for these networks with a focus on scalability and precise modelling of the industrial use case. These tools and methods enable researchers and engineers to estimate the performance of industrial ad-hoc networks and to observe the impact of the wireless communication on multi-robot-systems in industrial applications.
- Different ad-hoc networks are implemented and tested in industrial applications. This includes a MANET and a DTN. The performance of these systems is observed and their suitability to different use cases concerning mobile robots in industrial applications is examined. These implementations are used to validate the previously introduced methods and models and to present the usefulness of these methods for the development of industrial ad-hoc networks.
- Lastly this work also contributes new control algorithms to the field of mobile robotics. Different algorithms are developed, that control mobile entities for the optimization of coverage of an industrial MANET. Such algorithms were not previously described in a way, that they adhere to the specific requirements of industrial applications.

1.3 Structure

The current section Section 1 describes the motivation for this work as well as the contributions and structure of the following sections.

Section 2 highlights two use-cases that examplify the usefulness and goals of this work. Additionally the benefits of the developed tools and methods are described from the point of view of the industrial application.

The related work regarding ad-hoc networks, industrial communication and network simulation is discussed in Section 3. In the related work existing systems and methods and their applicability to the examined industrial use-case are described. The new contributions of this work to the existing context is emphasized. Additionally the industrial application and the specific characteristics and requirements of this application are described.

In Section 4 new metrics and methods for the evaluation of industrial wireless communication are introduced. Additionally existing methods and metrics are examined for their applicability to the context of mobile ad-hoc networks in industrial environments. A particular goal of this section is the introduction of models and tools for the simulation of communicating mobile robots in an industrial environment, which utilize ad-hoc networking technologies. The impact of these technologies on the performance of the robotic systems shall also be simulated. This section includes the proposal of new models and improvement of existing models.

The developed and presented methods and metrics are applied to three different communication systems in Section 5. Firstly, the characteristics of the ad-hoc channel in industrial applications are examined. Afterwards three industrial communication tasks are solved utilizing three different ad-hoc communication technologies.

1. Safety-critical messages are transmitted in a multi-hop fashion between mobile robots, providing real-time-like links.
2. A DTN is implemented in an industrial environment and provides new communication abilities in a sparse network and challenging environments.
3. A system is described that utilizes the controllable movement of robotic client to improve the coverage of a MANET in a production facility.

All of these systems are modelled and examined using the novel methods and tools previously described.

1.4 Published works

Several conference and journal articles were published in preparation for this work. This work is based upon these published articles and expands their content. The following table contains all preliminary works and a brief summary of contents in chronological order.

Table 1: List of published works

Reference	Title	Central content
[5]	Flooding-Based Network Monitoring for Mobile Wireless Networks	A protocol for real-time-like communication in ad-hoc networks is proposed, implemented and tested in industrial applications. Section 5.2 expands upon the contents of this publication. The co-authors mainly contributed as reviewers in the process of publication preparation and as advisories during the concept state.
[6]	Simulating Mobile Networks for Industrial Applications	This work proposes to use a game engine a base for the development of a combined network and robotic simulation tool. Section 4.2.4 expands upon the contents of this publication. Patrick Prozke helped in the software implementation and empirical validation. The other co-authors mainly contributed as reviews in the process of publication preparation and as advisories during the concept state.

Table 1: List of published works

Reference	Title	Central content
[7]	Delay Tolerant Networks in Industrial Applications	This work examines the possibility to use delay tolerant networks in industrial applications and proposes a statistical model to estimate the expected performance of such networks. The content of this paper is the main source for section 5.3 and methods presented in section 4.2.3. The co-authors mainly contributed as reviewers in the process of publication preparation and as advisories during the concept state.
[2]	Wireless Communication in Industrial Applications	Industrial applications are surveyed and communication technologies compared. This work finds that only a combination of technologies will be ableto fulfill future requirements. This work is not explicitly the content of any specific section but mostly regards the industrial context and current state of the art The authors contribution to this work was mainly in the field of ad-hoc communication and the industrial context.

Table 1: List of published works

Reference	Title	Central content
[8]	Advanced Models for the Simulation of AGV Communication in Industrial Environments	This work expands upon [6]. The work proposes and selects models and methods for the simulation of industrial, robotic-based ad-hoc networks. This work was the basis for many of the simulation models described in section 4.2.4. The co-authors mainly contributed as reviewers in the process of publication preparation and as advisories during the concept state.
[9]	On Ad Hoc Communication in Industrial Environments	In this work the properties of ad-hoc communication channels in industrial environments are examined. NEPs are used to analyze the density and dynamic of the potential ad-hoc networks. The methods presented in this article are recapitulated in section 4.2.1, while the findings are present in section 5.1. The co-authors mainly contributed as reviews in the process of publication preparation and as advisories during the concept state.

Table 1: List of published works

Reference	Title	Central content
[10]	Real-time Alarm Dissemination in Mobile Industrial Networks	A scheme is proposed to disseminate safety-critical messages within an ad-hoc network. The dissemination system is combined with the FBNM system from [5] to notify participants if the current network state does not allow for the time-critical dissemination This paper is part of the content presented in section 5.2. Eike Lyckowski majorly contributed to the statistical analysis of the available data. Other co-authors mainly contributed as reviews in the process of publication preparation and as advisories during the concept state.
[11]	SDN Controlled Visible Light Communication Clusters for AGVs	In [2] the combination of multiple communication technologies to reach industrial communication requirements is proposed. In this work the use of SDNs to coordinate the routing between technologies and to exploit global fleet management information for a more efficient routing is proposed. The contents of this paper are an example application for industrial ad-hoc networks, given in section 2. The authors contribution to this work was giving access to an test bed for the empirical experiments.

Table 1: List of published works

Reference	Title	Central content
[12]	Mobility Models for the Industrial Peer-to-Peer Context Based on Empirical Investigation	The common mobility models RWPM and Manhattan are examined and improved for a more precise modeling of industrial AGV movement. The presented mobility model are expanded upon in section 4.2.4 of this work. The co-authors mainly contributed as reviews in the process of publication preparation and as advisories during the concept state. Eike Lyczkowski also majorly contributed to the finding and fitting of probability distribution functions.
[13]	Testing AGV Mobility Control Method for MANET Coverage Optimization using Procedural Generation	This work contains two contributions. Firstly, a method for the procedural generation of simulated factory environments is introduced. Secondly, a mobility control method is introduced which enhances the coverage of an ad-hoc network of mobile clients. This network is tested in the procedurally generated factories in order to prove its functionality independent from the application environment. The developed system and methods are described in the sections 4.2.4.8 and 5.4. The co-authors mainly contributed as reviews in the process of publication preparation and as advisories during the concept state.

Figure 2 presents the relationships between the works summarized in Table 1. The properties of the industrial use case are investigated in [2] and [9] in terms of communication requirements and channel characteristics. The insights generated in these works

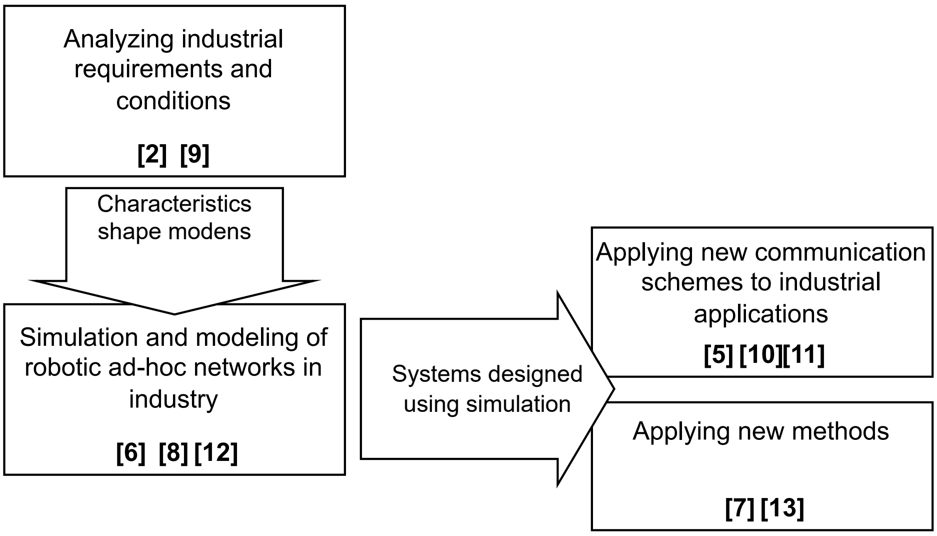


Figure 2: Relationship between published works

are used to shape and parameterize the models and methods proposed, developed and tested in [6], [8] and [12]. These methods are the bases to apply new communication technologies and schemes to the industrial use case ([5, 10, 11]) and to develop novel communication [7] and AGV control schemes [13]. [7] and [13] have, in contrast to [5, 10] and [11], a focus on the development of new methods for the prediction of communication performance.

2 Use Cases

The goal of this chapter is two-fold. Firstly, this chapter presents two use-cases, which illustrate the benefits provided by this work. They show how the results presented, and tools published in this work can be used. Secondly, the chapter describes the expected advantages of ad-hoc communication in industrial environments compared to more common infrastructure networks.

Within the field of ad-hoc communication research a current trend is to investigate the applications of ad-hoc networks to specific scenarios or environments. Previous work showed, that in order to produce meaningful results an ad-hoc network must always be examined under conditions mimicking or identical to the expected use-case [14]. Cavilla et al. [14] illustrates this for indoor scenarios like the industrial use-case. Some other applications specific networks examined in the last years are for example VANETs [15] and Flying Ad-hoc NETworks (FANETs) [16]. In these applications the specific requirements, environments and movement patterns of clients are considered in the design of communication systems. Based on these considerations specialized networking and routing strategies are applied, which offer unique advantages to the specific use-case. In this work identical considerations are made for the industrial application.

2.1 Example Use-Case

In the following section three example use cases are presented. The first illustrates an application of the presented methods, models and tools, while the next two focuses on the benefits gained by implementing different types of proposed ad-hoc communication.

2.1.1 Example Use-Case for the Proposed Tools, Models and Metrics

When evaluating and predicting the performance of networked robotic systems, capturing the impact that the communication has on the operation of the robotic system is important. The communication solution can be evaluated either in terms of network metrics (throughput, latency, jitter,...) or the robotic system in terms of robotic metrics (functionality, speed, energy-consumption, ...). The robotic system impacts the network and the network influences the robotic system. Therefore, in this section a number of relevant or common metrics for this interaction are introduced, before describing the use case.

Figure 3 presents the interaction between a robotic system and its communication system. The operation of the robot depends on the availability and quality of the wireless communication channels. On the other hand the mobility and characteristics of the robot operation affect the wireless channels on which the wireless communication depends. Any system that wants to evaluate the applicability, effectiveness and performance of a communication technology to a robotic system must model this interaction. In the past this interaction was not always reproduced / modelled correctly.

Modern factories are planned and built with wireless communication in mind. Therefore certain requirements are often set, when designing the networking infrastructure.

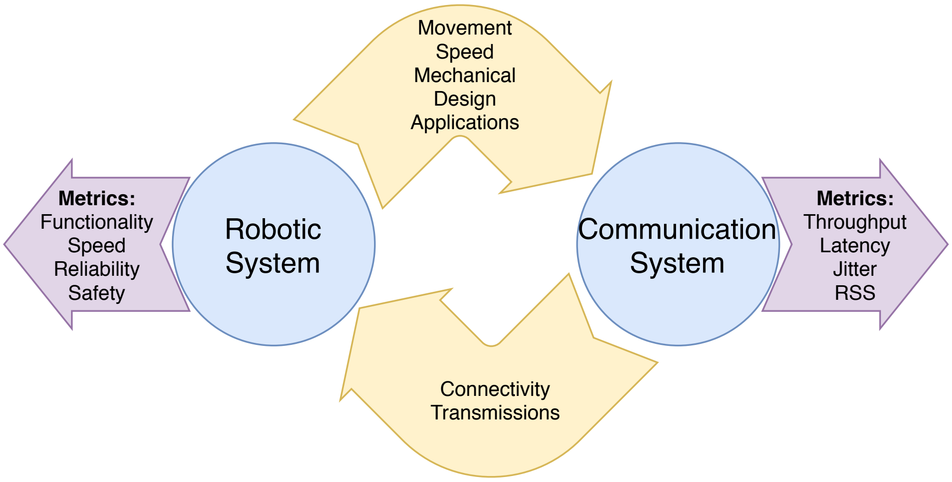


Figure 3: Interactions between a robotic system and its communication system. Including the metrics resulting from both systems.

However, these requirements are often based on networking metrics. E.g. a minimum Received Signal Strength (RSS) must be reached at all positions. These requirements are applied, because they are testable and seem to indicate a certain performance or coverage. However, observations show that fulfilling these requirements can often neither guarantee performance nor coverage. For example, if a minimum RSS is required, the easiest way to achieve this RSS is to use an excessive amount of APs with high transmission power. This however does introduce a high amount of interference and negatively influence the wireless communication. Other metrics like throughput, latency, jitter, Packet Error Rate (PER) or Bit Error Rate (BER) describe the performance of the wireless communication on different layers of the Open Systems Interconnection (OSI)-model. These metrics can be used to characterize the available communication, but they have two disadvantages. Firstly, their connection to the performance of the robotic system is complex and indirect. Secondly, their testability in a factory environment might not be a given. Requirements like "at all positions" are neither practical nor possible to test. Additionally they must also contain any possible combination of communication participant position and object positions in the environment. Evaluating an industrial wireless communication system solely on the network performance is therefore often not practicable.

The performance of the AGVs can alternatively be described in terms of robotic performance metrics. Often these metrics describe the ability of a robotic system to fulfill a certain task. This work assumes, that the AGVs are designed in a way, that allows them to fulfill the given transportation tasks. So the remaining metric is the performance and

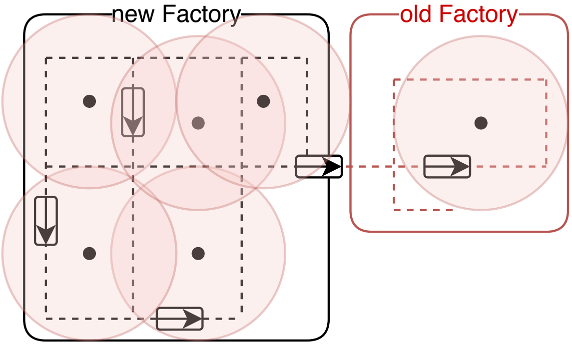


Figure 4: A new building shall be added to a factory. The new factory is build with AGV transportation and sufficient wireless communication in mind. The AGVs periodically require connection to the fleet management. The old part of the factory has non-complete network coverage. Can P2P communication between the AGVs be used to enable an effective operation of the AGVs, even with insufficient coverage?

reliability of the robotic system to transport goods within the facility. For AGV-systems this performance is often described as completed transportation tasks per hour per AGV ($T/h/AGV$). This metric is evaluated for the complete fleet of AGVs. The reliability is for example expressed as the average time till human intervention is required. Industrial automation generally has the goal to be autonomous for as long as possible. These metrics are only relevant to the presented use case, if their simulation / modelling also considers the impact of the wireless communication on the performance.

A possible scenario, in which modelling and simulation of interacting robotic and communication systems is necessary, is introduced in Figure 4. In this scenario an existing factory shall be expanded and modernized. The original factory had only limited network infrastructure and incomplete network coverage. The new factory is planned with wireless communication in mind. Additionally AGVs are introduced to the factory-floor. The open question, if the AGVs can service the old part of the factory, without installing additional communication infrastructure, is a resulting question for the presented use case. An ad-hoc network between the AGVs shall be implemented to bridge gaps in the coverage of the APs. The performance of the AGV-fleet depends on many parameters: The factory layout, the AGV-characteristics (e.g. velocity), the factory environment and the availability of communication must be considered.

The tools, proposed in this work, enable users to predict the behavior of the AGV fleet. The simulation tools can predict the transport performance of the mobile robots. The impact of different network design considerations can be checked. The tools and models are designed to help in planning of future factories.

2.1.2 Example Use-Case for Cooperating AGV using Ad-Hoc communication

A **MANET** can be beneficially implemented if data must be exchanged between mobile clients. Imagine the use-case of two AGVs cooperatively transporting a bulky object.

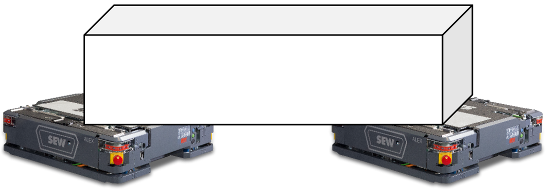


Figure 5: Use-case scenario: Two AGVs cooperatively transporting a bulky object.

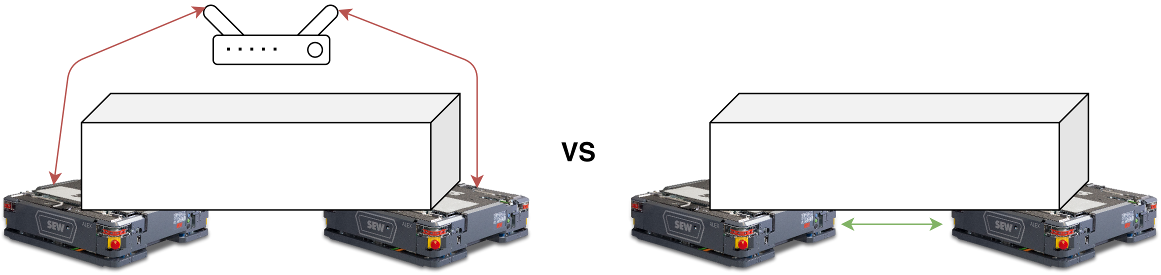


Figure 6: Two possible ways to implement communication between the leader AGV and the follower AGV.

Such a use-case is present in factories, where a heterogenous set of objects has to be transported by a homogeneous group of AGVs. In order to enable this use-case and to minimize the forces applied to the object minimizing the relative movement between both AGVs is a goal.

This use-case (see Figure 5) is often referenced as driving in formation or platooning. In these references one mobile robot is set to be the leader. The leader completes the necessary movement to complete the transport of the object. All other robots, that transport the object are classified as followers. The followers have the task to maintain the initial relative position to the leader as precisely as possible. In most implementations this is done with a control loop on the follower robot. The input of the control loop is the position and velocity of the leader robot, the output is the linear and angular velocity for the controlled follower. The parameters of the leader robot are (in most cases) more precisely and timely measured by the leader robot. Therefore the data (position and speed) has to be transmitted from the leader to the follower. The characteristics of the utilized communication link are essential for the resulting control error by the follower. Generally low latency and high reliability are desirable.

The air-channel bridged by the P2P-communication is much more benevolent, than the two air-channels required for the infrastructure communication (see Figure 6). The bridged distance is for example higher in the infrastructure scenario and less signal-attenuating obstacles are present. But more importantly the air-channels in the infrastructure scenario changes over time, while the P2P channel stays relatively unchanged due to the lack of relative movement. The relative movement between source and destination and the AP causes changes in the distances of and presence of obstacles on the signal propagation paths. Additionally the movement might cause handovers to other APs. All of these lead to packet loss and therefore increased latency / age of information for the control loop.

An important consideration is that the examined use-case is not an isolated system, when comparing communication solutions. An industrial wireless network (e.g. IEEE 802.11) is used by more than the two observed clients and impacted by this parallel communication. Other participants and external signal sources interfere with the communication. P2P communication enables the utilization of out-of-band communication in the form of state-of-the-art communication solutions like VLC or radar. These very local communication technologies have the advantage of low susceptibility / probability of interference and channel congestion. But they have the disadvantage of limited range and high susceptibility to blockage of the Line-of-Sight (LoS). Using ad-hoc communication enables the effective implementation of these communication technologies. Over-all utilizing P2P communication, if source and destinations are direct peers, often offers performance advantages.

2.1.3 Example Use-Case for industrial DTN

The other central advantage of ad-hoc communication is the coverage. Subsequently a use-case is introduced, where the introduction of a **DTN** offers new communication channels and is beneficial to the performance of an AGV-Fleet in a future factory.

Lets consider a future factory in which, during normal operation, parts of the factory are not accessible to humans. This allows mobile robots to, for example, reach higher speeds due to reduced safety concerns. In the considered factory the warehouse is build for autonomous mobile robot operation. A warehouse is one of the most challenging environments for wireless communication. The high number of signal-attenuating obstacles and moving objects decrease the coverage and performance of many communication technologies. Therefore in this use case example the mobile robots act autonomously within the warehouse. They enter the warehouse with a transportation task and leave the warehouse once the task is completed. During completion of the task communication is not required and might not be available.

Figure 7 illustrates the utilization of a DTN in the envisioned warehouse / factory. The process is described as following:

I. In the presented factory, warehouse and production zones are fundamentally different. In the production zone APs offer coverage for wireless communication. In the warehouse no wireless communication is necessary. Connectivity is therefore not or only sparsely available. In this scenario an AGV enters the warehouse.
II. Within the warehouse the AGV experiences a fault. For example an error in a firmware version. The central challenge is now, that humans must not enter the warehouse and at the same time the AGV has no connection to the fleet management to report the error or fix the firmware. This situation can only be resolved

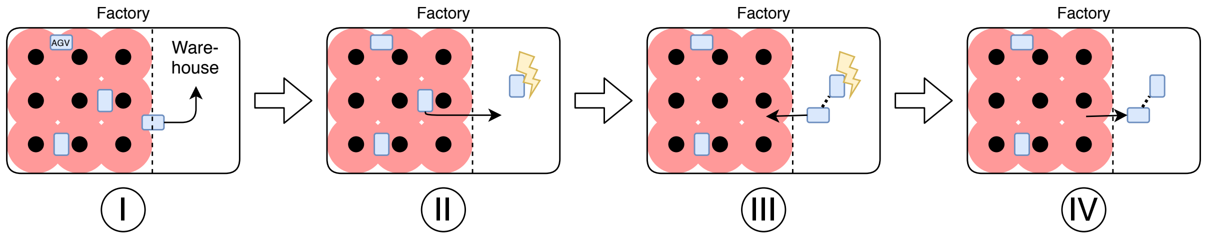


Figure 7: Utilizing DTN in the factory of the future. A faulty AGV transmits its error via a DTN from a low-coverage zone to the fleet control. Via the DTN a firmware update is transmitted to the faulty AGV, solving the fault.

with two options. First the network can be expanded to guarantee coverage in the warehouse. But this is costly. Secondly, through human intervention servicing of the robot can be achieved at the cost of disrupted operation in the ware house. However, indirect communication can offer a link between the AGV and the fleet management.

III. In this scenario a DTN offers the required additional indirect communication channel. A second AGV enters the warehouse during its operation. Once the two AGVs are within communication range, the first AGV sends an error/status message to the second AGV, which stores the message. The second AGV subsequently leaves the warehouse and transmits the message to the fleet manager.

IV. The fleet management decides to send a firmware update to the faulty AGV. This can either happen automatically or triggered by a human operator. The second AGV drives back into the warehouse and transmits the firmware update to the stuck AGV. The fault situation is resolved and normal operation commences.

The two described use-cases illustrate the usefulness of very different ad-hoc solutions for the industrial application. However any available solution must not only be applicable, but also economical to be applied to the industrial environment. The effects of communication solutions on the performance of robotic systems are highly complex. In this work new methods, models and simulation tools were created to enable predictions and estimations regarding the impact of communication on a robotic system.

2.2 General Benefits of Industrial Ad-Hoc Communication

Ad-hoc communication systems, in contrast to infrastructure communication systems, do not rely on network infrastructure. They create direct communication links between two or more communicating entities.

Utilizing ad-hoc communication in the factory scenario offers two distinct benefits. The ad-hoc communication firstly improves the performance of the communication channel and secondly improve the coverage of a communication solution.

In certain use cases (see Figure 8) direct P2P communication outperforms the communication in an infrastructure network. In infrastructure networks the BS or AP receives messages from the registered clients and repeats these, if the receiver is also within

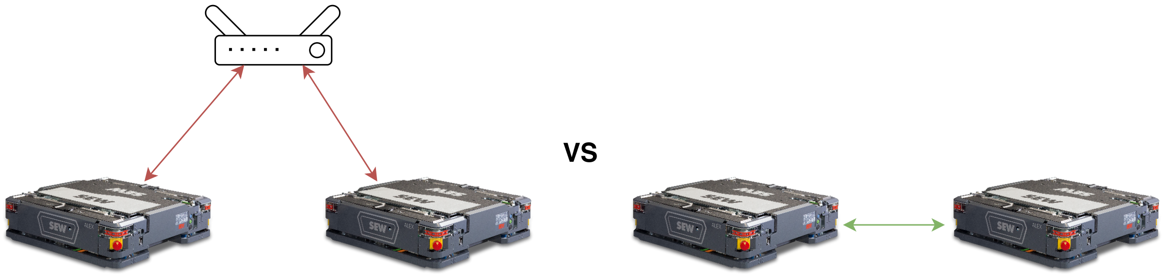


Figure 8: Comparison of infrastructure and ad-hoc communication in D2D use-case. Highlighting differences in propagation channel between clients and clients and infrastructure.

range of the BS or AP. This leads to two reasons for a better performance for P2P communication.

1. The transmission of data from the transmitter to the receiver only contains the direct transmission when using P2P communication. But in infrastructure networks the transmission contains at least three steps. The transmission by the transmitter, receiving and processing by the AP/BS and the re-transmission of the data by this infrastructure entity. These additional steps add delay and unreliability to the communications. The severity of these channel degradation depend on the second reason for worsened performance:
2. The characteristics of the air-interface between the source and destination clients are often better than the properties of the air-interface between source and infrastructure and infrastructure and destination, since the cooperation often requires physical proximity. Often the distance between the two pair in P2P communication is much smaller than the distance between the mobile clients and the infrastructure. Additionally presence of signal-attenuating obstacles is rarer, due to the smaller distance. The nature of many P2P applications (e.g. platooning [17, 18]) also leads to reduced relative movement between source and destination. This in turn reduced the number of handovers and other changes on the air-interface.

The reduced latency and raised reliability of ad-hoc communication are not applicable to all use cases. The use case of two mobile robots holding a formation is illustrative to this distinction. In this use case a leader robot follows a given path and a follower robot holds a defined position relative to the leader. If the movement control loop of the follower is running on the follower, than utilizing P2P communication is highly beneficial due to the previously described advantages. If the control loop is processed in the cloud (e.g. utilizing cloud robotics), then no benefit is gained by employing P2P communication.

But improved communication is not the only advantage of P2P communication, even more importantly P2P communication offers additional communication channels and

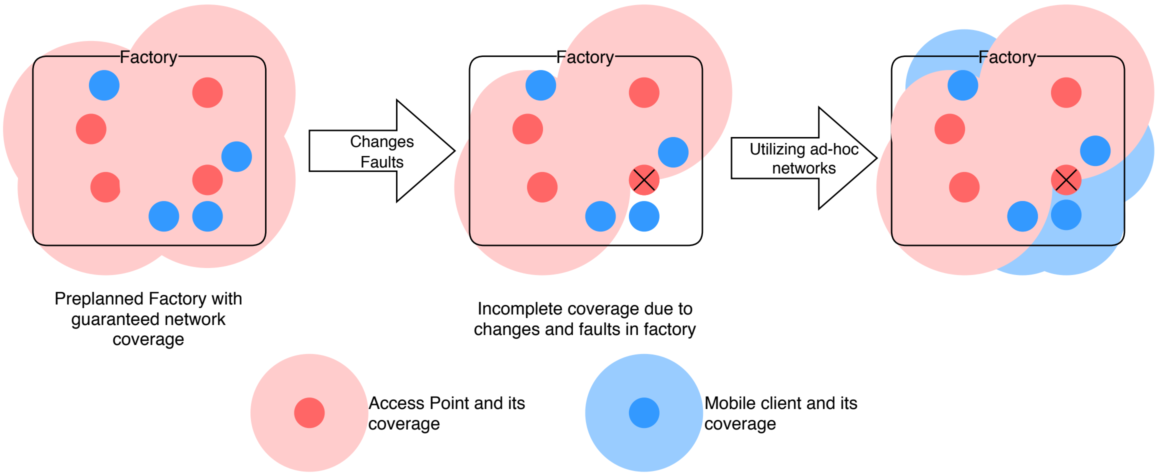


Figure 9: Simplified top-down view on factory. Originally the factory is planned to have complete coverage but changes in the environment and faults in the hardware create non-complete coverage. Ad-hoc networking is used to improve the coverage.

opportunities for data exchange. This can also be described as an increase in the communication coverage.

Figure 9 illustrates a common occurrence in factory applications. An often set requirement for industrial wireless communication is a full coverage of the factory. The coverage is mostly measured in terms of RSS of the closest AP. Modern factories are usually designed with wireless communication in mind. Extensive measurements are taken to place enough APs to guarantee the requested RSS. This process however has multiple disadvantages:

- The measurements are expensive in terms of cost, time and man-hours.
- Many metrics, like RSS, are not necessarily suitable to predict the effectiveness of a communication network
- Even small changes in the factory alter the signal propagation within and require additional measurements or lead to incomplete coverage
- Technical faults in the hard- and software lead to incomplete coverage

Therefore the guarantee of complete coverage is unlikely for any industrial environment. There are options to minimize the chance of incomplete coverage: for example placing an excessive amount of APs and extensive pre-operation testing and measurements. But these strategies increase the cost the the communication solution. Due to the inability to guarantee coverage, the examination of new solutions to improve the coverage is of high priority.

Utilizing ad-hoc communication (e.g. MANET and/or DTN) improves the coverage in a factory. The scale of this benefit depends on the type of the implemented ad-hoc network and used communication technology. Cellular networks like LTE or 5G might include Side-Link capabilities. When utilizing a Side-Link the range of a BS is expanded by one hop. Using a MANET expands the coverage by the maximum number of hops of this MANET. Lastly in some application a DTN might be applicable. These networks do not offer classical connections, but offer omni-present coverage. Possible use-cases for MANETs and DTNs are provided in the following section.

3 Related Work

This work relates to a number of fields of research. Most notably the research field of ad-hoc communication solutions and the field of industrial communication. Additionally methods from the field of numerical and statistical simulations are utilized. The field of mobile robotics is also relevant due to the characteristics of the mobile clients.

In the research field concerning ad-hoc communication solutions any system is examined, that enables direct communication between two peers. In this field research on all layers of the network is conducted. Goals are for example efficient and secure routing algorithms [19, 20], effective solutions for medium access management [21], communication security [22], the design of new methods for special applications [23, 24] and much more. In this work ad-hoc solutions are applied to the industrial application. The focus is on the selection and customization of effective routing solutions and their application the this special scenario. Changes to the lowest layers of the network are not part of this work, in contrast the chosen routing solutions must be implementable with a wide variety of communication technologies (IEE 802.11, VLC, etc.). Additionally, an implementation of physical layer security (e.g. encryption) is assumed. Routing-Layer security is not within the scope of this work. The inclusion of mechanism against routing layer attacks (e.g. Black-Hole-Attacks, White-Hole-Attacks) [25] or generally the inclusion of malicious nodes is part of future work. In the coming subsection 3.2 three different types of ad-hoc networks are described, which are all relevant to this work and the industrial application. These types are MANETs, DTNs and WSNs. Additionally works regarding the utilization of mobility for network coverage optimization are surveyed. This is a particular research problem from the field of robot networks and relevant to the examined industrial use case.

Industrial communication is a wide field of research concerning any kind of data exchange on the factory-floor. This work focuses on wireless communication, due to the mobility of the examined clients. Wireless communication is a special case in the context on industrial communication. But the wireless solutions continuously gain in importance and applicability for many industrial use cases [1, 26]. In terms of width, this field also encompasses all layers of the network. For this work the given industrial environment, industrial communication requirements and industrial use cases are of particular interest. This work is limited to the special case of mobile wireless communication. Indoor scenarios are not a particular focus, but, due to their prevalence in the industrial context, assumed. Subsection 3.3 describes current trends in the field of industrial communication, while subsection 3.4 generally surveys research work regarding wireless communication in the industry. The focus is on research regarding different communication technologies and standards and research that focuses on the characterization of the signal propagation channel in industrial environments.

Lastly this work utilizes methods known from the field of numerical and statistical simulation. In particular models are proposed or chosen and improved the emulate different aspects of communicating mobile robots in an industrial application. These models are specifically validated and subsequently utilized for different communication scenar-

Figure 10: AGVs in a production facility for electric drives.

ios. The adaption of wide-spread networking models to special use cases is an ongoing trend [14].
In the following subsection 3.5 relevant metrics, models and parameters are described. An additional focus is on a survey of available network simulation tools, robot simulation tools and hybrid simulation tools. The available tools will be evaluated in terms of applicability to the examined industrial use case.

3.1 Industrial Application

3.1.1 The Industrial Environment

Industrial environments are highly heterogeneous. A communicating AGV-fleet might be applied to electronics production, sawing mills, steel production or to car assembly lines. The environments and the effect of these environments on any applied wireless communication are therefore as heterogeneous as these environments. The environment impacts the design of the applied mobile robots, the communication use-cases, the requirements in terms of communication quality, the signal propagation within the environment, the availability of communication technologies, the design goals for wireless communication systems and much more.
The first thing to specify about an industrial application is the size. Factories are relatively large, when compared to other indoor scenarios, but small in comparisons to outdoor applications. Very small AGV-use-cases might only encompass $\leq 100\,\mathrm{m}^2$, while large applications include facilities of $\geq 500\,000\,\mathrm{m}^2$. For the application of ad-hoc networks, especially multi-hop ad-hoc networks factories of $\geq 10\,000\,\mathrm{m}^2$ are being considered. Most often the number of mobile clients (here i.e. AGVs) directly scales with the size of the industrial application. In today's application ≤ 10 to ≥ 100 mobile robots are used [27]. Systems with ≥ 1000 AGVs are already envisioned. The size of the application and the number of clients are often the most basic parameters to describe an ad-hoc network application scenario. Another important parameter is the movement of

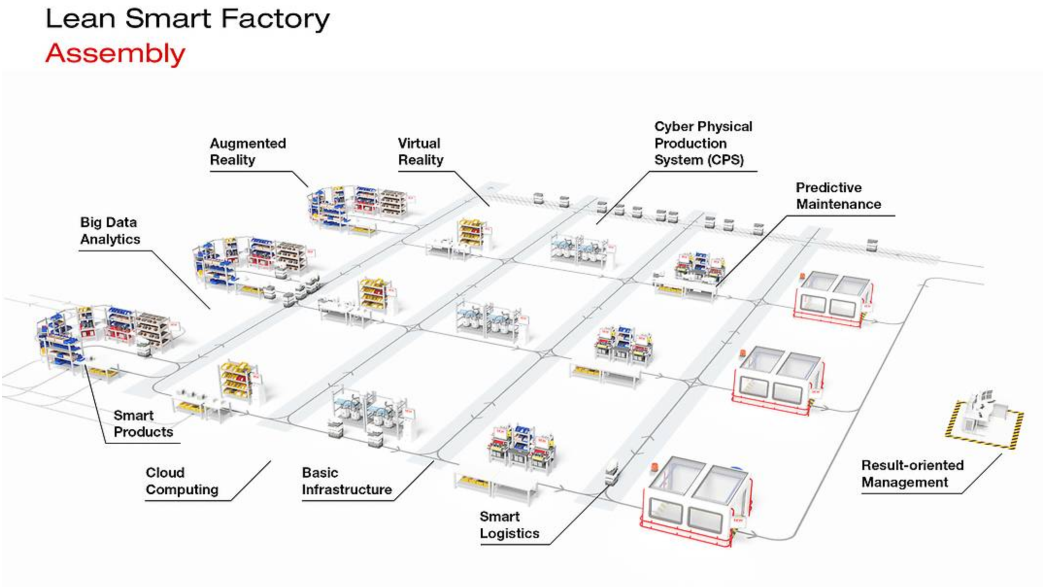
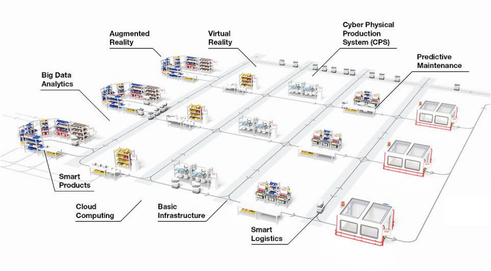


Figure 11: Envisioned factory of the future. Including path layout of AGVs within the factory.

the clients.

The movement speed of AGVs is relatively uniform for all applications, between $0.5\,\mathrm{m/s}$ and $2\,\mathrm{m/s}$ [28]. But for future applications speeds of up to $10\,\mathrm{m/s}$ are envisioned. Due to safety concerns these speeds are only achievable in isolated parts of a factory, in which no interactions with humans occur, for example a ware house. But not only the speed of the clients in important, when describing their movement. The movement pattern is also highly relevant. Often simplified models like the Random Way-Point Model (RWPM) or the Manhattan model are applied (e.g. [29, 30, 31, 32, 33]). Figure 11 summarizes some of the concepts and paradigms that shape the factory of the future, including a likely layout for a future factory. The figure shows, that, while the Manhattan model might be applicable, other models like the RWPM or the random walk mobility model are far to abstract to accurately represent the AGVs mobility. Therefore the selection and design of such models requires custom adaptions to the industrial use-case. The proposal of new mobility models for this use-case is one of the contributions of this work as well as the modification of other models.

Industrial environments are highly heterogeneous. Figure 12a shows the concept a modern factory, that adheres to the matrix production principle. This factory was planned from the ground up with Industry 4.0 in mind. They are described as green-field factories, since their inclusion of Industry 4.0 paradigms and technologies started at the empty green field, rather than with the existence of a previous factory (i.e. brown-field). These factories have two advantages in terms of wireless communication. Firstly, the wireless coverage within the factory is often planned before building the factory. In the



(a) Matrix Production

(b) Brown-Field Production

(c) Arc furnace in steel mill [34]

(d) Obstructed ware-house[35]

Figure 12: Examples for industrial environments

design phase of the factory, simulations of the signal propagation and/or surveys of the RSS are conducted [36]. Secondly, the grid-like layout enhances the range of wireless communication along the transportation paths within this factory [37].

In Figure 12b a brown-field factory is shown. In this production facility electric drives and gear-boxes are produced. This factory was planned and build as a modern factory before the trend of Industry 4.0 and over the years modernized to incorporate Industry 4.0 standards. In such an environment wireless communication is far more challenging than in the previous example. Reaching the same communication quality and reliability as in the example of Figure 12a instils far higher costs in terms of money and man-hours. The number of signal-attenuating obstacles is far higher and the effective placement of network infrastructure is often not possible.

Figure 12c shows another industrial environment with challenging environmental conditions on the mobile robot. In this environment the most demanding requirements concern the mechanical design of wireless communication equipment and the robotic system. Placing off-the-shelf wireless equipment in such environments might not be possible due to the environmental conditions (e.g. temperature, vibration, mechanical robustness). Or the design and installation encores higher costs, than in less demanding environments. The figure also presents an extreme scenario, for which the influence of steel mill equipment and molten metals on wireless communication systems is to the best of our knowledge unknown. In this and other extreme environments the redundancy and self-repair characteristics of ad-hoc solutions offer unique advantages.

Even the pre-planning capabilities in green-field factories does not avoid all environments, that are demanding for wireless propagation. One such environment is presented in Figure 12d, which shows an automated warehouse. In contrast to many other industrial applications the clients in this scenario might even move three-dimensionally, not two-dimensionally. Additionally the number of signal-attenuating obstacles is very high while at the same time communication ranges of up to $\geq 50\,\mathrm{m}$ might be required due to the size of the ware house. The placement of communication infrastructure is also often impeded due to limited space and many moving/moved parts.

In the previous section the heterogeneity of industrial environments was presented. Additionally the challenges arising from these environments are described. In terms of wireless communication these environments are described as scattering-rich and show strong multi-path components [38]. The presentation of the different industrial environments is by no means complete, but shows an adequate cross-section of industrial applications. The technologies (robotic and communication) applied to these use-cases are presented in the subsequent sections.

3.1.2 Mobile Multi-Robot Systems in the Industry

Mobile Robots in industrial applications fulfill a variety of tasks. Figure 13a presents three different types of mobile robots for the factory floor. On the left an AGV for the transport of standardized boxes, containers or crates is shown. Within these crates up to $1500\,\mathrm{kg}$ of material, tools or waste are transported. The central mobile robot was designed to assist workers in the assembly of heavy machinery. Work pieces are placed on top of the robot. The robot automatically navigates between assembly point in the production process of the currently transported piece. The right-most mobile robot is equipped with a 6-Degrees of Freedom (DoF) robotic manipulator. With this robot arm, simple manipulations of work pieces are automated. Additionally this robot is able to feed work-pieces to other machines or robots. All of the three robots are designed for the same kind of indoor industrial environment.

The next example of an industrial mobile robot (seen in Figure 13b) in contrast is build for outdoor applications. This robot was designed to transport shipping containers within a container terminal. The last example (Figure 13c) is a specialised AGV for the transport of explosive material, but for a similar environment, as the first three examples.

The structure and components of AGVs are fairly standardized [41] . These components are:

Tool

A tool to fulfill the given task. For example the 6-DoF robot arm, a conveyor belt, a hoisting mechanism or similar.

(a) Variants of AGVs by SEW-EURODRIVE GmbH&Co.KG

(b) AGV for outdoor container terminal [39]

(c) AGV for carrying explosives [40]

Figure 13: Examples of mobile robots for industrial use-cases

Drive / Drive-Train
The drive / drive train describes a system of parts, that allows the mobile robot to move within the environment and to reach the desired position for the tool. Most industrial mobile robots are wheeled robots, that use drive designs like differential robots, mecanum-wheels or an Ackermann-drive [42].

Navigation and localization
The mobile robot must know its position within the factory to reach desired destinations. This is usually combined with a system to avoid obstacles and plan routes to destination. Systems like Simultaneous Localization and Mapping (SLAM) or guiding wires are used for localization and as a basis for navigation. Localization systems based on the RSS or Received Signal Strength Indicator (RSSI) of communication technologies have also been introduced to the factory floor for localization [43].

Processing
One or more processing units are required to fulfill the necessary processing tasks in controlling the AGVs actions.

Communication
The mobile robots in industrial applications require communication to other devices. For example to exchange data with other mobile robots and machines to cooperate with them or to coordinate tasks. And the mobile robot communicates to a CCU, that coordinates the movement and tasks of the AGVs [44]. Utilizing wireless communication is a given, due to the mobility of the clients. Different communication technologies are applied. In the past infra-red communication was often applied. Currently the IEEE 802.11 variants are widely used. And new technologies, like cellular networks (i.e. private LTE and private 5G), radar communication and VLC are being tested for the use case of AGVs.

Single robots are rarely used in industrial applications. More frequently AGVs-fleets are applied. In these systems multiple robots solve tasks cooperatively or in parallel. The number of robots in a factory varies between a few and a few hundred [27]. In the future even factories with thousands of robots are envisioned. The robotic groups are either homogeneous, meaning all robots are the same, or heterogeneous, meaning that different types of robots cooperate. Due to maintainability and redundancy a homogeneous group of robots is desirable, but in some cases the heterogeneity of the tasks requires the same heterogeneity in terms of robotic systems.

The AGVs in the factory are rarely fully autonomous. In most cases their cooperation and coordination is controlled by a CCU. This unit interfaces with other enterprise systems to enable an effective deployment of the AGVs. The standard VDA5050 for example uses this architecture [45].In contrast, if CR is the applied type of robot control, even the low-level kinematic and localization tasks of the mobile robot are performed by the cloud (i.e. one or more centralized control units) [46].

Herrero-Perez et al. [47] introduced a decentralized control system for AGVs. This control system avoids dead-locks, while respecting critical safety zones. Even this system utilizes a centralized auctioning system to select the most appropriate AGV for a task.

3.1.3 Robot Communication

Figure 14 describes the most prevalent form of communication from or to mobile robots on the factory floor. Many of the tasks of the mobile robots require availability and a certain quality of communication. The communication is classified as one of two categories regarding the communication partner of the AGV:

1. **Communication with other machines on the factory floor**
   Communication to other clients on the shop-floor is necessary for local cooperation and coordination. An AGV might for example exchange data to a machine or storage facility before transferring the transported goods to the other clients. This data concerns for example the source, type or status of the transferred goods. Two AGVs might also directly (or via AP) communicate with each other. Typically exchanged data might be robot status, traffic information or navigation data. Local communication with a user/human via a hand-held device might also be beneficial for example for trouble-shooting, remote control, maintenance or setup. All of

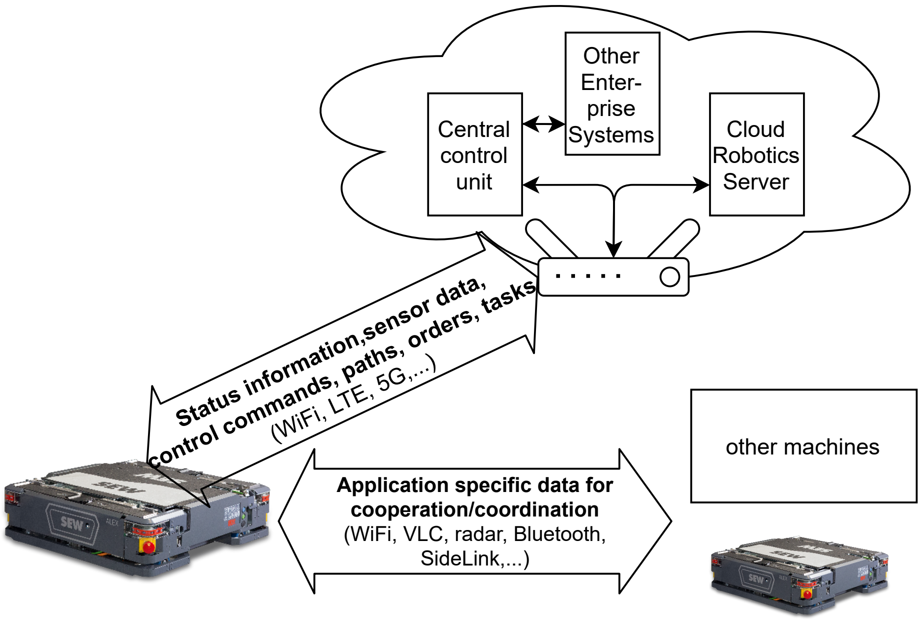


Figure 14: The two main types of communication of mobile robots in an industrial communication. Included are also examples for communicated data and available communication technologies

the above mentioned communication can either utilize a P2P-link or a link via an BS or AP.

2. **Communication with network-based services**
   The factory and the material flow within the factory is most often controlled by enterprise systems like SAP or ERP . These systems manage orders and capacities within the factory for an efficient utilization of the available resources. They interface with the CCU of the AGV-fleet. This system distributes order information to the AGVs. The efficient usage of AGVs without such a coordination tool is only possible in rare scenarios. Additionally some systems on the shop-floor might not be available via P2P communication but only accessible via an interface in the enterprise network.

Some often used communication protocols in the context of mobile industrial robots are for example the Transmission Control Protocol/Internet Protocol (TCP/IP), User Datagram Protocol (UDP), Message Queuing Telemetry Transport (MQTT) and WebSocket connections. For maintenance the HyperText Transfer Protocol (HTTP) is also often used. The frequency and amount of send data over these protocols highly depends on the examined application. Subsequently a number of communication use-cases for mobile industrial robots are described and compared. Examples for the utilized communication protocol and communication technology are given.

The most common form of communication in current industrial multi-robot-systems are so called order information. An order describes a task for a mobile robot. For example, to get a crate or object from a certain position and deliver the crate to another position. These orders are issued by a CCU within the enterprise network and received by the mobile robot. The frequency in which these orders are issued is fairly low and only a small amount of information is transmitted. These orders are typically send via IEEE 802.11 or cellular networks. Often used Protocols are UDP, TCP/IP or MQTT. Only very little bandwidth is required and transmission delays of up to several seconds are tolerable. Of a very similar type are the status updates, that are send from the mobile robot to the CCU. They are sent once every 10 to $30\,\mathrm{s}$ and have the same communication requirements. These updates contain for example the AGVs position, status, speed and battery state among others.

However, the specific implementation of this type of communication might differ from the standard, since many manufacturers of AGVs use proprietary communication. For example, instead of sending orders to final destinations these orders can also be send for each way-point between the starting position and the destination. The interval of sending the current AGV status to the CCU might also be as low as $\leq 500\,\mathrm{ms}$.

Another use case is the remote control of the mobile robots. Remote control is applicable in two different scenarios. Firstly, the robots might operate under the principle of Cloud Robotics [48]. Secondly, the robots might be remotely controlled by an operator. In both cases the server or operator reacts to sensor data received from the robot and issues movement commands to the robot. In case of cloud robotics raw sensor data is sent to the server, while for remote control by an operator a live-video feed is the most likely form of sensor data. In both cases a high throughput for the up-link from the robot to the network is required and the latency of both the up-link and the down-link must be minimal. Often UDP or TCP/IP is used for the communication and the IEEE 802.11 standard or cellular networks are often applied communication technologies [46, 1].

Lastly, the operation of mobile robots often requires cooperation between machines. These machines might be other mobile robots or stationary equipment. This communication is necessary to coordinate actions. For example cooperatively transporting a bulky object or transferring a crate to a storage facility. In both cases the amount of transferred data is relatively low. But the delay of the data is of high importance. UDP and TCP/IP is often used for this communication. Standards communication technologies like IEEE 802.11 and ZigBee or Bluetooth are often applied but also specialized technologies like radar communication or VLC are used [2].

Additionally, mobile robots are often not the only clients that use wireless communication. Different machines and tools use the same medium and hand-held devices often use the same communication technologies or a different technology within the same frequency-band [49, 50]. Therefore interference by these devices has to be expected.

3.1.4 Industry-specific Challenges

There are particular challenges to the industrial context, which are not common in other use cases. Challenges arise from the application of wireless communication technologies, the industrial environment, the mobile robots, the required communication and the utilized control systems.

The industrial environment has previously been characterized as particularly challenging for wireless communication due to the high impact of multi-path propagation [38]. The challenge of the high number of signal-attenuating obstacles is further increased by the presence of many conductive materials. Therefore, the signal propagation characteristics in this environment are very relevant to the applied communication technology. A characterization of these properties is an important challenge tackled in this work.

Other, non-technical, challenges are present in the industrial application. The frequency channel might already be occupied or reserved for other systems. The industrial environment is quite dynamic. Smaller changes like machine parts, mobile robots and the movement of crates constantly change the propagation characteristics. Additionally bigger changes, like new machines and storage facilities are observed regularly, which more drastically change the propagation environment.

The high number of clients in the industrial environment are also a challenge. Different sensors, tools, hand-held devices, machines and other clients saturate the wireless channel [51]. Other sources for electro-magnetic noise (e.g. electrical drives) might also impacts the communication.

Another challenge concerns the movement and placement of communicating clients. The movement of the mobile clients is highly restricted to predefined paths. The mobile robots must not stay at all positions for prolonged durations, since they block paths or positions.

Guaranteeing connectivity and coverage in such an environment is hardly possible. Ad-hoc systems can be used to alleviate some of these challenges.

3.2 Ad-Hoc Networks

Ad-hoc networks are wireless communication networks, that rely on the direct communication between clients without requiring network infrastructure like APs or BSs [52]. Different types of ad-hoc communication solutions have been applied to a wide variety of applications.

MANETs describe networks with relative movement between the clients. This relative movement leads to time-variance in the network topology and therefore complex routing challenges [53]. They are often applied in scenarios, where mobile clients require communication, but infrastructure is either unavailable or has been destroyed [54].

Another type of ad-hoc network are DTNs. MANETs assume, that at any time a route between any two clients can be found. In DTNs a more sparse network deployment is assumed, in which clients remain disconnected for a prolonged duration of time. DTNs were originally proposed for interplanetary space-probe communication [55, 56]. But they have also been applied to use cases in which clients were spread sparsely and no network infrastructure was available, like wild-life observation [57].

In contrast to the clients in MANETs or DTNs, the clients in WSNs do not move. These networks connect distributed sensor nodes, which sense information and collect this information at data sinks [58]. The focus of these networks is energy-efficiency. These

Table 2: Communication standards and supported topology

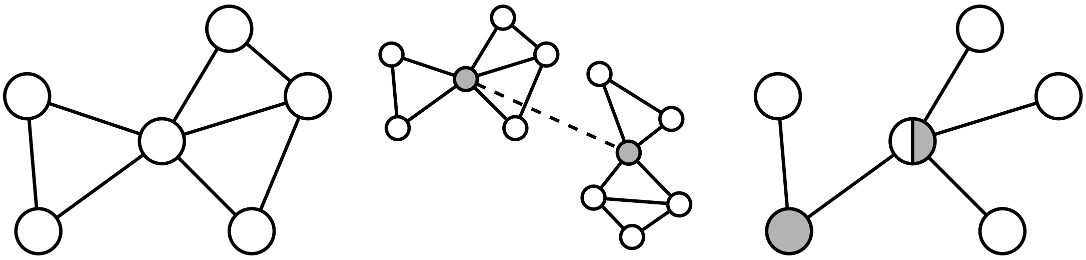
Communication technology	Available topology
IEEE 802.11	• Infrastructure • Ad-hoc (Mesh)
LTE, 5G	• Infrastructure + Side-Link
Bluetooth	• Peer-to-Peer • Scatter-Net
ZigBee	• Mesh

networks share certain properties with the systems developed and examined in this work, and are highly relevant due to their prevalence in industrial applications [59, 60]. The Mobile Sensor Network (MSN) is a variant of the WSN in which some or all of the sensors are mobile [61, 62, 63].

In the last decade many basic principles for the efficient implementation of ad-hoc communication were developed. The field of ad-hoc communication passed the hype phase of the Gartner hype cycle. Right now many researcher are looking into new applications for these technologies. VANETs are one of the most recent and highly anticipated applications for peer-to-peer communication. In the presented work the application of industrial communication is considered. The goal is t introduce the ad-hoc communication technologies to the factory floor. In [64] and [10] low latency communication for the transmission of safety-critical messages using a MANET was proposed. This is required in many industrial application scenarios. [7] introduces DTNs and the ability to predict the performance of DTNs to the industrial application. WSNs are already the most common type of ad-hoc network in industrial applications due to their role in the trend of Industry 4.0 and are only a side note in the presented work.

Ad-hoc communication is not possible with all types of communication technology. Many standards do not support any P2P-communication (e.g. 3G and lower), only very limited P2P-communication (e.g. LTE, 5G) [65, 66, 67] or P2P-communication in specific modes (e.g. IEEE802.11) [68]. Other standards like Bluetooth or ZigBee are explicitly designed for ad-hoc communication [69, 70].

Ad-hoc networks can have different architectures (examples in Figure 15). A general distinction is made between non-hierarchical and hierarchical networks [71]. In non-hierarchical networks all clients have the same roles, tasks and operate equally (as seen in Figure 15a). In hierarchical networks specific clients take the role as e.g. cluster-head (gray). Figure 15b presents an example hierarchical ad-hoc network. The cluster heads get additional tasks in terms of traffic management and routing. In the presented example the cluster-heads work as gateways between clusters. From a technical point-of-view all clients can fulfill these tasks, since they are technically identical in terms of capability. A scatternet is for example present, when using Bluetooth as the communi-



(a) non-hierarchical (b) hierarchical / clustered (c) Scatternet

Figure 15: Different topological structures for ad-hoc networks. Clusterheads/Master are shown in gray.

cation technology. In this topology a group of clients is divided into one master (gray) and multiple slaves. Every client can be master in up to 1 group and slave in multiple groups. A scatternet topology (like shown in Figure 15c) is the result.

Using ad-hoc communication has some advantages and disadvantages over using infrastructure or cellular network. The biggest disadvantage of ad-hoc networks is, that their performance in terms of throughput, latency and jitter is often worse, than the performance of an infrastructure network. Additionally ad-hoc networks scales negatively with the number of clients in the network [72]. On the other hand ad-hoc networks are independent from infrastructure and allow communication even in highly disconnected and challenging scenarios. Additionally this independence enable the utilization of mediums, in which the propagation characteristics impede achieving high coverage using infrastructure (e.g. VLC). Network infrastructure is often used to connect a wireless network to a wired back-bone network [26]. This functionality is necessary for the industrial application, but not always given in ad-hoc networks. The addition of gateways to the ad-hoc network is therefore required. This solution has previously shown to be effective, even in challenging use cases, like the industrial environment [73]. Another important advantage of infrastructure network is their simpler and less time-variant topology. Planing the coverage of an industrial plant is simpler for infrastructure networks [36], than for ad-hoc networks [74]. On the other hand an ad-hoc network often offers more than one route between a transmitter and a receiver, which adds reliability and lowers the risk of complete disconnection [75]. However ad-hoc networks are not meant to replace infrastructure networks in the factory of the future. Instead the addition of ad-hoc networks to the roster of available communication possibilities is meant to further enhance and improve the available communication.

The terms mesh and ad-hoc network are not always clearly separated. But in many instances a mesh network describes a certain type of ad-hoc network. In these networks multiple APs connect wirelessly in an ad-hoc fashion. This creates a wireless backbone network for the clients connected to these APs [76]. Many of the works regarding these mesh networks can also be applied to mobile robots [77], but they are generally optimized for static applications. In this work the desired network for the mobile robots will therefore be named *ad-hoc* network and not *mesh* network.

3.2.1 Mobile Ad-Hoc Networks

Mobile Ad-hoc NETworks (MANETs) are a special type of ad-hoc networks in which the clients are mobile. This introduces the additional challenge of time-variance in the topology. This means that routes in the network do not only need to be found but also regularly checked and updated [52]. This enhances the importance for efficient route search and maintenance strategies. In the literature routing algorithms are classified as either proactive or reactive. Many of the curent methods for mobile ad-hoc communication and metrics for the evaluation of this communication have been surveyed by Quy et al. [53].

A proactive protocol maintains a routing table to all other clients of the network at all clients in the network (also called table-driven) [52]. These networks show a very high performance in terms of latency for the first message transmitted between two clients since there is always a up-to-date route present at the transmitter. However these networks do not cope well with adding or removing clients. Additionally the performance worsens drastically on a bigger or more mobile network, caused by the amount of additionally required overhead traffic [78]. For these reasons proactive networks are only considered for small local sub-networks. These sub-networks are especially interesting for cooperative use-cases in which low-latency is of high importance.

In the following section some proactive routing protocols are surveyed. Destination-Sequenced Distance-Vector (DSDV) routing [79] is a next-hop routing algorithm based on distance vectors. This means, that the transmitter of a message does not know the full route to the destination, but only the next hop towards this destination. DSDV was developed to be loop free, require no internodal coordination and have a low spacial routing complexity. The Optimized Link-State Routing (OLSR) protocol [80] is based on a similar principle of finding the shortest route in a routing graph via the appropriate neighbour. This routing strategy optimizes the process of route/link-state advertisement by only advertising the link-states from a selected number of nodes. This reduces the amount of overhead introduced by the proactive routing approach. Lastly the Wireless Routing Protocol (WRP) [81] was designed as a efficient routing algorithm that reduces the probability of loops in the route. WRP showed a very high efficiency, compared to other state-of-the-art routing algorithms.

Reactive protocols only search for routes and maintain these routes, while they are actively used [52]. This reduces the overhead of reactive protocols, when compared to proactive ones. But this strategy also leads to a higher delay for the transmission of the first messages in a communication, since this initial message is delayed until a route is established. Compared to proactive protocols, these reactive protocols scale better in terms of number of participants and mobility of participants [78]. Therefore reactive protocols are considered as means for factory-wide communication in this work.

One of the first reactive routing protocols for MANETs was Dynamic Source Routing (DSR) proposed by Johnson et al. [82]. In contrast to DSDV and OLSR this protocol does not store the next hop towards a destination, but a complete route. This strategy is often referred to as source routing. This was introduced to guarantee loop-free routes. Ad hoc On-Demand Distance Vector (AODV) [83] again uses the next-hop routing strategy and distance vectors and is therefore the reactive counterpart to DSDV. AODV quickly adapts to a dynamic network and guarantees loop-free routes by using destination sequence numbers. Temporally-Ordered Routing Algorithm (TORA) [84] is another reactive routing protocol, which utilizes the "temporal order" of topological changes to be more efficient in handling large and dense mobile networks.

Hybrid routing is a mix of different routing approaches. In most of these protocols a sub-network is classified in which proactive routing is used, while reactive routing is used globally. Most of these protocols use other well-known proactive and reactive protocols for the respective parts of the routing [78]. The selection of the protocols and the selection of the sub-networks are differentiating the available hybrid protocols. Hybrid protocols also mix MANET routing with other routing strategies, like DTN [85].

The Zone Routing Protocol (ZRP) [86] is a routing strategy, in which zones around each nodes are defined. For destinations within these zones up-to-date routing table entries are maintained. For destinations outside of this zone a route discovery must be employed. However this route discovery also benefits from the available routing information of the zones.

Other routing protocols, like GRID [87], utilize additional information about network, clients or channel to offer more efficient routing. GRID in particular utilizes the location information of the nodes to extrapolate topology information and enhance the efficiency of the routing. Such a strategy is also be interesting for the investigated use case concerning robotic clients, since almost all mobile robots have knowledge about their local or global position.

Over time many of the well-known routing protocols have been adapted to fit specific applications or enhance aspects of their design. For example [88] and [75] added a back-up mechanism to AODV in order to enable Quality of Service (QoS) functionality. A link failure prediction mechanism was added to DSR [89]. OLSR itself is an improved version of a previously existing link state routing algorithm.

The mobility of the nodes is the central challenge of MANETs, when compared to other ad-hoc networks. This mobility leads to changes in the channel characteristics between transmitter, destination and all relay nodes. These networks therefore require far higher attention to the process of route maintenance and the route discovery itself must be more efficient. Static routing solutions are generally not applicable. Additional considerations have to be taken when designing or adapting a routing protocol for a specific use case, like the energy efficiency or robustness against very high communication delays.

MANETs have the same advantages and disadvantages as general ad-hoc communication with the added challenge, that continuous route maintenance requires additional resources and worsens the performance of the network. The challenge is comparable to the roaming in cellular networks.

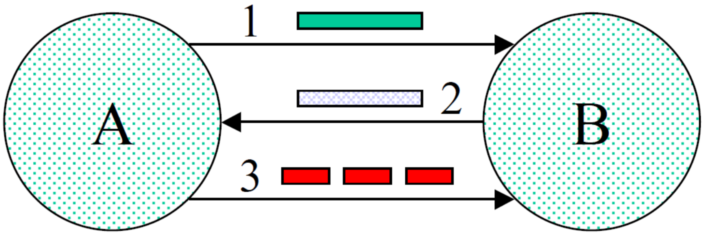


Figure 16: Message exchange in epidemic routing [94]

3.2.2 Delay-Tolerant Networks

Delay Tolerant Networks (DTNs) are a more sparse form of MANET. A MANET assumes, that at every point in time a route from a transmitter to a receiver can be found. However, if the network becomes increasingly sparse or the environment increasingly challenging some clients or groups of clients can entirely disconnected from the network. DTNs work on the principle of using the movement of the clients as a form of transmission medium [90]. The transmission in DTNs works with the principle of store-and-forward. This means, that all participants of the network store a message after reception and relay the message at a later point in time. Message ferrying [91, 92, 93] is a specific form of DTN in which the movement of a subset of nodes is controlled for an optimised transmission.

There is no classical routing since the network assumes, that no route is available. But there are algorithms, that govern if a message is send to / stored at a certain receiver or if the message isn't. These algorithms are often referred to as routing algorithms. The most basic algorithm of this type is Epidemic Routing (ER) [94]. In ER two encountering participants first send their list of stored messages, then request messages they have not stored themselves and lastly exchange the requested messages. The process is shown in Figure 16. Epidemic routing is the optimal strategy under the assumptions of infinite storage space and an uncongested wireless medium [95]. These assumptions are often not applicable, but nonetheless results of ER are often a good baseline to compare other algorithms to. Spray-and-Wait (SaW) is a DTN routing algorithm which limits the number of copies of a message, that are made during the forwarding process. Spyropoulos et al. [96] also proposed enhanced versions of this algorithm. Prophet [97] and Bubble Wrap [98] are other algorithms that optimize the dissemination of messages in a DTN in specific use cases. Modi et al. [99] surveys a wide variety of such algorithms and their use cases.

There is a number of use cases in which classical TCP/IP based networks are not applicable. For example due to high delays (e.g. space travel [100]) or sparse network topology (e.g. highly obstructed industrial use case). However, to the best of our knowledge, there has been no prior research regarding the application of DTNs to mobile clients in industrial applications.

Until now DTNs only found sporadic application in very limited scenarios. The trends towards the mobile usage of live media made the technology obsolete for the wider public. But for very specific use cases DTNs remain of high interest. This work proposes, that one industrial application of mobile robots might be one of those applications. Whoever there is a major obstacle towards implementation of DTNs to industrial applications. Which is the convince decision makers to use beneficial, but novel technologies. In this work simulation models are proposed, which enable researchers and engineers to estimate the performance of DTNs in industrial applications.

3.2.3 Wireless Sensor Networks

In contrast Wireless Sensor Networks (WSNs) are probably the most widely applied ad-hoc networks in industrial applications [59, 60, 101, 102]. Many applications require the sensing of environment parameters in a wide area. For these tasks sensor nodes are spread over the relevant area. These nodes collect information concerning certain environmental characteristics (temperature, pressure, vibrations, light levels, presence of fires [103], patient vitals [104], etc.). A wireless network is used to relay collected data between the sensor nodes and collect the data at data sinks [58]. The central focus of these networks is energy-efficiency, since the life-time of the battery-supplied sensor nodes limits the life-time of the network.

There are variants of WSNs that consider different types of node mobility. These networks are called Mobile Sensor Network (MSN). In these networks some or all nodes move initially or continuously. Different works have proposed algorithms for the movement of these nodes and the relaying of messages between these nodes [105, 106, 107].

The Industry 4.0 trends of condition monitoring and predictive maintenance lead to many applications for WSNs in this context. Gungor et al. [60] surveyed the challenges and approaches in the field of industrial WSN implementations. They come to the conclusion, that industrial WSNs are highly effective in improving the connection between the real-world (e.g. a productions facility) and the underlying business processes and management. However, there are also remaining challenges for effective implementations. One of the challenges is the lack in modelling capabilities for industrial environments and knowledge about the wireless channel characteristics in such applications. Both are addressed in this work. The authors also explore the applicability of different communication technologies, which is also the central aspect of the work of Al Agha et al. [101]. Combination of wired nodes and wireless nodes have also been used for industrial automation tasks [59].

Compared to other ad-hoc networks WSNs have some advantages regarding the application to the industrial use case. These advantages lead to the more wide-spread adoption of this technology. The first advantage is the static nature of the clients. This introduces a more stable and predictable behavior of the network. Both are characteristics, that are highly valued to decision-makers in the industry. Which is an additional reason for this works focus on offering new methods to predict the behavior of ad-hoc networks in industrial environments.

WSNs are the most common ad-hoc networking technology on the factory floor. These networks support trends like condition monitoring and predictive maintenance. This work barely contributes to this field, but instead uses methods that are also used in this

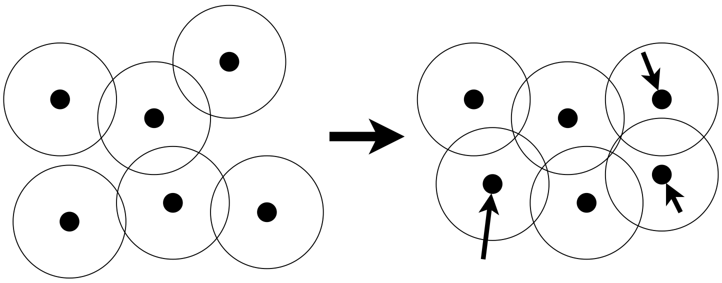


Figure 17: Nodes and their sensor coverage utilize mobility to close coverage holes.

field for other communication technologies (e.g. SDN for MANETs).

3.2.4 Utilization of node mobility

Many works assume, that the communicating clients move on their own. And that their mobility must be accepted as an impediment to the wireless networks. However in some applications the movement of the clients is actually controlled. The application of mobile robots, wirelessly communicating in an industrial environment is one such application. In previous work the mobility of clients has been used as an additional communication channel [90], to optimize the coverage of a network [108] (see Figure 17) or to establish and hold connectivity within a group of mobile robots [109].

The mobility of the clients is utilized in DTN, MANET and WSN applications. In the DTN application this is often referred to as message-ferrying [91, 92]. In this research problem one or more mobile nodes must find an optimal route to disseminate messages within a DTN. In WSN applications the mobility of nodes is used to optimize the coverage of the sensor network. In WSNs every node has a coverage range. Within this range the node detects changes in the environment. Different coverage problems are actively researched in the WSN community [63, 106, 107, 110]. Controlling node mobility in MANETs mostly considers mobile robots that have to, for example stay as a connected group [109] or stay connected to a source, while exploring an unknown environment[111].

Other works do not focus on maximizing sensing coverage, but for example on improving the connectivity and throughput of an ad-hoc network [61]. The focus in [112] is the introduction of one or more mobile sinks. These are introduced to improve the performance of the network or to more equally distribute energy consumption between the sensor nodes. Parasuraman et al. [113] utilize a robots mobility to reestablish lost connections. This work is unique, due to its usage of a complex signal propagation model. Most of the previously mentioned works are based on models like the Unit-Disk-Model, which assumes that communication is always possible, if transmitter and receiver are within a certain range. [113] in contrast uses a model which includes path loss, shadowing and multipath fading. In [114] multiple mobile robots establish a connection in a complex environment, which is expressed as an optimization problem.

Previously mentioned goals were the utilization of the mobility of robotic clients for coverage optimization. An important difference to previous work in this context are the properties of the considered industrial environment. For example the often proposed free movement [113, 114] of the robotic clients is not possible in an industrial applications. On the shop floor robots are limited to move on specific paths and are only allowed to remain in some positions for a prolonged duration of time, in which no obstruction of paths or machinery occurs. Additionally the negative impact of removing mobile robots from transportation tasks has to be considered in the overall performance impact.

This work adds methods for reactive system simulation to the field of reactive networks / message ferrying. And also mobility methods that are optimized for the industrial use case.

3.3 Trends in the industry

In the industry a constant drive towards higher efficiency and lower cost is observed. In the past this lead to different industrial revolutions, which drastically changed industrial environments, work conditions and processes. The current revolution Industry 4.0 has communication as a central aspect [115]. Some central aspects to this revolution are flexibility, sustainability and efficiency.

One goal in terms of flexibility for many factories is to move from a high-volume mass production to a more flexible one-of-a-kind production, which allow for the manufacturing of a wide verity of products and product variants in the same facility [116]. This enables a reduction in cost and more specialized/custom end-products for the customer. There are different strategies to reach this goal, which all require a more direct communication between the producing and planning parts of the factory. One strategy to reach the requested flexibility is the matrix production.

Figure 18 shows a schematic top-down view of a factory adhering to the paradigm of matrix production. A number of production cells are placed within these factories. Every production cell performs a specific production step (e.g. assembly, soldering, coating, etc.). Now a wide variety of products is produced by taking different paths through this factory. Therefore the flexibility of this production concept is based on the flexibility of the transportation solution between the production cells. The AGVs, which are the central use case examined in this work, fit very well into this role. Smart AGVs [117] are required, because they enable collaboration with the employees, synchronize to the production and flexibly adapt to changes in the environment or process. The effective deployment of these smart AGVs is only achieved, if the exchange of data between the AGVs and other elements (employees, production cells, fleet control, management) is possible.

There are a number of trends regarding communication for industrial automation. The mobility of clients like mobile robots [118] favors wireless communication technologies, which are examined in detail in subsection 3.4. Other trends regard the structure of networks and the flexibility of this structure and the ability to establish real-time connections through a network.

Software-Defined Networks (SDNs) enable control over traffic flow in different types

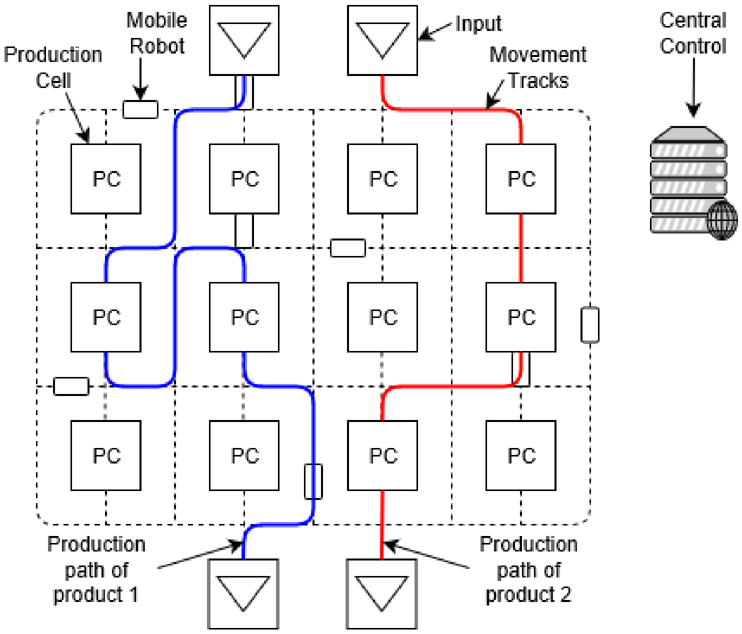


Figure 18: Concept of matrix production in a simplified top-down view of a factory [2]

of networks. Their basic idea is to divide the network into a data transmission layer and a control layer [119]. Khandakar et al. [119] provide an overview on the applicability of SDNs to the use case of industrial automation and propose an architecture for a software-defined industrial automation network. [1] proposes, that the global network view of the SDN controller enables effective roaming schemes for moving AGVs in a production facility. A special variant of SDN is the Software-Defined Wireless Sensor Network (SDWSN) [4]. These combine the functionality of WSNs with the flexibility of SDNs.

Many industrial applications require real-time communication. Real-time systems complete certain processes or calculations within a defined and guaranteed time slot. Which makes them applicable for critical and safety relevant tasks. A machine or system must be safe, if an error in its operation endangers or injures humans. Achieving this real-time behavior has two components, firstly offering an upper-bound communication latency between clients and secondly avoiding any packet loss [120, 121]. Time Sensitive Networks (TSNs) have the goal to enable such communication [3]. However, only recently were TSNs introduced to the wireless communication context, by utilizing the new communication standard 5G Ultra-Reliability and Low Latency Communication (URLLC) [122]. The research focus in the last years has been on time-synchonization techniques [123], scheduling [124] and applicability [125].

3.4 Wireless Communication in the Industry

In the past wired communication was often preferred to wireless communication in the industrial context. This was due to the higher reliability, performance and lower probability for interference. But with the aforementioned trend towards flexibility and mobility comes the requirement to utilize wireless communication technology. Different communication technologies have been applied for different use cases. In this section use cases will be described and scientific work regarding different communication technologies and the signal propagation characteristics in the industrial environment are surveyed.

Typical wireless clients in the industrial applications are:

Hand-held clients
A variety of hand-held clients are used in current and future factories. Smartphones and tablets are used to connect employees and to enable constant communication. Through them employees access data-sheets or connect to outside resources. They also gain additional insight and control over local resources on the factory floor. They move with the humans through the complete facility or in specific zones.

Tools
Some tools, like wrenches, transmit data for the purpose of quality control. This helps to ensure their proper usage. These tools move slightly but normally stay in roughly the same zone of the factory.

Machines
Machines like mills, equipped with Programmable Logic Controllers (PLCs), are connected to external systems. These connections are occasially be wired, but in many cases wireless communication is also applied.

Movable goods
Many objects are moved within the factory. Boxes, crates, work-pieces and material for example. In certain situations equipping these objects with smart hardware might be beneficial. This hardware can allow, for example for: the identification of crates/ materials or the tracking of goods and work-pieces. This in turn allows for the collection of data-sets to enable optimization based on big data principles.

AGVs
Lastly mobile robots, like AGVs move through the factory and require connection to other devices and/or a central fleet controller.

The operation of AGVs relies on the availability of wireless communication links. They require communication with other machines and often to a centralized control unit [1]. Zhan et al. [46] survey the IEEE 802.11 and ZigBee standards in terms of their applicability to this use case and also propose possible goals for standardization work regarding wireless AGV communication. Other works introduce the wireless control of AGVs [126] or the introduction of redundant links to mobile robotic clients in an industrial environment [127]. In the past wireless communication was often introduced to production facilities in order to enable use cases like AGVs. Today wireless networks are most likely already present and the AGVs have to utilize the given network / infrastructure. Therefore the available wireless communication technologies and research regarding them is surveyed in the following section.

3.4.1 Communication Technologies

The following Table 3 compiles wireless communication technologies for the industrial use case. The table presents typical use cases and related work regarding their application. A more expansive comparison is given in [2].

Table 3: Comparison of wireless communication technologies for industrial applications

Technology	Properties	References
IEEE 802.11	• low cost • high throughput • off-the-shelf components • high prob. for interference • high jitter/ latency peaks	[1, 46, 70, 128, 129, 130]
Bluetooth	• low cost • P2P-capability • low energy consumption • roaming highly detrimental • low throughput • high prob. for interference	[69, 70, 130, 131, 132]
ZigBee	• low energy consumption • P2P-capability • high availability • low throughput • high prob. for interference	[70, 130, 133]
LTE	• private and non-private networks available • high throughput • out-of-band communication • high cost (for private network) • limited experience	[1, 134]
5G	• high throughput • low latency • high reliability • out-of-band communication • high cost (for private network) • limited experience	[1, 2, 46]
VLC	• high reliability • low jitter • signaling capability • low throughput • out-of-band communication • not market ready	[2, 135]

Table 3: Comparison of wireless communication technologies for industrial applications

Technology	Properties	References
Radar	• high throughput potential • out-of-band communication • sensing capability • not market ready	[2]

In the past AGVs have been connected with technologies like infra-red communication or inductive communication. Today the different IEEE 802.11 variants are most commonly used. They offer a good mix of high throughput, low latency, high availability and low cost. Only recently have use cases, like CR, emerged in which these technologies are not sufficient. This is due to the non-determined transmission delay and possibility of packet loss in WiFi. WiFi is not suitable for motion control or safety-critical transmissions [1, 49, 65].

Different works have compared different communication technologies in terms of their applicability to specific industrial use cases. [70] compares the three IEEE 802 based standards WiFi, Bluetooth and ZigBee. Typical performance metrics, but also the co-existence, are reviewed. A similar comparison, excluding ZigBee, is provided by Ferro et al. [131], while Shin et al. [130] focuses on the PER characteristic of WiFi and ZigBee. A focus on co-existence is also given in [133]. Lee et al. [132] additionally compare the ultra-wide-band communication to the IEEE 802 standards. The industrial application and AGVs in particular have also been surveyed [1, 69, 127].

The support for P2P communication varies between the different communication technologies. Some require P2P connections, while others only enable some aspects of P2P communication. None of the above mentioned technologies have no P2P-capabilities. Bluetooth, ZigBee, VLC and Radar are based on P2P connections. Their propagation properties or protocol implementation do not support/require network infrastructure. The IEEE 802 standards support an ad-hoc mode in which P2P communication is possible. However the native ad-hoc mode only supports direct P2P-communication. For a multi-hop ad-hoc network custom (MANET) routing protocols must be included. If this custom routing is present, then a fully capable ad-hoc network can be created using the IEEE 802 technology. LTE and 5G support so called Side-Link capability. This means, that a normal BS-based network is created and afterwards the connectivity to the BS can be expanded by one hop. With this capability a client can not only connect to a BS, but also to any other client, that is directly connected to a BS. This capability however is currently theoretical. The LTE specification defined this functionality, but no supplier produces hardware with that capability. The same functionality is part of the 5G capabilities. For 5G there is also no hardware available, but due to use cases like vehicular communication a sidelink implementation is likely in the future.

The current state of the art is examining different communication technologies for industrial applications, but most of these technologies use the electro-magnetic spectrum.

In this work VLC is examined and also the possibility to combine this VLC and other communication technologies.

3.4.2 Channel Characteristics

After we reviewed some of the research work regarding the inclusion and usage of wireless communication in industrial use cases in the last section, our goal in this section is to review work, that focuses on the physical aspects of this communication. Knowing the characteristics for radio propagation is very important, when applying wireless communication to a use case. In this section research work regarding characteristics of the industrial wireless channels are presented and also works utilizing specific models to emulate these characteristics are surveyed.

The industrial environment has long been a subject of research. Early on experiments showed, that in the industrial scenario some normal assumptions do not apply. Rappaport [38] showed, that in industrial environments, noise is not the most detrimental factor to wireless signals, but multi-path propagation. An observations, which was confirmed by power-delay-profile measurements for a wide array of frequencies by Karedal et al. [136]. The authors noted, that this has many negative implications for common assumptions in the design of wireless communications systems. Therefore a system, that is not designed with the industrial use case in mind, might suffer in terms of performance, when used in this environment. Other measurements were conducted by Chrysikos et al. for the $2.4\,\mathrm{GHz}$ [137] and the $3.5\,\mathrm{GHz}$-band [138]. The goal of these measurements was to develop path loss models for the signal propagation in mixed industrial and office environments. These measurements lack the temporal component necessary to characterize multi-path propagation, but offer models, which are highly relevant in the prediction of coverage in the design of wireless communication networks.

Signal propagation models are used to estimate the coverage and range of wireless communication [139]. They are most often used to determine the pathloss P_l as a function of various parameters, most notably the distance d between transmitter and receiver. Equation 1 presents the general form for a signal propagation model F.

$$P_l = F(d, p_1, p_2, ..., p_n) \tag{1}$$

There are models that are more or less complex and require more or less knowledge about the environment. Generally the more complex models require more detailed environmental knowledge. Generating this knowledge often also requires more elaborate measurement setups to, for example, determine propagation parameters in the observed environment. But this allows them to simulate more complex signal propagation phenomena, like fading, reflection or even multi-path propagation. Some example models, sorted by complexity and modeling capability, are presented in Figure 19.

Sarkar et al. [139] survey a wide variety of signal propagation models. Both, regarding the path loss, but also regarding other propagation aspects (e.g. delay-spread). The indoor use case is particularly challenging for wireless communication and also signal propagation modelling. Cavilla et al. [14] showed that using simplified propagation

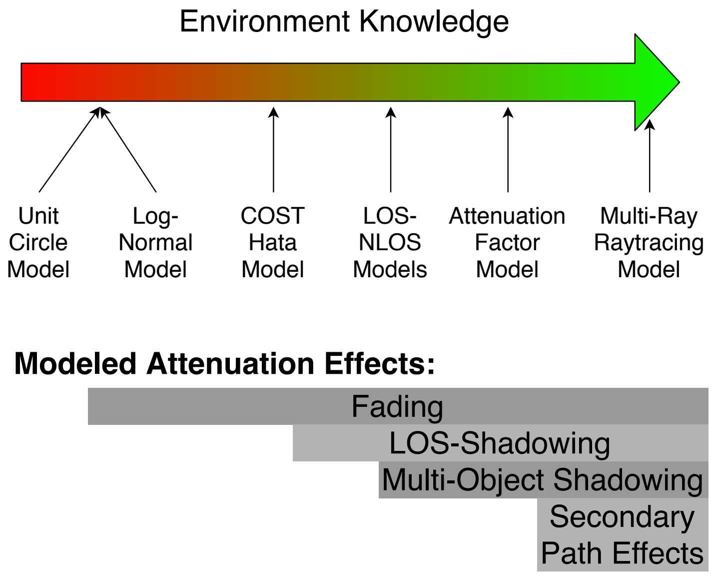


Figure 19: Propagation model examples sorted by complexity [8]

models result in non-robust behavior of a simulation. An alternative model is proposed, which reflects the spatial diversity of the indoor scenario. This model has subsequently also been used to plan the coverage of industrial wireless communication networks [36]. Even more complex models are used by German et al. [140] to model indoor communication and show good results, when compared to empirical measurements. However these models also come with high cost in terms of required environmental knowledge and processing power. They are therefore rarely applicable, when investigating big networks with hundreds or thousands of clients. Additionally many optimization methods like [141] are not applicable to dynamic environments, such as production facilities.
The unique characteristics of industrial ad-hoc channels are examined the the impact of these characteristics on the communication is estimated. This was not done previously.

3.5 Modelling and Simulation

Simulation is an important tool in network and especially MANET research. Simulation enables researches to test strategies, protocols and optimizations with minimal cost in terms of work and money. The central advantages of simulations in MANET research are:

Cost
Ad-hoc networks might need to be excessively big (thousands or tens of thousands of nodes) to present certain behaviours. Implementing such a network in the real-world is very expensive in terms of time and money.
Repeat-ability
The effects of altering specific system parameters on the end result are important in many works. This is easily possible in a simulation, by changing one parame-

ter and keeping all other parameters. In the real-world however, there are many uncontrollable parameters taking influence on experiments. For this reason many empirical measurements are repeated under changing circumstances in order to eliminate unintentional changes in the results.

However, these advantages come at a cost. This cost is, that any model used in a simulation needs to be validated. The goal of this validation is to make sure, that model and real-world behave similarly/identically. A model can only be seen as validated for the use cases and parameter range for which the model has been compared to a real-world implementation. There are different types of validation. The direct validation by comparison to the real-world is called operational validation [142].

In this work modelling and simulation is used to examine parameter combinations, which were not implementable in the real-world. Central aspect of the used simulation is the simulation of the robotic system and the simulation of the communication system, as well as their interactions. Another important aspect for simulation are the examined metrics. The availability of certain metrics requires the use of certain models. For example if the RSS shall be evaluated, then a detailed physical layer model of the use case is required. In the coming sections these metrics, the required types of models as well as available simulation tools are surveyed.

3.5.1 Performance Metrics

Metrics are values describing the characteristics and properties of a system. Depending on the application or use case different metrics might be evaluated, while examining the same system. In the following common metrics are presented, with their relation to the evaluated system, a description and research works, in which these metrics were used. Afterwards the typical use cases, advantages and disadvantages of the metrics are described.

The pathloss, RSS, Signal-to-Noise-Ratio (SNR), Signal-to-Interference-and-Noise-Ratio (SINR) and delay-spread besides others are metrics describing the physical layer of wireless communication. The RSS is the remaining signal strength at the receiver in a transmitter receiver pair. A higher RSS indicates a better communication channel. Many communication methods base their roaming on the respective RSS-values [143]. The SNR and SINR are both metrics, that describe the relation between usable signal and unusable / interfering signal. In regards to interfering signal, intentional Radio Frequency (RF)-signals (Interference) and unintentional RF-signals (Noise) are observed separately. And while the SINR does include the effect of interference, the SNR does not. The RSS, SNR and SINR are all related to the pathloss of a wireless channel. They are all indications of the power received by the receiver. The delay-spread also does not only define the power received by the receiver, but also the time at which the power was received. This allows for the characterization of multi-path propagation through the use of Power-Delay-Profiles (PDPs) [38]. The Received Signal Strength Indicator (RSSI) is decisively different from the RSS. The RSSI is measured by almost all networking equipment, but the RSSI is only an indicator for the true received signal strength. The RSS in contrast is only measured with specialized and calibrated equipment.

Al-Shora et al. [89] proposes a more reliable variation of DSR, which utilizes the RSS as a metric for channel quality. Ivanov et al. [36] use the RSS to define the coverage of an industrial wireless network. The SNR was used by German et al. [140] in the comparison of different signal propagation models for indoor applications. The SINR in contrast is used if the interference is a central part of the evaluated system [130, 144, 145]. Rappaport [38] used the delay-spread of signals in the industrial environment to identify the multi-path propagation as a central challenge in this use case. These observations on multi-path propagation were confirmed by Karedal et al. [136] using the same method and metric.

The throughput, latency and jitter are metrics, that define the connection characteristics, which a communication method offers to the communicating application. The throughput is the amount of data, which is transferred in a specified time frame. The metric is often given in bits/s or bytes/s. When testing the throughput, the packet size used in the test, the duration of the test and the periodicity of packet generation (constant, burst, sine, etc.) are important to note. A common tool for testing the throughput is *iperf* (iperf2 / iperf3). The latency of a communication is the time between sending a packet and receiving a packet. Often one-way and two-way latency is used. The one-way latency is the time until the packet reaches the receiver. Measuring this latency requires a clock synchronization of transmitter and receiver. Measuring the two-way latency does not require clock synchronization and describes the time until a sent message is acknowledged. This two-way latency is also called Round-Trip-Time (RTT). The RTT is often measured with the common tool *ping*. In networks with very high latency ($\geq 1\,\mathrm{s}$) the term delay is used equivalent to one-way latency. The jitter describes the variance of the latency. Which means, that a network with a constant latency has no jitter, regardless of the severity of the latency.

Many scientific works utilize the throughput or latency of a network as a metric for the networks performance [72, 146, 147, 148]. These metrics often shown to illustrate the general capabilities of the chosen communication technology and the effects of changes / optimizations to networking protocols [21, 75, 149]. The latency is often examined in application in which timely transmissions are more important, than the ability to transmit large amounts of data (e.g. control applications) [150, 151]. Jitter is in important metric when examining Voice-over-IP applications [152, 153] and wireless control applications.

The aforementioned metrics are often used for wired or infrastructure networks. In ad-hoc networks, especially MANETs, additional metrics are relevant in reaching for example a high throughput. The first important metric in MANETs is the Packet-Delivery-Ratio (PDR). This metric describes the percentage of packets, that reach their destinations. In many MANET routing schemes packets are lost due to buffer overflow, during transmission or in other ways. Generally a the packet loss should be as low as possible. At the same time these routing protocols must minimize the amount of required route-requests, route-replies and so on, which represent overhead in the network. A high amount of overhead effectively reduces the usable throughput of the underlying communication technology. In some ad-hoc networks (mostly WSNs) the reduction of energy consumption caused by communication is essential. This is done by sending more rarely or with less power. The energy consumption is a common metric, but not very relevant to the examined industrial application. DTNs are additionally evaluated in terms of their storage requirement.

Alasmary et al. [68] for example examine the impact of mobility on vehicular networks in terms of the PDR. In [154] the PDR as a metric for the efficiency of a cluster-based routing protocol. The overhead of routing protocols is often a point of comparison, when proposing new routing protocols or optimizations to existing ones [33, 82, 85, 155]. The energy consumption of a wireless network is mostly a metric applied to systems based on battery-powered devices. In these applications either the metrics energy consumption or network life-time are applied. The network life time is the duration, for which a WSN lasts, until a certain percentage of nodes or coverage is lost / offline[156, 157, 158].

All of the previously described and reviewed metrics describe the performance of the network. When looking at the application of wirelessly communicating mobile robots in industrial environments the performance of the robotic system must also be noted. Since robotic systems have a very heterogeneous set of tasks, there are not many standard metrics for the performance in these tasks.

If the task of the robot can be described as a control problem (e.g. following a path, applying a force, placing an object), then the performance can be determined in terms of control error. In other cases the performance of the robot can only be described in context to the fulfilled task and in the ability to consistently fulfill this task under the influence of a variety of environmental factors. In this case the probability for an error to occur is an applicable metric, this is especially relevant, if the error resolution requires human intervention.

3.6 Simulation Models

Our goal is to develop methods, which enable us to simulate communicating multi-robot systems in industrial environments. In the previous sections we summarized some of the advantages of such a system and some of the metrics, which help in the comparison of simulated systems. In this sections models are described that simulate parts of the examined use-case. Prior to that the general architecture / process of the simulation is described.

Figure 20 describes the common process of simulating MANETs. This is a fairly linear structure. A mobility model is used to generate node positions over time. The mobility models are mostly self-contained and have only a small number of parameters (number of nodes, speed, wait-time, etc.). From the positions of the nodes the physical transmission channel is modelled using a propagation model. This model calculates the path-loss between a transmitter-receiver-pair. Typical parameters are the communication range, path-loss-exponent and / or type of environment. The network model simulates all layers of the network, including the generation of test packets on the application layer. These messages are transmitted using the previously simulated physical layer. The simulation of the network creates data about its performance in terms of

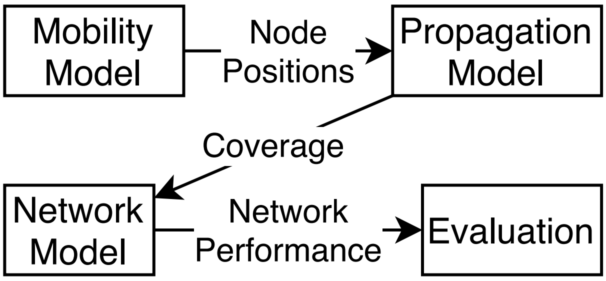


Figure 20: Common model architecture in MANET simulation [8]

network metrics (e.g. throughput, latency, etc.). This data is then analyzed to generate statements regarding the goal of the simulation.

There exist a number of common **mobility models** for many different applications and scenarios [159]. Some examples are the RWPM [160], the Manhattan-Model [161, 162], Random-Walk-Model [162], random direction mobility model [163] and group mobility model [164].

The RWPM is one of the most commonly used mobility models in the research of ad-hoc networks [29, 165]. In this model all n clients are randomly distributed on a predefined area. Every client then chooses a random destination and moves towards this destination with a speed randomly selected from a range of speeds. After reaching the destination the client waits for a random duration, selected from a predefined range, and afterwards proceeds to the next random destination. This behaviour leads to an uneven probability distribution of the nodes on the application area. The probability for node presence is higher at the center of the area, than at the borders. This behavior was observed by Bettstetter et al. [160]. The random direction model and random walk model are similar to the RWPM in terms of parameter (number of nodes, application area). In the random direction model the node selects a random direction and then moves in this direction until reaching the border of the application area, where another direction is selected. In the random walk model however the node constantly changes the direction of movement, the model was developed to emulate the movement of humans or animals, which do not always move towards exact destinations. The Manhattan model restricts the movement of the nodes to a grid of horizontal and vertical streets [161]. This model is often used to emulate the movement of cars and other vehicles in urban environments. Group mobility models [164] control groups, which are either predefined or selected during the model operation. These mobility models use a base mobility model for the movement of nodes, but the base model is not applied to single nodes, but node groups. Within these node groups no relative movement occurs.

However, simplified models, like RWPM, produce inconsistent results in in-door scenario [14]. Other models, for example a model based on a movement graph, were suggested, as they more accurately represent the limited movement within buildings.

The physical propagation of signals between a transmitter and a receiver is simulated using a **signal propagation model**. These models come in a wide variety of complexities (see Figure 19) [166]. Possibly the simplest model is the Unit-Disk-Model, which is often used for non-numerical simulation due to the simple mathematical definition [31]. Other models mostly strive to determine the signal loss caused by bridging the air-distance between transmitter and receiver and the resulting SINR or SNR [147]. The log-normal model calculates the path-loss based on a reference path-loss and a path-loss exponent, which must be empirically determined. Expanding on this model the AFM [14] also incorporates the signal attenuation by obstacles on the line of sight. Obstacles like walls, windows and furniture dampen the signal and reduce the received signal strength. This model is also referred to as Multi-Wall-Model [167]. However these models simplify the case of blocked line of sight, as in these scenarios the direct (primary) propagation path is often not the dominant one. Secondary paths, enabled through reflection, refraction and scattering now contribute the biggest part of the received signal strength. Models based on ray-casting simulate these effects [139]. These models are quite complex in terms of required environmental knowledge and computational resources. Therefore optimization methods have been proposed to enable real-time simulation with such models [141]. However these optimizations (pre-simulations) can not be applied to scenarios with dynamic environments.

In many works [72, 147, 168, 169, 64] wireless networks are modelled using analytical models. These models, include movement, application area, etc. and are abstracted by highly simplified assumptions. These assumptions enable the description of these networks by the analytical models. This has the advantage of achieving independence of all implementation details, that are outside of this basic set of assumptions. But the disadvantage is, that this set of assumptions must be very carefully chosen, otherwise the statements, extracted from the analytical model, are not applicable in relevant use cases.

As previously mentioned, the mobile robots move in a certain way, impacted by the availability and performance of wireless links. To the best of our knowledge there are no simple models emulating such reactive robot behavior. The simulation and modelling of robots is often very detailed in terms of physical and software fidelity.

The simulation tools described in the following lack some fundamental functionality to be considered for the examined use-case.

In the following sections existing tools for the simulation of wireless networks and robotic systems are surveyed (see Figure 21). Additionally hybrid simulation tools are described, which are able to simulate inter-connected robotic systems.

In this work the existing models are improved for the examined use case and new models and simulation architectures are proposed.

3.6.1 Network Simulation

Many ad-hoc routing schemes and network optimization techniques are only tested in simulations. This is due to the high cost associated with the implementation and operation of a network test-bed. Additionally many networks and optimizations must be tested with a high number of mobile nodes, moving in a large area. In the following a

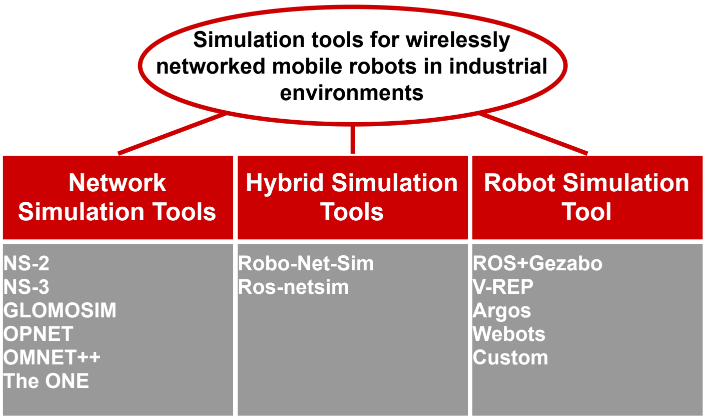


Figure 21: Simulation tool types, relevant to the examined use case

number of actively used network simulation tools are surveyed, with the focus on their applicability to the described use-case of mobile robots in an industrial environment.

NS-2 [170] is a network modelling tool originally developed in 1989 as a variant of the REAL network simulator. Many researcher and institutions contributed to the functionality of the simulation tool. Even after the introduction of the successor NS-3, NS-2 has stayed relevant especially in the field of ad-hoc network research. NS-2 is a discrete event simulator, which means, that network processes (e.g. receiving a packet) are stored in a scheduler. This enables a consistent timing among the different layers and sub-systems of the network. The simulated network (devices, traffic, application, etc.) is described using the scripting language OTcl. The tool simulates wired and wireless networks, infrastructure and ad-hoc networks, static and mobile networks. The available network models are of high fidelity and widely tested. Some recent communication standards are not yet implemented for the NS-2 simulation tool. Additional tools often used in conjunction with NS-2 are the visualisation tool ’VINT network animator (nam)’ and the graphing tool ’xgraph’. In multiple works the capabilities of he NS-2 simulation tool has been continuously expanded [171, 172]. The tool has for example been used for the original work proposing DSR [82], in the hybrid simulation tool Robo-Net-Sim [173] or the testing of new Medium Access Control (MAC) back-off algorithms [21].

NS-3 [174] is the successor of the widely used NS-2 simulation tool. NS-3 does not utilize the OTcl scripting language. Instead the simulations are written in C++ or python. Seven central improvements were achieved in this tool:

1. New software core with integration of a Python scripting interface
2. Higher attention to realism in the design of the clients and their network stacks
3. Support to integrate open-source software modules build into the architecture
4. Focus on virtualization and the inclusion of light-weight virtual machines
5. Native integration to test-beds and function for easy adaption to real devices
6. System to configure and document all relevant simulation parameters
7. An architecture that enables tracing and higher flexibility in the choice of metrics

These decisions lead to NS-3 being one of the most used network simulation tools for many kinds of networks. Some examples for NS-3 applications are: ad-hoc satellite networks [100], video streaming networks for unmanned flying vehicles [175], networks based on millimeter-wave communication [165] and software defined networks [176]. Additionally the chosen architecture motivates researchers to create expansions for this tool, increasing its relevance. For example the click router framework received an integration to the NS-3 simulation tool [177], DTN routing protocols were implemented in the simulation tool [178] and mobility models for three-dimensionally moving flying clients were introduced [179].

GLOMOSIM [180] is another frequently used simulation tool. The focus in GLOMOSIM's development was on the simulation of large-scale networks with highly heterogeneous communication technologies (wired, wireless, satellite). Scalability, the ability to simulate hundreds or thousands of nodes with acceptable processing time, was very important. Parallel processing, enabled by PARallel Simulation Environment for Complex systems (PARSEC), was the basis for the achieved scalability.

Table 4: GLOMOSIM as an example for available models [180]

Network layer	Available models in GLOMOSIM library
Physical	Free space, Rayleigh, Ricean, SIRCIM
Data Link	CSMA, MACA, MACAW, FAMA, 802.11
Routing	Flooding, Bellman-Ford, OSPF, DSR, WRP
Transport	TCP, UDP
Application	Telnet, FTP

The scalability is an important factor for the envisioned use case, as many networks with 100 or more mobile robots must be simulated. Additionally the simulation will require additional resources to simulate the behavior of the mobile robots. GLOMOSIM has for example been applied to vehicular ad-hoc networks [181] and WSNs [182].

A complete tool set for network design is offered by OPNET [183]. OPNET supports the model design, simulation and analysis of a wide variety of communication networks. The OPNET tools are designed for researchers and for engineers, maintaining or optimizing networks. It has been used for the simulation of mobile ad-hoc networks [184], interface interference analysis [145] and for research regarding the inclusion of smart antenna for wireless communication [185]. A comparison between OPNET and NS-2 showed very similar modeling behavior [186]. In the examined scenario OPNET showed slightly more precise modeling, compared to NS-2. It was however noted, that the cost associated with using the full functionality make it not as attractive for researchers.

OMNET++ [187] is another discrete event simulator. The structure of OMNET++ does not limit it to network simulation, but any system, which can be modeled within the discrete event structure. Similarly to OPNET it was applied in a wide variety of networking applications, including the analysis of flying ad-hoc networks [188], the comparison of multi-cast protocols [30] and the design of a mobile node architecture for multi-interface communication [189].

There are also simulation tools, which are specialized for specific types of networks. Due to their lower complexity they are often easier to use for that specific use case. The ONE [190] is such a simulation tool. It was designed to simulate DTNs, which utilize vehicles for packet transport.

There are some common aspects, in which all of these simulations are lacking, in regards to the envisioned use case. This begins with the representation of the environment in which the nodes move. These are often flat, without any obstacles or representation for indoor scenarios. This also impacts the movement of the nodes, as these often move randomly and disregard any presence of obstacles. This random movement behavior does also not represent the true movement of mobile robots in industrial applications. In these applications the robots often show certain repeating patterns in their movement and it has previously been shown, that it is highly important to consider these patterns when looking at the performance of ad-hoc networks [191].

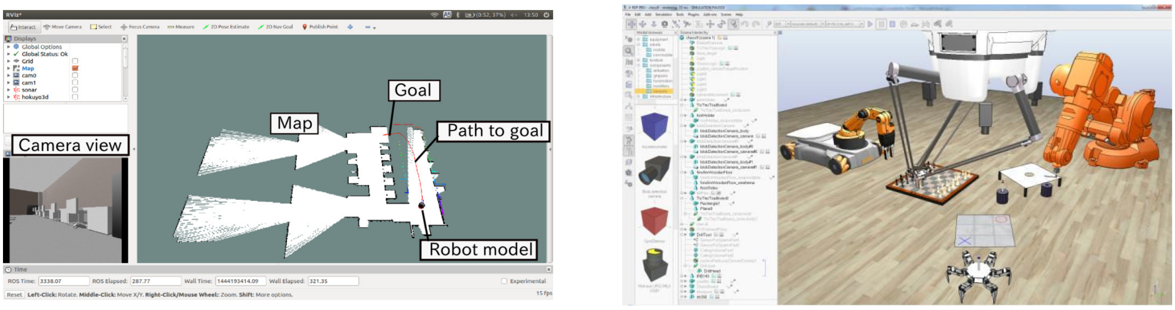
Another important aspect missing from many of these simulation tools is the reactivity of robotic nodes to the state of the communication network. In network simulations it is generally assumed, that the nodes move and need to be supplied with a network. However, that a node might stop its movement, because a network connection was lost, is often not assumed. But this is common behavior, when examining networked robotic systems (e.g. Cloud Robotics). Additionally one of the goals of this work is to actively control the movement of mobile robots to optimize the communication conditions of other mobile robots. With the previously shown linear model stack (see Figure 20) simulating this reactive behavior is not possible. Generally complex behavior of the nodes can only be simulated by modeling these robotic systems.

3.6.2 Robot Simulation

Simulating robotic systems has the goal to predict the complex interaction between environment, sensor, processing and actuators. They are used to verify the functionality of novel control algorithms, train robot operators and more. Depending on the goals of the simulation, different metrics are important to the design of the simulation tool.

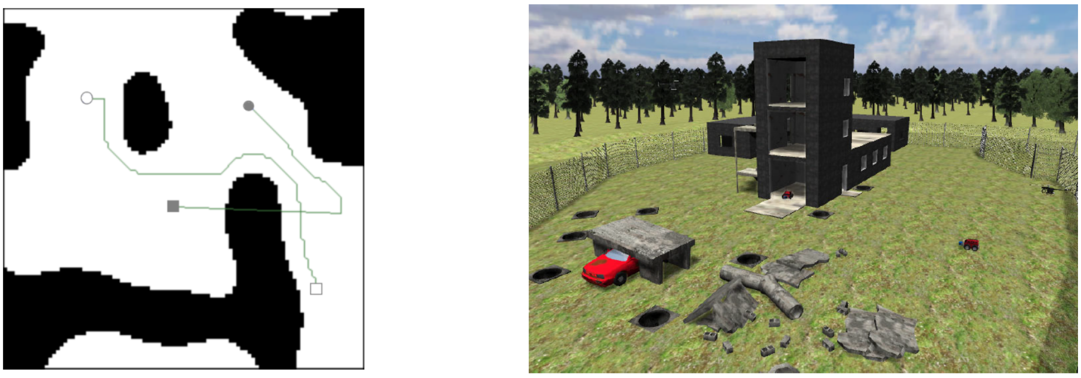
Simulation tools for singular tasks, like grabbing, sorting, handling or moving often require very high physical fidelity in order to determine, if mechanical design and control algorithms reliably solve the task. Other simulation tools simulate with lower fidelity, which enables simulation scalability in terms of number of robots and size of application. Lastly swarm simulation tools simulate hundreds to tens of thousands of robots with low physical fidelity. The ability of a simulation tool to efficiently model large number of robots is called scalability. Usability is an important metric, if non-experts must use the tool for example for the purpose of operator training. Another important metric is the ability to port code from the simulation to the real robot. This reduces the cost of development.

Today many simulations are carried out in the ROS [196], utilizing frame works like



(a) Map generation with Robot Operating System (ROS), visualized with RViz [192]

(b) Heterogeneous set of robots simulated in CopelliaSim(V-REP) [193]



(c) Mobile entities interacting in 2D cave environment simulated by Player/Stage [194]

(d) Robot testing environment in custom simulation tool based on game engine [195]

Figure 22: Different robot simulation tools

Gazebo [192]. These simulations are very powerful when examining singular robots or small groups of robots. They offer highly detailed models for many common sensors and actuators as well as high-fidelity simulation of the physical environment. These tools are very well documented and therefore easily accessible for researchers and engineers. Additionally, since ROS is often used for the control of real robots, tested code can often be transferred to the real robot after the simulation. ROS-based simulations can also use other ROS tools, like RViz, for visualization or analysis (see Figure 22a).

The ROS is very flexible in terms of applicable robotic systems. The simulation tool has been applied to unconventional mobile robots, like flying miniature robots [197] or spherical robots [198]. The types of tasks solved by these robots is as heterogeneous as the robots themselves. Past applications were for example the cooperative exploration of an area by a heterogeneous robot group [199] or the design and integration of an innovative virtual reality based interface [200]. The ROS has also been examined in terms of wireless communication capabilities for P2P communication and the researchers observed, that the utilized messaging system based on TCP/IP and UDP does not guarantee reliable communication [201].

Most ROS-based simulations do not include simulation capabilities for the wireless channel and abstract the required communication and assume ideal channel conditions. ROS-based simulations are generally very flexible and can be expanded to include the required models, however other disadvantages appear. The high physical fidelity of the simulation for example comes at the cost of high processing requirements, decreasing the scalability of the simulation.

CopelliaSim (formerly V-REP) is another robot simulation tool with a focus on versatility and scalability [193]. Many different types of robots can be simulated in this tool (see Figure 22b). Outdoor and indoor application are modelled. Parasuraman et al. [113] used CopelliaSim to simulate an outdoor scenario in which a mobile robot loses connection and afterwards restores this connection. The implementations of the wireless channel are rudimentary, but this application shows the expand-ability of CopelliaSim.

Scalability and flexibility were central design considerations in the development of ARGoS [202]. ARGoS shows good performance even with large groups of heterogeneous robots. ARGoS has the ability so partition the experiment space and use different physics engines for the different parts of the experiments. In previous comparisons [203] the lack of functionality offered by ARGoS was described as fairly small, when compared to other tools, like CopelliaSim and Gazebo.

The simulation tool Webots has also been used to simulate communicating mobile entities [18]. The mobile entities were used in a platooning challenge and their performance was investigated. The same tool was used for humanoid robots playing soccer in [204]. In this work the communication is simulated with a simplified model and employing a static limited baudrate.

[205] and [195] implemented a custom simulation tool using publicly available game engines. These engines offer many of the basic models for robot interaction, sensor simulation and physical models. These custom systems are for example used to train robot operators. Therefore usability was more important than expand-ability. The very high flexibility and the ability to shift the simulation focus between scalability and fidelity make this approach very promising for the presented use case.

Many of these simulation tools work in the same manner. A scenario (robot, environment, controller, etc.) is built and the simulation is started, showing the performance of the robot with a specific metric. The results obtained by this method however are limited to the pre-build scenario. If a robotic system must be tested for a scenario as complex and dynamic as the industrial application, this might cause high cost in terms of scenario building. Arnold et al. [194] propose a promising alternative approach. In their work the scenario is procedurally generated, simulated and automatically analyzed. This automated process greatly decreases the cost for scenario generation and also result review. Such an approach might be useful for the examined use case.

Generally many robot simulation tools are very powerful in regards to the simulation of these robots, but lack simulation capability for communication networks. Additionally the high physical fidelity often comes at the cost of scalability. The approach to implement custom simulation tool using game engines however is promising, since the focus of these simulations can be freely set between fidelity and scalability in these tools.

3.6.3 Hybrid Simulation

The lack of network models in robot simulation tools was previously noticed and addressed [173, 206, 207].

Ye et al. [206] developed an integrated robot network simulation tool based an the robot simulation tool GOLEM. With this tool the simulation of up to 254 mobile robots in a 2D area is possible. An interface to the ms - 2 was created and wireless signal propagation models implemented. The developed tool was used to simulate a group of robots exploring an unknown area and collecting resources. Today GOLEM and ns are not longer supported. GOLEM can also not simulate a three dimensional environments. The simulation tool is not longer developed and does not support the simulation of modern communication standards.

In 2012 Kudelski et al. [173] introduced Robo-Net-Sim. Robo-Net-Sim combines different robotic and network simulation tools. The tool supports NS-2 and NS-3 on the network site and ARGoS for the robot simulation. Scalability was a major concern, when selecting appropriate simulation tools for the network and robot simulation. The tool was subsequently used to simulate a network topology optimization utilizing the mobility of mobile robots [208]. This hybrid simulation tools is more promising, since the utilized NS-3 is still a state-of-the-art network simulation tool. ARGoS is a fairly powerful tool, but compared to other modern tools ARGoS lacks in functionality and expand-ability [203]. Additionally the online documentation and support for this tool is very limited.

ROS-NetSim is a very recent addition to the hybrid simulation tools [207]. The work by Calvo-Fullana et al. introduces an architecture to combine network simulation and robot simulation. The architecture is presented and evaluated using a perimeter control scenario in which the robots patrol an outdoor environment. The architecture works with a wide variety of network and robot simulation tool, like ROS/Gezabo and NS-3. Due to the timing of the publishing it was not considered for his work. But it is generally very promising and will be considered in future work.

Hybrid simulation tools are the most promising simulation tools for the examined use case. However, many of the available systems have disadvantages or were introduced to late. Due to the high complexity of adapting existing network simulation tools or robot simulation tools using these tools as a basis to create a new hybrid simulation tool was not considered. Instead a new custom hybrid simulation tool was implemented using a game engine. This new simulation tool is focused on scalability and usability. The reduction of functionality to the the relevant basics enabled additional research in the implementation of actual communication functionality.

3.6.4 Procedural Generation

Procedural generation was used in some scenarios is section 5.4. This is not the first use of procedural simulation in the context of mobile robotics [194], but to the best of the authors knowledge the first use of procedural generation in the context of MANET simulation.

The works of Chen et al. [209] introduces an very powerful method to create streets

and city layouts in procedural simulations, while Smelik et al. [210] survey different methods for the procedural generation of virtual worlds. Some of the methods used in this work are similar to the once described by Tutenel et al. [211].
Novel methods for the procedural generation of factory-environments for network simulations are proposed in this work. They are used to simulate a system in hundreds of different factories instead of simulating them in only a few scenarios.

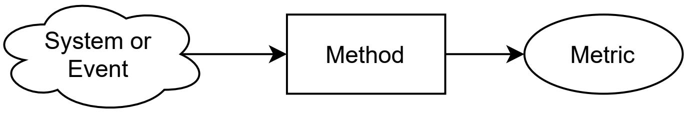


Figure 23: Methods are used to observe or examine a system or event. They generate results in the form of metrics.

4 Metrics and Methods

The goal of this section is to describe available metrics for the evaluation of ad-hoc communication solutions applied to mobile robots in industrial environments. Furthermore methods for the evaluation of these systems via simulation and experimentation are presented. In the following Section 5 these proposed methods are applied to different industrial ad-hoc use cases and the metrics are used to evaluate implemented solutions. The general relation between an observed system, the method of observation and the generated results are presented in figure 23.

The performance of any technical solution to a given problem can be described in terms of a metric. These metrics are the primary means to compare different solutions to the same problem. Depending on the focus of a solution, different metrics might be applied to the same problem. Therefore in this work different metrics might be used when compared to previous works, due to the different examined application. Some of the available metrics have already been described in Section 3.5.1. In the following Section 4.1 new metrics are proposed for the flexible ad-hoc communication of robotic clients in industrial applications and some known metrics are applied to this new scenario. The direct performance and behavioral metrics of this robotic system are considered as well as the performance of the communication system and the underlying physical propagation channel. The presented metrics are also used to characterize the communication systems presented in Section 5.

The proposal of new metrics and their application also necessitates the development of new methods or adaption of known methods to capture and analyze these metrics. These are in particular developed with the following goals:

Simulating and modeling aspects of the use case
As previously mentioned, simulating networks has particular advantages in the process of designing and optimizing solutions for these networks. The ability to simulate big networks with ≥ 100 participants was central to this work, since the performance of many ad-hoc networking solutions highly varies with the network size and density. Due to time and cost restraints, the required size of networks could not be implemented in the real-world. As surveyed in Section 3.5 there are no simulation solutions, that completely fit the requirements, therefore existing models had to be adapted and new models and tools had to be implemented.

Enabling empirical measurements of the use case
In many simulation-based works metrics are applied, that are quite difficult to

Table 5: Examples for metrics that are part of the system design and metrics that require specific implementation of their measurement.

System inherent metrics	Specifically measured metrics
Buffer sizes,	Throughput,
System stability,	Overhead,
Energy consumption,	PER,
Expected duration of error-free operation	Time till task completion

measure in the real world. Some of the challenges for empirical measurements are: Collecting data without impacting measurements, fulfilling the strict requirements for testing on the active factory floor, mitigating non-precise clock synchronization, etc.

The first subsection of Section 4.2 focuses on a method to measure and characterize communication channels in industrial MANETs. The following section describes different aspects of the complete system (e.g. mobility, robot behavior, signal propagation, etc.) in terms of applicable models. New models are proposed and existing models are adapted to more precisely model the examined use case. A particular focus is on the development of a light-weight model for the mobile industrial robots (i.e. AGVs) behavior within the factory to enable a scalable and easy-to-use model, implementable in, for example, network simulation tools.

4.1 Metrics

[9, 7, 8] and [13] centrally contribute to the following chapter. These works propose new metrics, apply known metrics to the industrial use case and evaluate the use-fullness of these metrics to the examined applications.

Comparison, optimization and improvement; all of these tasks are only possible by utilizing metrics to assign a numerical values to certain aspects, characteristics and results of a system. The most basic metric is the statement of functionality. Testifying, that a proposed or examined system offers a certain functionality. This functionality can be expanded with statements about possible conditions which enable or disable the functionality of the system. Some metrics might result from the design of the system. Others might be specifically measured to characterize or debug the system. Table 5 presents some examples for these different types of metrics. The presented classification is not always clear. Metrics like the overhead might depend on the systems design, but their actual value can only be determined during the run-time of the system.

In the following sections both types of metrics are presented. For each metric the possibility to measure this metric is described. Additionally the applicability of the metric to the examined use case is evaluated. The metrics are sorted in regards to the network layer to which they are associated (see Figure 24).

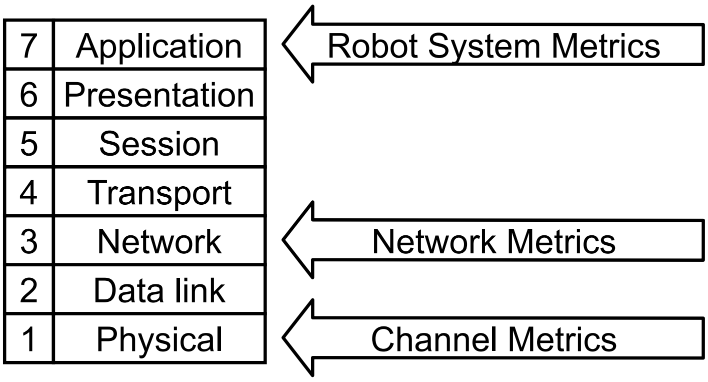


Figure 24: Association between network layer (according to OSI model) and examined metrics.

4.1.1 Channel Metrics

Channel metrics describe metrics of the physical layer of the network. These metrics concern the actual transmission between the transmitter and receiver and the ability to transport data that can be demodulated. Some notable metrics were surveyed in Section 3.5.1. Metrics like the pathloss, SNR and SINR are highly relevant and important to observe. They are important in the design of the physical layer of the communication technology, but do not necessarily relate to the performance or the behavior of the resulting network. The BER describes the percentage of bits, which are flipped between transmitter and receiver. Bits might be flipped due to errors in the demodulation process caused by interference, noise or low signal strength. Some of these errors can be repaired using channel coding (e.g. the Hamming code [212]). Therefore the PER, which describes the percentage of non reparable packets in relation to the total number of transmitted packets, is not necessarily equivalent with the BER. Both BER and PER are interesting, when analyzing the capabilities of communication technologies under varying environmental conditions. The disadvantage of both metrics is, that they are often not accessible on the application layer. Often these metrics are only available and utilized on the microcontroller or other hardware, which accesses the medium. Access to these metrics is often not available on the application layer.

The previous metrics have also the central disadvantage, that their interpretation depends on the examined communication technology. When examining a heterogeneous set of technologies, such as VLC, WiFi, LTE and Bluetooth, the resulting values for BER and pathloss will be just as diverse. One unifying metric is the time-varient ability to transmit a data packet between a transmitter θ and a receiver ρ at time t:

$$c_{\theta\rho}(t) = \begin{cases} 1 & \text{message sent at time } t \text{ by transmitter } \theta \text{ reached receiver } \rho \\ 0 & \text{message sent at time } t \text{ by transmitter } \theta \text{ did not reach receiver } \rho \end{cases} \tag{2}$$

The proposed method further assumes, that a message, which was sent at time t is

Table 6: Coherence time for different communication technologies / carrier frequencies.

Carrier frequency f_c	Communication technology	Coherence time T_c
$900\,\mathrm{MHz}$	ZigBee	$64.7\,\mathrm{ms}$
$2.4\,\mathrm{GHz}$	Bluetooth, WiFi, LTE, etc.	$24.2\,\mathrm{ms}$
$5\,\mathrm{GHz}$	WiFi, 5G, etc.	$11.6\,\mathrm{ms}$
$60\,\mathrm{GHz}$	WiFi, Radar, mmWave, 5G	$9.7\,\mathrm{ms}$
$600\,\mathrm{THz}$	Visible Light Communication (VLC)	$97\,\mathrm{ns}$

also received at time t. This assumption is based on the observation, that all examined communication technologies use the electromagnetic spectrum as the medium with a transmission speed of $c = 299\,792\,458\,\mathrm{m/s}$, while the communication range in industrial environments is $\leq 100\,\mathrm{m}$ with the relevant communication technologies. The maximum time for message transmission on the physical medium is therefore $\approx 3.3 \times 10^{-7}\,\mathrm{s}$. Which is much smaller, than the $3\,\mathrm{ms}$ to $50\,\mathrm{ms}$ delay experienced on the upper layers of the network stack. This method therefore assumes that the delay due to transmission is negligible compared to delay due to buffering, back-off and other mechanisms.

$c_{\theta\rho}(t)$ is only a snapshot of the current state of one connection of the network. If $c_{\theta\rho}(t_1)$ was tested at time t_1 to be either 1 or 0, then there is a certain probability for this to hold true for a duration δt, so that $c_{\theta\rho}(t) = c_{\theta\rho}(t + \delta t)$. This duration for which the characteristics of a wireless connection are unchanging is expressed by the coherence time. The coherence time T_c is the duration during which the impulse response of a wireless channel does not change and is inversely proportional to the maximum Doppler spread. A wireless channel is unchanged for a longer period, if the receiver moves slower or if a lower modulation frequency is used. A popular estimation for the coherence time is Clark's model [213](see Equation 3). Using this model and movement speeds ($v = 2\,\mathrm{m/s}$), the following coherence times are calculated for different communication technologies (see Table 6).

$$T_c = \sqrt{\frac{9}{10\pi f_m^2}} = \sqrt{\frac{9}{16\pi}\frac{c}{v}f_c} \tag{3}$$

In this work different metrics are used. For empirical measurements the connection state $c_{\theta\rho}$is often used. For modeling and simulation purposes the pathloss, SINR and PER are very important.

The connection state $c_{\theta\rho}$ has the central advantage to be measurable without specialized hardware and during normal operation of the network. The outcome is independent from the mobile device and used communication technology. $c_{\theta\rho}$ enables analysis regarding the network topology, route life time and more. The connection state is also a central part in the network characterization using NEPs, which is described in section 4.2.1. The connection state is also used to define if a wireless connection is bidirectional or unidirectional. The connection is only bidirectional, if the following is true:

$$c_{\theta\rho}(t) = c_{\rho\theta}(t) \tag{4}$$

Analyzing the presence of unidirectional links is highly relevant to the ad-hoc network research. Many ad-hoc routing schemes necessitate bidirectional links. A challenge in empirically measuring $c_{\theta\rho}(t)$ is the time synchronisation of t between multiple nodes. A possible solution is described in Section 4.2.1.

Simulating an industrial ad-hoc network is also in important part of this work. The simulation emulates $c_{\theta\rho}(t)$, but for the simulation itself many of the other metrics are used. Namely, the pathloss, the SINR and the PER.

Simulating the physical channel is based on a linear model structure, which models the physical transmission, signals path and signal modulation / demodulation. This model structure is presented in Figure 25. The position of the networked multi-robot-system is used in combination with the environment configuration to determine the pathloss over the length of the connection. The necessary propagation model can be more or less complex. Very complex models use thousands of ray-casts to determine the impact of multi-path propagation on the pathloss. By including the send power of a signal and the antenna gain on the path of the signal, the RSS is calculated. This received power is then combined with other received power, in the form of noise (unintentionally emitted) or interference (intentionally emitted). These received powers are combined either through a simple relation of the different powers or through an examination of constructive and destructive interference. The SINR is the result of this process. If interference is not modeled only the SNR can be simulated. Based on the SINR and knowledge about the applied modulation / coding scheme the demodulation probability $P(c_{\theta\rho})$ or the ability to utilize the channel $c_{\theta\rho}$ can be determined.

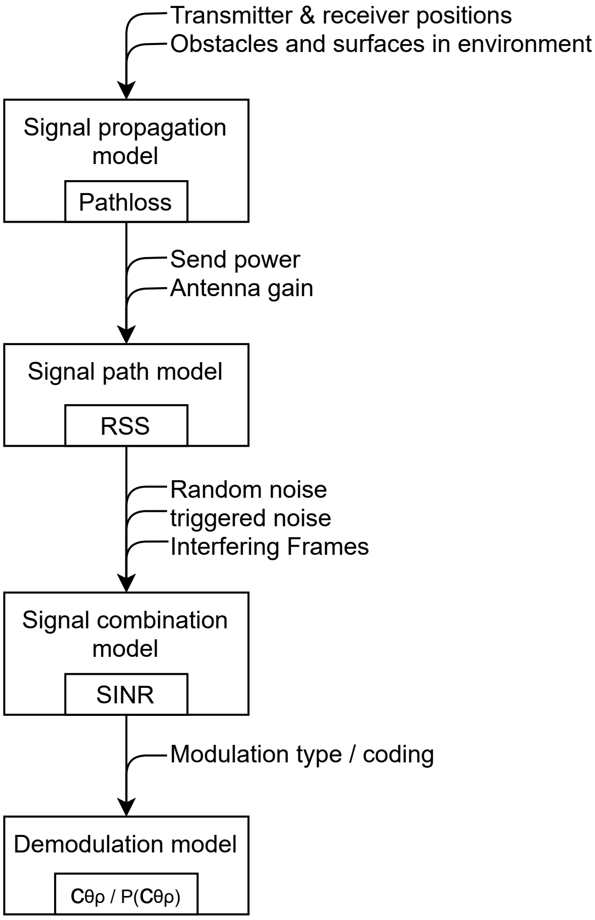
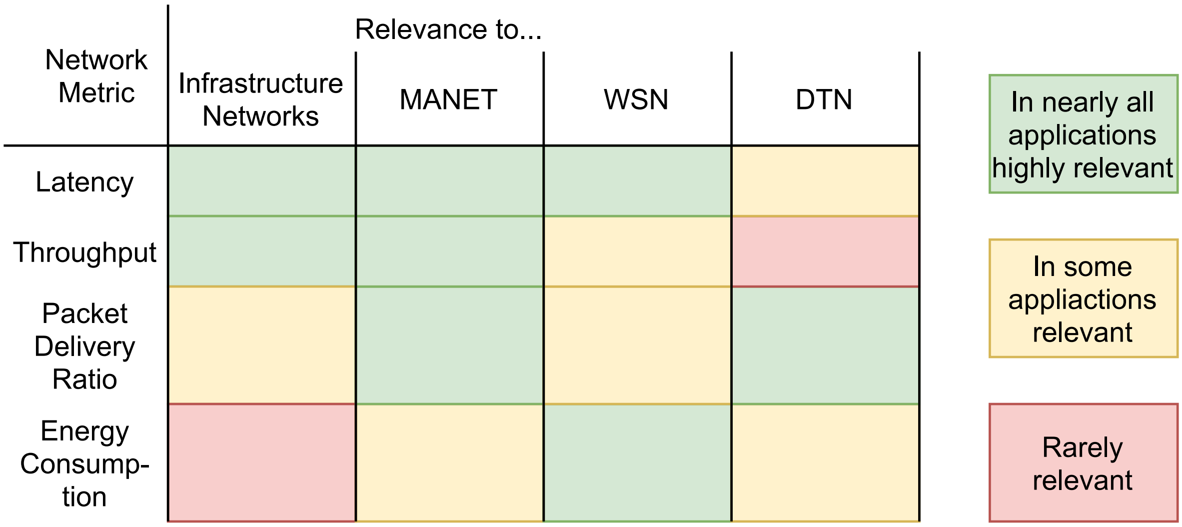


Figure 25: Models and parameters from physical configuration to connection state.

4.1.2 Network Metrics

Often the performance of a network is measured in terms of throughput, latency or, if applications like Voice-over-IP are concerned jitter. These high level performance metrics are easily measurable with tools like *ping* and *iperf*. However, the measurement setup is still highly relevant and must be carefully designed to produce relevant and comparable results. And while these metrics were originally not designed for ad-hoc networks, they are still applicable to them. DTNs are an exception, since metrics like throughput are not useful in these networks and many common tools are not applicable. A quick summary of metric and network type combinations is shown in Figure 26.

In the context of ad-hoc networks, especially MANETs, metrics like overhead, route life time and Packet-Delivery-Ratio (PDR) are of additional relevance. In MANETs the routes between participants changes constantly, therefore static routing can not be applied. During the operation route discovery and maintenance produce traffic in the form of route discovery packets, route acknowledgements, etc. This traffic consumes



Network Metric	Relevance to... Infrastructure Networks	MANET	WSN	DTN
Latency	🟩	🟩	🟩	🟨
Throughput	🟩	🟩	🟨	🟥
Packet Delivery Ratio	🟨	🟩	🟨	🟩
Energy Consump-tion	🟥	🟨	🟩	🟨

🟩 In nearly all applications highly relevant

🟨 In some appliactions relevant

🟥 Rarely relevant

Figure 26: Overview of network metric and network type combinations.

a part of the available bandwidth but does not contribute to the throughput of usable traffic. The relation of user traffic to control traffic is called overhead. To improve the performance of the network is often achieved by minimizing the overhead. The possible loss of routes due to the dynamic of the network can also create packet loss, which reduced the PDR. Packet-loss can either be problematic to the application or can be balanced by retransmissions, which in turn reduce the throughput.

Other ad-hoc networks, especially WSNs are often judged according to their energy consumption and the resulting network life time. The energy consumption is not of primary concern, when examining mobile industrial robots as clients in the ad-hoc network. The energy consumption of actuators (e.g. drives, manipulators) is fare higher than the energy consumption of the wireless communication. Therefore, the reduction of energy consumption of the wireless communication is not a primary goal of this work.

In the literature the terms delay and latency are both used to describe the time frame between sending a message and receiving the message or an corresponding acknowledgement. In this work the term latency is used for MANETs and other networks that establish communication routes. And can either describe the one-way time for transmission or the RTT. The term delay is used for DTNs, which do not define clear routes for communication.

In the setting of a communicating AGV-fleet these performance metrics are less suitable to determine the performance of a network and more suitable to judge its applicability. Certain use cases will require certain channel qualities at a certain time. In [2] we defined six scenarios for communication in the factory of the future. For each use case a frequency for packet generation, a packet size, a the number of participating devices, and a required throughput can be estimated. This is however only a worst-case throughput as this maximum throughput will only occur, if all devices simultaneously experience the same communication scenario, which is highly unlikely. By using a simultaneity factor a more realistic required throughput can be estimated. Generally certain use cases require certain network performance characteristics at certain times and positions. As an example:

> **Cooperative transport**
> During cooperative transport two or more AGVs cooperatively transport a heavy and/or bulky object. They exchange positions and speeds in order to hold a formation as precisely as possible. Imprecise coordination leads to additional forces on the transported object and possibly damage to the object. The relative movement of the AGVs can be avoided by enabling highly reliable low-latency communication. Some example requirements might be a latency of $\leq 20\,\mathrm{ms}$, jitter $\leq 5\,\mathrm{ms}$ and reliability $\geq 99.99\,\%$. These requirement must be fulfilled during the task. In terms of availability this can be defined as being available throughout the path, taken by both AGVs.
>
> **Unsorted Grasping**
> The unsorted grasping task describes the process of picking a lose object from a batch with a robotic manipulator. To complete this task 3D images of the unsorted object are often send to the cloud, processed and possible poses for the robot arm are returned. This creates a burst of data within the network, to transmit the 3D image. Therefore a high throughput is required. This type of communication is only required at the specific spot at which the grasping must be done. This throughput is also only required once, if the task is completed successfully afterwards.

The previously mentioned examples show, that the network performance requirements are quite diverse. In their actual requirements and also in the conditions, under which these requirements are applied. This diverse set of requirements also makes the evaluation of the impact of not fulfilling these requirements on the performance of the robotic system more challenging. If, for example, a latency of $\geq 200\,\mathrm{ms}$ occurs, while sending a 3D image to the cloud processor, this barely impacts the performance of the robot. If the same latency occurs, while two robots drive cooperatively, the resulting forces on the transported object can destroy or damage the object. Therefore observing the complete use case is always important, when comparing networks according to performance metrics like throughput or latency.

Different communication technologies can offer different performance advantages. These communication technologies prioritize certain metrics in their design. And while these technologies are highly capable in one metric, these capabilities are often a trade-off regarding other characteristics of the design.

Figure 27 shows different performance metrics of different communication technologies, mapped to a scale from 0, for very poor performance, to 1 for the best available performance. This figure enables the fast identification of strengths and weaknesses of the compared communication technologies. Bluetooth and ZigBee for example, are very

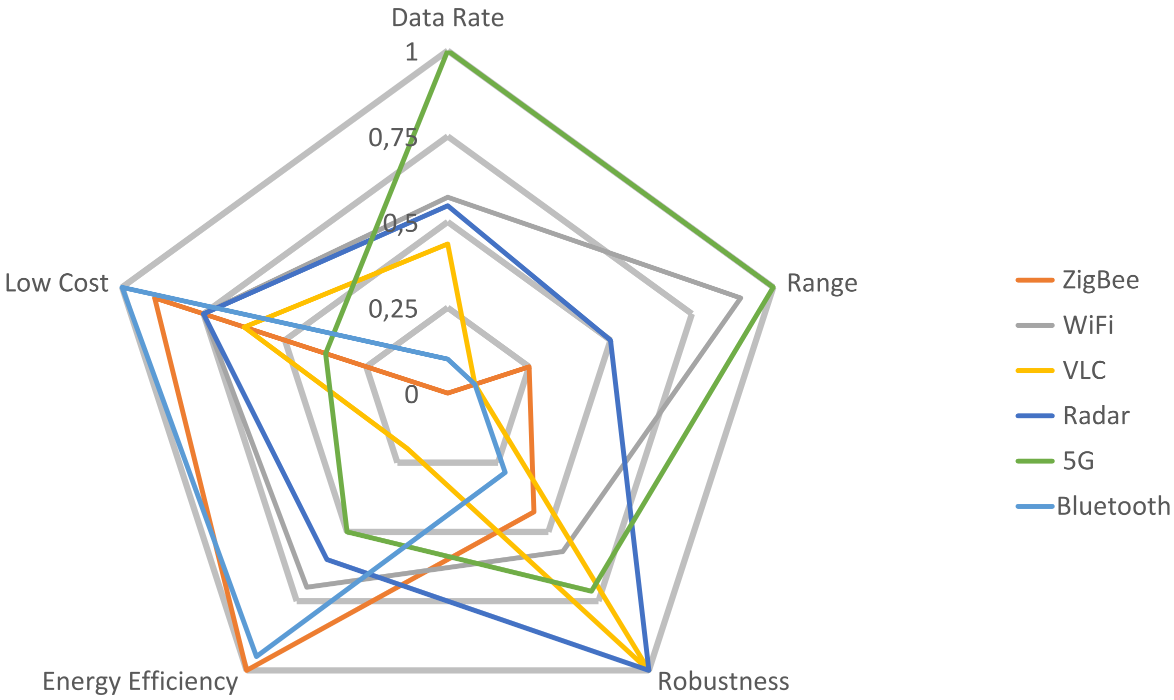


Figure 27: Comparison of different industrial communication technologies for different metrics on a scale from 0 to 1 [2]

cheap and energy efficient, but they only offer limited data rate. 5G in contrast offer excellent data rate and communication range, but at high implementation cost and high energy consumption. As previously described the communication of the AGVs are very heterogeneous and the different tasks best fit to different communication technologies. The unsorted grasping example can benefit from the high data rate offered by 5G, while the cooperative driving example might utilize the high robustness of the VLC.

The available performance of a communication technology can drastically vary depending on the environmental conditions. In many communication standards the maximum data rate is split between all present devices, while the communication of other participants in the network can also for example increase the experienced latency on a channel. Therefore using a communication technology, that has worse performance, but operates on a different channel than the primary communication technologies, might be beneficial in some use cases.

These network metric are very useful to compare communication technologies. They can only be applied to communication networks, if these work under identical conditions. These metrics are not necessarily useful, if the communicating devices are industrial robots. High communication latency due to congestion registers in both the network metrics and by the robotic systems. However the impact of the latency peak might vary with the current state of the mobile robot. Therefore a events in the networks might be easily recognizable using network metrics but barely recognizable when analyzing the robotic system or vise versa. Due to this other non-network metrics are used in this work, based on the robotic application of the network itself and the availability of communication opportunities.

An additional metric, that is often overlooked is the availability of a network / route. This describes if, when or with what probability a certain communication opportunity persists. This availability has a high impact on the performance of a robotic systems, that depends on this communication. Additionally the robotic system is highly affected by the complex and dynamic industrial environment.

Previously $c_{\theta\rho}(t)$ was introduced. $c_{\theta\rho}(t)$ is a binary value, that describes the ability of transmitter θ and receiver ρ to exchange information. When analyzing a complete network examine a single connection might not be very useful, instead the topology of the complete network can be described as a Nodal Encounter Pattern (NEP) $C(\theta, \rho, t)$.

If n is the total number of nodes in the network, then $n^2 - n$ is the total number of possible connections in the network, assuming that a node can not connect to itself. The network connectedness N_c is a measure for the completeness of the underlying topological graph. The topological graph is complete, if $N_c = 1$. The graph consists of isolated vertices, if $N_c = 0$, with:

$$N_c(t) = \frac{1}{n^2 - n} \left(\left(\sum_{\rho=\rho_1}^{\rho_n} \sum_{\theta=\theta_1}^{\theta_n} C(\theta, \rho, t) \right) - n \right) \tag{5}$$

A base assumption is, that all nodes in the network utilize transceivers. Therefore the groups of transmitters and group of receivers is identical and $\theta_n = \rho_n$. The direct connectedness can also be related to the multi-hop connectedness, which emerges, when utilizing an appropriate routing scheme. This relation is presented in Figure 28 based on real-world NEP measurements. The presented observations are based on long-term measurements and therefore relevant to the observed industrial use base, but not transferable to other applications, environments or even factories.

The previous definition $C(\theta, \rho, t)$ only describes direct connections between θ and ρ. In Section 4.2.1 a method to generate the nodal encounter pattern $C^X(\theta, \rho, t)$ for an X-hop network from $C(\theta, \rho, t) = C^0(\theta, \rho, t)$ is proposed.

Another important aspect of a network connection is the duration of its availability. In an environment with strong multi-path components in the signal propagation or high interference by other communicating devices, short-term disconnections often limit the availability of a route. While in highly dynamic networks the route life time is naturally low, due to the relative movement of the nodes. Short route life time in MANETs require more overhead for route requests and route repair. The route life time is therefore an important metric to characterize a wireless ad-hoc network or the prerequisite of an application of a wireless ad-hoc network.

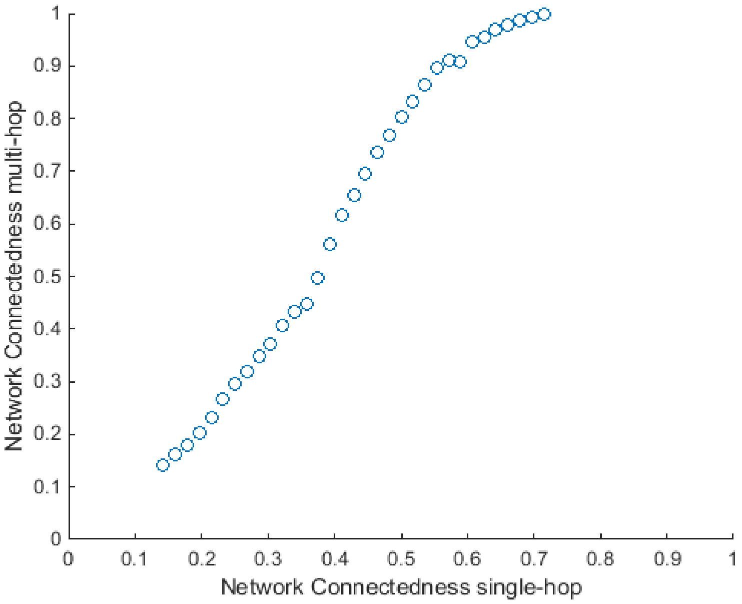


Figure 28: Network connectedness as calculated from NEP of single-hop ad-hoc network relates to connectedness in a multi-hop network. Based on empirical measurements in industrial application.

4.1.3 Robot System Metrics

Robotic systems are mostly designed to complete specific tasks. And their performance is evaluated in terms of ability, reliability and robustness of fulfilling this task. Specific performance metrics of this task can also be used to evaluate the performance of the robotic system. Therefore we identify typical tasks of the examined AGVs and the performance metrics, that are available for these tasks (see table 7).

The most important use-case for mobile robots in industrial applications is the transport of goods and tools. In this use-case a fleet of AGVs completes transport orders to support the production process. Generally the performance in this use-case is not given for a single mobile robot, but for the combined fleet. The performance is evaluated in terms of completed transport tasks per hour per AGV ($T/h/AGV$). For the operator of the fleet the "Time till human intervention" is also of primary concern. Many different scenarios can occur in which the operator needs to enter the field and resolve critical situations. Examples are:

- The dead-lock of multiple AGVs at an intersection [47]
- Mechanical wedging during handover of crates
- Communication loss, insufficient network capability and other communication-based causes

Of these reasons only the last is relevant to the presented work. Reducing the need for human intervention by enhancing the coverage of the wireless network and enabling message relaying between AGVs is a goal of this work. The coverage also has a direct

Table 7: Tasks of mobile robots in industrial applications and available metrics.

Task	Description	Metrics
Intralogistics	AGVs transport material, goods and tools throughout the factory. They need to receive orders from a CCU and transmit status messages to the CCU. If this communication is not successful the AGV can not continue with the following task or ceases movement until a reconnection occurred.	- Time till human intervention - Transports per hour - Serviceable area - Resource utilization
Assembly assistance	AGVs are used as mobile assambly area, reducing the need to lift and transport heavy work pieces, while ensuring correctness in assembly process. AGVs need to communicate with local machinery and human workers. Manuals and other documentation is pulled from the network.	- Process time overhead - Assembly line performance
Cooperative transport	Two or more AGVs cooperatively transport a heavy or bulky object. They need to exchange position and speed information for precise formation control. Latency and jitter have major impact on the precision of the underlying control loop.	- Position error from ideal position - Forces on transported object - Available routes for cooperative transport
Handling of goods	The AGV takes a work-piece from an unsorted crate and feeds the work piece into a machine. Task can be divided in sub-tasks (e.g. unsorted grasping).	- Positions at which the functionality can be provided - performance of sub-task completion

impact on the area, which is serviceable by the AGVs. When designing an AGV system there is also the task of optimizing resource utilization. An AGV fleet is usually designed with more AGVs than necessary to cope with peaks in ordered transport tasks, failures in AGVs and charging times. The number of unused AGVs must be minimized. Using non-occupied AGVs for network optimization (e.g. placing them strategically for coverage optimization) also optimizes the utilization of available resources and might place the currently unused AGVs beneficially for the next transport task.

4.2 Models and Methods

In preparation to this work, we published related work, which is relevant to this chapter: [6, 8, 12] and [13] contributed towards simulation models for the general simulation of ad-hoc networks in industrial applications. In [7] a stochastical model for DTNs is developed, while [9] regards models of methods to use NEPs,

Our goal is to evaluate the impact of wireless communication solutions on the performance of mobile robots in industrial applications. In the previous Section 4.1 a number of relevant metrics were introduced, which can be used to evaluate this performance. In this section methods and models are introduced, which enable the observation and simulation of systems and their description in terms of metrics (see figure 23).

This section is split into four main parts:

1. Using Nodal Encounter Patterns (NEPs) 4.2.1 to characterize wireless peer-to-peer channels in factory environments and to estimate the applicability of ad-hoc communicatin technologies
2. A test-bed using the hardware-in-the-loop paradigm to examine the effect of network characteristics on the behavior on mobile robots 4.2.2
3. A simplified statistical model for the effectiveness of DTNs in industrial applications 4.2.3
4. A number of models to simulate the impact of ad-hoc networks on the industrial application, including a simulation tool for this use-case 4.2.4

4.2.1 Nodal Encounter Patterns

NEPs represent the time-variant topology of an ad-hoc network. In this work they are presented in the form $C(\theta, \rho, t)$. The NEP gives the result 1, if the transmitter θ is able to successfully transmit a packet to receiver ρ at the time t. This encodes the changing topology of a peer-to-peer network.

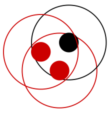
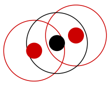
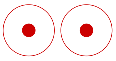
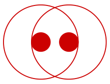
There are two reasons, why the availability of NEPs can be beneficial to this research. Firstly they characterize the time-variant topology of an ad-hoc network in an industrial application and secondly to enable the simulation of industrial ad-hoc systems without relying on mobility models or signal propagation models.

Three central metrics are used to characterize an ad-hoc network using NEPs: The network connectedness, the presence of unidirectional connections and the route-life-time. Additionally a method is presented to evaluate the applicability of multi-hop networks based on single-hop NEPs. The methods to use these metrics and to enable their evaluation are presented in this section, the results, obtained from real NEPs are presented in Section 5.1.

NEPs can also be used to simulate the performance of ad-hoc networks. A NEP can replace the mobility model and signal propagation model in classical network simulations (see Figure 20). This is especially beneficial, if no validated mobility and signal propagation model for a specific application scenario (e.g. industrial) exists.

4.2.1.1 Recording NEP in industrial settings

Table 8: Types of connections. APs and their range shown in black. Nodes and their range shown in red.

Type	Example		Evaluation by network trace	Real situation
true positive		Both nodes within range of each other and AP	in range	in range
false positive		Both nodes within range of AP but not of each other	in range	not in range
true negative		Both nodes not within range or each other and AP	not in range	not in range
false negative		Both nodes within range or each other and not in range of AP	not in range	in range

In previous works NEPs have not been recorded, but were extracted from network traces [214]. This approach has the advantage, that widely available traces can be used and that networks with hundreds or thousands of nodes are available. However these traces are recorded by the APs of an infrastructure network. The extraction approach then assumes, that in a similar ad-hoc network all nodes, which are registered at the same AP, also encounter in the ad-hoc network. This can lead to different scenarios, which are be wrongly evaluated based on assumptions seen in Table 8.

The goal is therefore to record the NEP of mobile robots in industrial applications. A requirement for these measurements was the minimization of the impact on the industrial operation. These resulted in the following requirements:

- The impact on other wireless communication within the same frequency band must be minimal.
- No software must be added to the mobile robots.
- No access to the wired network / internet is permitted.

Therefore new hardware was added to the robots, which implemented the sending, receiving, processing and logging of test messages. These test messages are used to probe the channel in a specified interval. The hardware is added to n mobile robots, which then constitute the groups of transmitters and receivers. Every recording is done with a specific communication technology (e.g. IEEE 802.11 b/g/n) with a specific configuration (e.g. transmit power of $20\,\mathrm{dBm}$). A time interval for the sending of the test messages δt must be specified. δt also specifies the resulting time-resolution of the recorded NEP. The highest possible time-resolution is desirable. However, as the impact on other communication must be minimal during recording, the time resolution has to be chosen as

Table 9: Metrics processed from NEPs [9]

Metric	Calculation
Network connectedness	$N(t) = \frac{1}{n^2-n}\sum_\theta\sum_\rho C(\theta,\rho,t)$
Percentage of unidirectional connections	$P_u(t) = \frac{\sum_\theta\sum_\rho \lvert C(\theta,\rho,t)-C(\rho,\theta,t)\rvert}{2\cdot\left(\sum_\theta\sum_\rho C(\theta,\rho,t)-n\right)}$

a compromise. For most communication technologies we recommend a test interval smaller than the corresponding coherence time (see Table 6 on page 60).

The detailed protocol implementation is described in [9]. The protocol is based on the periodical sending of beacons by each participant. The reception of a beacon from transmitter θ at receiver ρ indicates, that at that exact time a data exchange between these two participants was possible. Each NEP is defined by a number of parameters:

- The number of participants n
- The interval δt at which the beacons are sent
- The total duration of the test T
- The used communication technology (e.g. IEEE 802.11) and parameters (e.g. transmit power of $20\,\mathrm{dBm}$)

Every participating node has a unique address A_n and an increasing sequence number $I_n(t)$. This sequence number counts the number of sent beacons per node. Every beacon send by the transmitter θ contains this sequence number $I_\theta(t)$ and the address A_θ. At the receiver ρ the received beacon is logged as entries to the receivers log L_ρ:

$$C_\rho(I_\rho) = \left(\begin{matrix} A_\rho & I_\rho & A_\theta & I_\theta \end{matrix}\right) \in L_\rho \tag{6}$$

The logs L_x of all n nodes can then be concatenated to L and processed. The nodes are not synchronized. Therefore a synchronization and drift compensation is required. For this an offset-vector $O_x(t)$ is calculated, defining the offset of node x at time t. One node n_r is chosen as a time reference with $O_{n_r}(t) = 0$. The other offsets can be calculated from L and/or regressed with a linear regression. After compensation the beacon log contains the reduced entries $\left(\begin{matrix} A_\rho & t & A_\theta \end{matrix}\right)$ with $t = I_\rho + O_\rho(I_\rho \cdot \delta t)$, creating the compensated logs L_Δ. Subsequently the NEP can be defined:

$$C(\theta,\rho,t) = \begin{cases} 1, & \text{if } \theta = \rho \\ 1, & \text{if } \left(\begin{matrix} A_\rho & t & A_\theta \end{matrix}\right) \in L_\Delta \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

The NEP can subsequently be used to evaluate the network connectedness, the presence of unidirectional connections or the Route Life Time (RLT) of connections (see Table 9).

The Route Life Time (RLT) of a connection can be defined based on the NEP. The RLT describes a duration for which data exchange between two network participants is possible. RLT is an important metric, as this metric relates to the reliability of the communication and the overhead necessary to manage the routing in the network. With the NEP the RLT can be determined with a resolution of δt. But first two timeouts must be defined. The timeout $t_s = r_s \cdot \delta t$ describes the duration for which a route between two participants must persist until the connection is counted as a route. The timeout $t_e = r_e \cdot \delta t$ is the time duration for which a connection must be lost, before a route is recognized as lost. Both timeouts were introduced to eliminate very brief encounters, as they do not represent partially usable communication opportunities and very brief disconnection as they only affect the quality of a connection but not necessarily the availability. The following assumption is made for the further analysis: $t_s = t_e = 3 \cdot \delta t$. This duration was selected, as $3 \cdot \delta t$ is the same as the route timeout after which the implemented ad-hoc routing solution starts searching a new route.

The recorded NEP only differentiates 0 and 1. A connection is either possible or impossible. A NEPs with lower intervals between test messages, corresponding to a higher time resolution can be recorded and then down-sampled by a factor of d. The NEP can then not only contain 0 and 1 but probabilities with a resolution of $\frac{1}{d}$. Let C be the original NEP with high sample rate of δt and measurements at each time $t \in T$. We reduce the time-resolution by the factor r. This down-sampled NEP is defined for each r-th time point of T. These time points are combined to $t_r \in T_r$. The down-sampled NEP is calculated by:

$$C(\theta, \rho, t_r) = \frac{1}{r} \sum_{\tau=t_r}^{t_r + r\delta t} C(\theta, \rho, \tau) \tag{8}$$

4.2.1.2 Calculating Multi-hop NEP from single-hop NEP

Calculating multi-hop routes from the NEP is also possible. The calculation is based on the assumption, that if A can communicate with B and B can communicate with C, then a multi-hop route from A to C can be formed. A method was developed, that can generate multi-hop connection information based on single-hop connection information. This method can utilize binary or probability connection information from a NEP. This information can be either 0 or 1 or be a probability between 0 and 1. Let $C^0(t)$ be the direct connection information based on the NEP. The NEP is a matrix of size $m \times m$, where m is the number of participants. C^0_{ij} is the probability with which transmitter i can send data to receiver j. The goal is to calculate $C^{n+1}(t)$ from $C^n(t)$. We expect the values of $C^0(t)$ to be probabilities between 0 and 1. The elimination of loops in the calculation of multi-hop route reliability is therefore very important. The route *A-B-C* does not get more reliable through the route *A-B-A-B-C*.

The process has the steps shown in algorithm 1.

For the calculation of C^{n+1} from C^n we first copy the values from C^n. This process

Algorithm 1 Calculate C^{n+1} from C^n

```
if $n$ is equal to $0$ then
    Copy $C^n$ to $dR$ (Equation 9)
else
    Use $dR$ from last hop iteration
end if
Remove probability to send from node $n$ to node $n$ from $dR$ (Equation 10)
for node $i = 1, 2, \ldots$ do
    Calculate next-hop probabilities for node $i$ (Equation 11)
    Combine probabilities of redundant routes (Equation 13)
end for
Remove used routes from matrix $dR$ of available routes (Equation 15)
```

begins with $n = 0$.

$$dC = C^n \tag{9}$$

dC is a copy of C^n, which will be altered in future steps. $K = K_S(A)$ is an operation, which inverts the probabilities in matrix A, with $K_{ij} = 1 - A_{ij}$. Also, let I_n be the identity matrix of size n. We first remove the probabilities from dC to send between identical nodes:

$$dR := dR \cdot K_S(I_n) \tag{10}$$

Now let c_i be the i-th column of matrix C. With the operation $A = B(a_n)$ the vector a_n can be expanded to a square matrix, which repeats the contents of a_n column for column. We expand c_i using this operation to $C_i = B(c_i)$. Now the transmission probabilities of a hop via i can be checked with:

$$D_i = dR \circ C_i \tag{11}$$

We define $a = \overrightarrow{\prod A}$ as a row-wise multiplicative collapse of the matrix A. Where each entry of a is the product of the corresponding row of A.

$$a_j = \prod_j A_{i,j} \tag{12}$$

This collapse is used on the complement of matrix D_i with $D_i = \overrightarrow{\prod K_S(D_i)}$. This connection probabilities are again combined with c_i and collapsed:

$$C_b = K_S\left(\overrightarrow{\prod C_h}\right) \text{ with } C_h = \begin{bmatrix} K_S(c_i) & D_i \end{bmatrix} \tag{13}$$

Combining C_b for all i yields the connection probabilities for a $n+1$-hop network. However, already used connections need to be removed from dR in order to keep the network loop-free and the calculated probabilities correct. The following conditional function is defined:

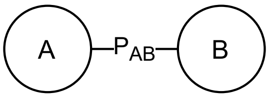
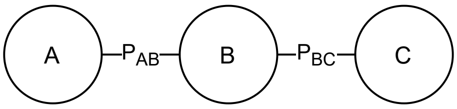
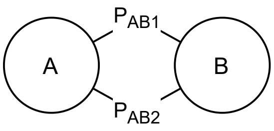
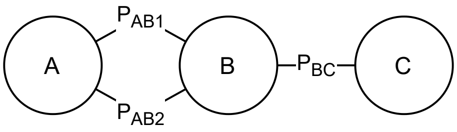
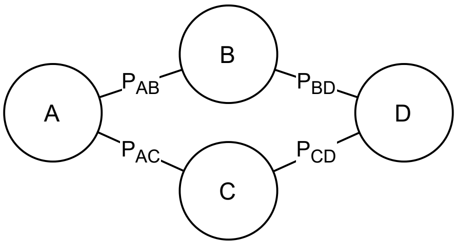
$$\o_i(x) = \begin{cases} 1, & \text{if } x \leq i \\ 0, & \text{otherwise} \end{cases} \tag{14}$$

$|\O_i|(A)$ is the element-wise application of $\o_i$ to all elements of A. Allready used connections are removed from dR with:

$$dR = dR \circ |\O|(C_i) \circ |\O|(C_i^T) \tag{15}$$

This process can be repeated for n hops until the largest relevant hop count and for every participant, in order to create $C^n(t)$. With this process any kind of multi-hop route can be examined and has an impact on the determined connection probability. This includes direct, multi-hop, parallel one-hop, partially parallel and fully parallel routes. All of these types are summarized in Table 10.

Table 10: Types of connections

Type	Example	Transmission Probability
direct		$P = P_{AB}$
multi-hop		$P = P_{AB} \cdot P_{BC}$
parallel one-hop		$P = 1 - ((1 - P_{AB1}) \cdot (1 - P_{AB2}))$
partially parallel		$P = (1 - ((1 - P_{AB1}) \cdot (1 - P_{AB2}))) \cdot P_{BC}$
fully parallel		$P = 1 - ((1 - (P_{AB} \cdot P_{BD}) \cdot (1 - (P_{AC} \cdot P_{CD})))$

Calculating the multi-hop topology of the network enables the evaluation of the benefits of implementing such multi-hop networks. Metrics like network connectedness or route life time can be used to evaluate the benefits. This examination is shown in Section 5.1.

4.2.1.3 Simulating industrial ad-hoc networks based on NEPs

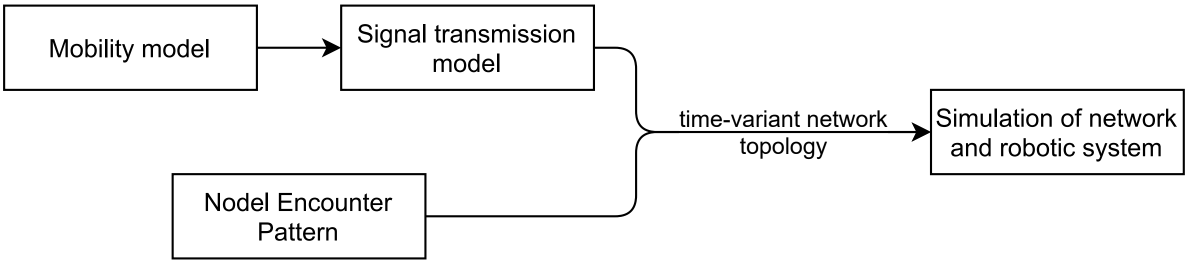


Figure 29: NEP as an alternative to mobility model and signal transmission model in network simulation

A NEP can be the basis for the simulation of a MANET. This process is described in Figure 29. The NEP can deliver the time-variant network topology, which is normally be a result of the signal transmission model. This enables us to test ad-hoc networking solutions under industrial conditions in a repeatable and realistic way. Additionally using the NEP as the basis for a simulation enables other researchers to test their networking solutions for the industrial use case, even if they do not have access to industrial production facilities.
The main advantage of this approach is, that no validation of any models is required. Since the NEPs are recordings they do accurately reflect the industrial use case. On the other hand the NEPs are only able to reflect the network conditions at which they were recorded. This means the simulation of, for example, faster mobile robots or alternative communication technologies is not easily possible.
Over all using NEPs is an exceptionally well suited method to test different routing and networking strategies in terms of applicability and performance in already existing industrial applications.

4.2.2 Hardware-in-the-loop test-bed

In the past sections the possibility to record data about network performance and topology on the factory floor and from other applications was shown. However, as previously described, the performance of the network is not necessarily correlated to the performance of a mobile robot, which utilizes these networks. In the coming Section 4.2.4 the possibility to simulate these systems is described. In this section a different approach was used.
Precisely simulating a mobile robot in complex control scenarios is very challenging. Therefore the hardware-in-the-loop paradigm is used to eliminate the need to simulate these scenario. The basic idea is, that certain communication scenarios (e.g. hand-overs, congestion, etc.) are recorded in terms of network performance (e.g. latency, throughput, packet loss, etc.). Then, within a defined test bed, one or more robots complete a task, while exposed to the previously recorded wireless communication conditions. This basic concept in presented in Figure 30.
This approach has an additional advantage. By selecting specific robot tasks and fil-

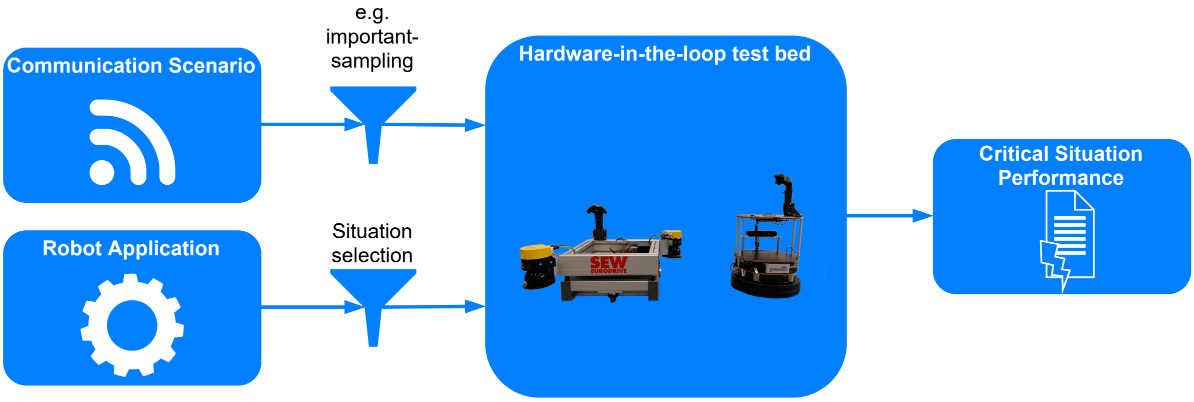


Figure 30: Basic concept of the hardware-in-the-loop test bed.

tering the network recordings, exceedingly unlikely, but critical control situations can be tested. An example for such an situation are two robots coordinating their movement, while AP roaming occurs. The added latency due to the hand-over is particularly critical in such situations and can cause collisions and require human intervention to resolve. These unlikely combinations of network situation and state of the robotic system are very critical in industrial applications. Due to the constant operation of the systems, even these unlikely scenarios occur frequently and disrupt the systems operation. Through means like tasks selection, filtering and important-sampling these situations can be provoked in the test bed. This enables an efficient development of solutions to complete these critical tasks.

The robots of the test bed were to be interchangeable and heterogeneous. The test bed must therefore operate independently from the robotic hardware. This includes the measurement of performance relevant metrics. Within the test bed the normally wireless communication of the cooperating / interacting robots is done via a wire. The communication over this wire is then delayed or intercepted according to the referenced wireless network characteristics. The basic concept is presented in Figure 31. The test bed can not simulate any communication with a lower delay, higher reliability or higher throughput, than the used wired connection.

In this test bed primarily applications concerning the control of robots via wireless links were tested. The performance in this application is defined by the control error of the position controller. Determining this precision without relying on subsystems of the used robots required the implementation of an external position tracking system. For these systems two solutions were investigated a high precision indoor GPS (Nikkon iGPS) [215] and a low-cost commercial system (HTC Vive) [216, 217] based on similar localization concepts. Both were suitable to determine the positions of multiple robots with sufficient precision.

With this system a platooning use case was implemented. A leader robot followed a predefined path, while a follower robot tried to keep a defined distance from the leader.

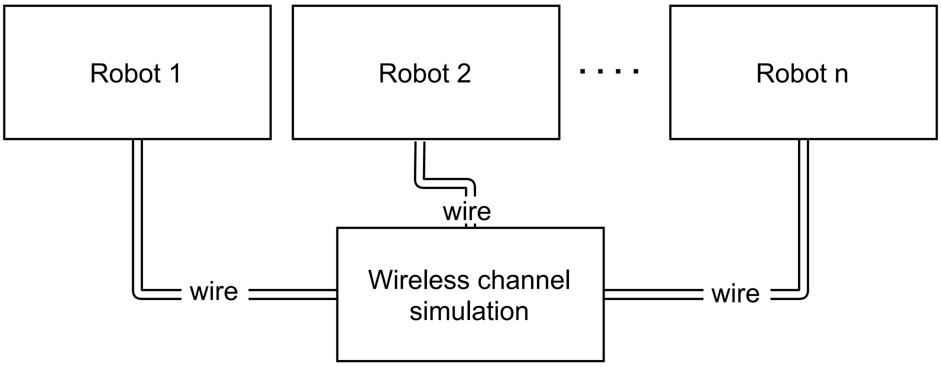


Figure 31: Communication on the test bed.

Wireless communication for position exchange between the two robots was simulated with LTE, WiFi and ad-hoc networks. The impact of communication latency and the presence of latency peaks on the control error was examined. The observations, provided by the test bed, for this use case are presented in Figure 32. The four observed metrics are:

- **Mean latency:**
  The average latency of the different modes of communication, averages over the complete duration of the measurement
- **Mean linear acceleration:**
  The average acceleration of the robot during the observation, positive and negative acceleration does not cancel out
- **Mean control deviation:**
  The average distance between the real and targeted distance of the robots, is also the control error input to the control loop
- **1% control deviation:**
  The lowest control deviation from the set of 1% highest control deviations

4.2.3 Statistical model for latency in industrial DTN

A model was developed to calculate the expected transmission delay in an industrial DTN [7]. The model was used to evaluate the basic applicability of DTNs to AGVs in industrial environments. The model uses the size of the industrial facility A, the communication range r, the speed of the AGVs v, and the number of AGVs N to estimate the Cumulative Distribution Function (CDF) of messages in an applied DTN.

The model calculates the number n of AGVs a message can reach within a time t. The coverage area A_{cn} is the area in which a receiver can receive the message from another participant of the DTN. Any message is generated by one participant of the network and therefore receivable within the communication range of this participant $A_{c1} = A_c = \pi r^2$. In a DTN every node can either have a particular message stored or have the message not stored. This binary state creates four possible state change. Each of these state

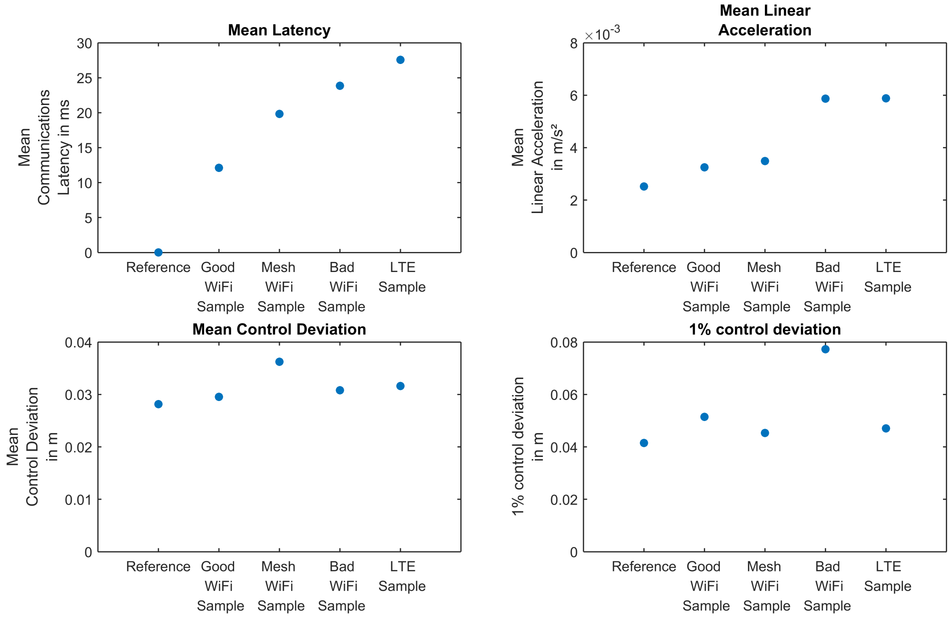


Figure 32: Example observations of robot performance within test bed using different communication technologies.

Table 11: Possible state changes in statistical model [7]

State change	Description	Description in terms of model	Probability
I	The nodes does not have the message saved, and does not receive the message	The node stays outside of A_cn	$P_I = \frac{(A-A_{cn})-0.5A_{cn+}}{A-A_{cn}}$
II	The nodes does not have the message saved, and does receive the message	The node enters A_cn via A_{cn+}	$P_I = \frac{0.5A_{cn+}}{A-A_{cn}}$
III	The nodes does have the message saved, but the message is removed from storage	The node leaves A_c via A_{cn-}	$P_I = \frac{0.5A_{cn-}}{A_{cn}}$
IV	The nodes has the message saved, and the message stays in storage	The node stays inside of A_cn	$P_I = \frac{A_{cn}-0.5A_{cn-}}{A_{cn}}$

changes has a certain probability to occur, which is listed in Table 11.

The state transfer depends on nodes traversing the transition areas A_{cn+} and A_{cn-}. The two different areas A and A_c and the two transition areas are described in Figure 33. The area A_c within which the message can be received expands every time a node receives and stores the message. The probability for an expanding A_c is $P_{n++} = P_{II} \cdot P_{IV}$. This

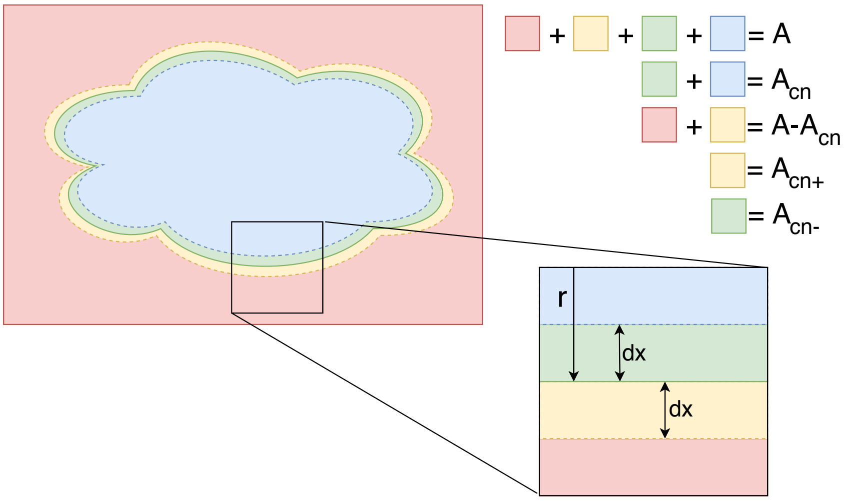


Figure 33: Explanation of A, A_c, A_{cn+} and A_{cn-}.[7]

means, that a node has to enter a serviced area and stay there for one time step dt in order to store the message. In a ideal DTN the storage size is unlimited, therefore the probability for the serviced area to shrink is $P_{n--} = 0$. The number of nodes, which store the message in time step $i \cdot dt$ is therefore described with:

$$n_{t+1} = n_t + R_s(N - n_t \cdot P_{n++}) - R_s(n_t \cdot P_{n--}) \tag{16}$$

The equation consists of three terms. The number of nodes, that had previously stored the message plus the number of nodes, that newly store the message, minus the number of nodes, that no longer store the message. Where $y = R(x)$ is the operation of statistical rounding [218]:

$$R_s(x) = \begin{cases} \lfloor x \rfloor, & \text{with probability } 1 - (x - \lfloor x \rfloor) \\ \lfloor x \rfloor + 1, & \text{with probability } x - \lfloor x \rfloor \end{cases} \tag{17}$$

A_c is the area in which the message can be received. This area is the combined coverage of all nodes, that currently hold the message. The serviced area A_c therefore changes with $n(t)$ with the following relation:

$$A_{cn} = A_{c(n-1)} + A_c \left(1 - \frac{A_{c(n-1)}}{A}\right) \tag{18}$$

This equation expresses, that the area increases with every node, that stores the message. However, the expectation is, that with more nodes storing the message, that the communication areas of these nodes are also more likely to overlap. Therefore the area increase per node decreases as A_c approaches A.

The areas A_{cn+} and A_{cn-} are border regions of A_c. A node passes through these regions, if the node enters or leaves A_c. The expectation is, that once a node enters for example A_{cn+} the node has a $50\,\%$ chance to proceed into A_c and a $50\,\%$ chance to move back to $A - A_c$. Determining the size of A_{cn+} and A_{cn-} is quite difficult, since the geometric shape of A_c is unknown. The two transitional areas must be borders of width $dx = v \cdot dt$ around the perimeter of A_c. Therefore two extremes for this perimeter can be examined. The minimal extreme is, that all coverage areas overlap in a way, that they form a circle with the area of A_c. This circle has a circumference of $2\pi\sqrt{\frac{A_{cn}}{\pi}}$. This circumference in combination with dx aids in the calculation of A_{cn+} and A_{cn-}. The maximum circumference in contrast is reached if A_c is made up from n non-overlapping circles of each of area A_{c1}. The combined circumference of these circles can be expressed by $2\pi n\sqrt{\frac{A_c}{\pi}}$. The maximum circumference case is more likely, if only a small part of A is covered by A_c, while the minimum is more likely if the opposite is true. This wheighting these two extremes is done with the correction factor $\left(\frac{A_{cn}}{nA_c}\right)^3$. The exponent 3 was determined by empirical measurements. The following approximation defines A_{cn+} and A_{cn-}:

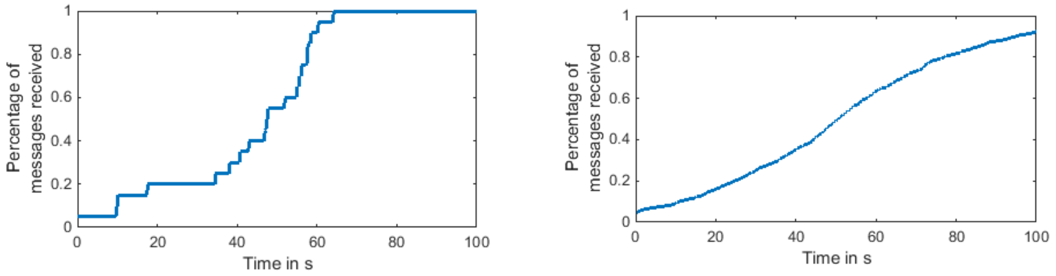
$$A_{cn\pm} \approx$$

$$\left(\frac{A_{cn}}{nA_c}\right)^3 \cdot \left(n \cdot dx \cdot 2\pi\left(\sqrt{\frac{A_c}{\pi}} \pm \frac{dx}{2}\right)\right) + \left(1 - \frac{A_{cn}}{nA_c}\right)^3 \cdot \left(dx \cdot 2\pi\left(\sqrt{\frac{A_{cn}}{\pi}} \pm \frac{dx}{2}\right)\right) \tag{19}$$

Finally the previously described expressions $n(t)$ (see equation 16) can be calculated. By expressing the metric as $\frac{n(t)}{N}$ it generates the CDF of message delays for the examined network. Due to the random components of $R_s(x)$ this CDF can look different with each calculation. Such an output CDF is shown in Figure 34a. Combining multiple calculations via averages is beneficial. This generates CDFs which offer a more general result. Figure 34b presents such a combined CDF based on 500 calculation with identical parameters. Figure 35 presents the effects of different parameters on the estimated delay in the DTN. The impact of N,A,r and v on the CDF are presented.

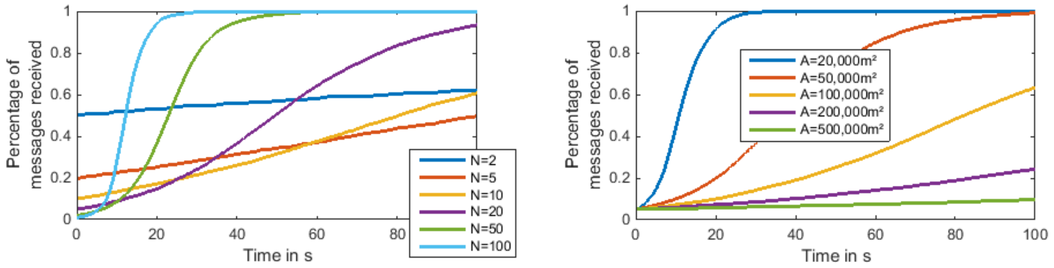
Both, Figure 34 and Figure 35 model DTNs with $N = 20$ mobile robots, $65\,000\,\mathrm{m}^2$ of factory floor A, a communication range r of $30\,\mathrm{m}$ and a node speed v of $2\,\mathrm{m/s}$, if not differently specified. All calculations were done for $100\,\mathrm{s}$ with a time step dt of $0.2\,\mathrm{s}$ and repeated 500 times.

The developed system is further validated and used to evaluate the applicability of DTNs to industrial applications (see Section 5.3). The proposed method can also be used to estimate the coverage of MANETs and non ideal DTNs by adjusting P_{n--}.

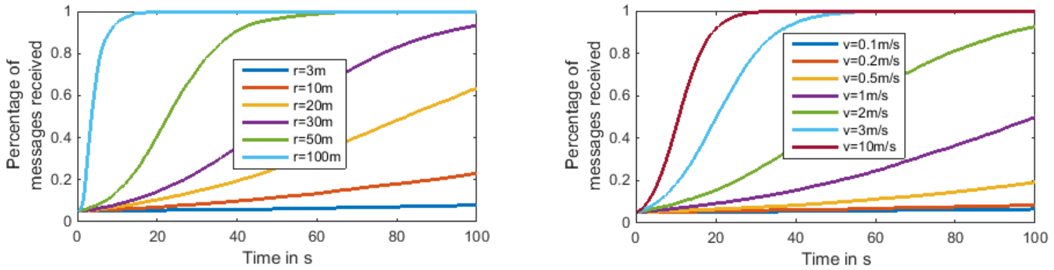


(a) Raw results for $n(t)$ (b) Average of 100 repeated calculations

Figure 34: Results of the statistical model with and without averaging.



(a) Simulation results with different values for N (b) Simulation results with different values for A



(c) Simulation results with different values for r (d) Simulation results with different values for v

Figure 35: Results of the statistical model with different parameters.

4.2.4 Simulating industrial ad-hoc networks

A central contribution of this work is the investigation towards models and methods regarding the simulation of networked multi-robot-systems in industrial applications. The goal is to simulate and evaluate the impact of communication solutions on the performance and behavior of these systems. In Section 3.5 available models and simulation tools were surveyed.No available system was noted as being able to simulate the interaction of wireless communication and multi-robot system sufficiently, while being scalable and modeling the specific characteristics of industrial applications.

In this section a new model architecture is introduced, which enables the simulation of

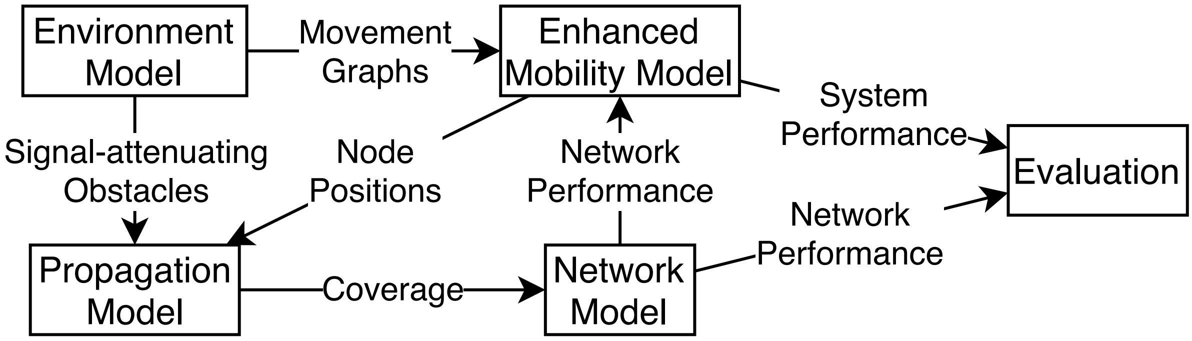


Figure 36: Improved model architecture for industrial MANET simulation with mobile robotic clients [8]

the examined use case, while utilizing existing models. Different models (e.g. environment, signal propagation, mobility, robot behavior, etc.) are proposed / improved and presented. Lastly a simulation tool is presented, that combines all of these models and capabilities.

4.2.4.1 Simulation Model Architecture

In Figure 20 (see page 48) a common model architecture is presented. The linear structure of interacting models however is not suitable for the simulation of two interacting systems. Therefore a new model architecture is proposed. The goal of this architecture is two-fold:

1. Enable reactivity between wireless network and multi-robot-system
2. Simulate the industrial application (e.g. environment, material-flow, client behavior, etc.)

The new architecture is based on the following improvements. The environment model is expanded to include a simplified three-dimensional representation of the simulated factory. Including paths for the mobility model and signal-attenuating obstacles for the signal propagation model. The mobility model is expanded and improved to more precisely simulate the movement patterns of AGVs on the factory floor. Additionally the mobility model is expanded with an AGV behavior model. This model describes the reactions of the AGVs to the varying network conditions. The signal propagation predicts the impact of the industrial environment on the ability of network clients to connect. The architecture is presented in Figure 36.

The improved environment model now supplies paths to the mobility models and basic three-dimensional representations of obstacles to the signal propagation model. The mobility model encompasses a movement model for the AGVs and a behavior model. The mobility model recreates the motion of robotic clients on the factory floor. The position of these clients are supplied to the signal propagation model, which, based on the presence of obstacles, position of clients, and interference of communicating devices

determines the ability for clients to communicate. The network model utilizes this this information. The network model simulates the generation and dissemination of data between the mobile devices. The behavior model of the clients, which is part of the mobility model, reacts to this data and the state of the network and adjusts the behavior of the mobile clients. An evaluation is enabled based on the performance of the network but also primarily on the performance of the multi-robot-system, which is provided by the mobility model.
A simulation is often defined by its configuration and the applied parameters. For each model the relevant parameters are described in the following sections. Some parameters are universal and can not be categorized to any specific model. Most notably the number of mobile clients n is highly relevant to any of these models.

4.2.4.2 Environment model

The environment model is the representation of the applications physical environment. In the presented case the environment model has two central tasks:

1. Provide information about signal-attenuating obstacles to the propagation model
2. Provide information about available movement paths to the mobility model

The environment model is a central part in enabling a more realistic simulation of the industrial context. Using simplified models for indoor scenarios of wireless networks is not robust [14]. This was observed in regards to mobility models and also signal propagation models. Therefore more realistic models were implemented. However, these models also require more information about the environment. The environment model has the task to provide these information. Examples for relevant environment information are:

- Positions and size of AGVs
- Position, size and dampening factors of obstacles
- Relevance of obstacles for AGV movement
- Position and characteristics of spectrum jamming sources
- etc.

Random motion of mobile clients creates AGVs that pass through walls and randomly enter and leave unconnected parts of the factory. Therefore a model for the mobility was chosen, which more realistically emulates the motion of the AGVs. AGVs in factory traverse over paths, which are defined zones in which the AGVs are allowed to drive. These paths consist of straight paths, curves, track switches and crossroads. In the factory the paths are design according to the kinematics of the AGVs. In the simulation the required level of detail needs to be defined and the necessity of this must be considered. In the environment model the paths are represented by a graph. This graphs consists of the v vertices $V \ni [V_1, ..., V_v]$. Every vertex has a defined position in $P \ni [P_{V1}, ..., P_{Vn}]$. The vertices represent the crossroads and track switches, but also positions at which AGVs typically stop and complete certain tasks. Edges are the paths between the vertices and represent the trajectories over which the AGVs can traverse. Every edge e_n is defined by a starting vertex and an end vertex, with $e_n \ni \begin{bmatrix} V_s & V_e \end{bmatrix}$.

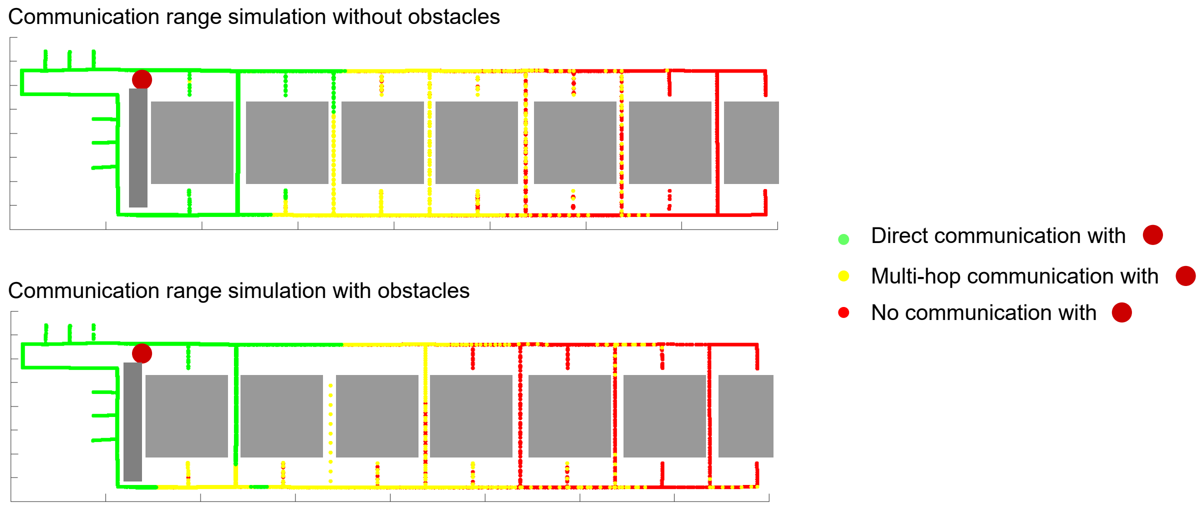


Figure 37: Comparison of direct on multi-hop communication range within a factory, regarding and disregarding signal-attenuating obstacles.

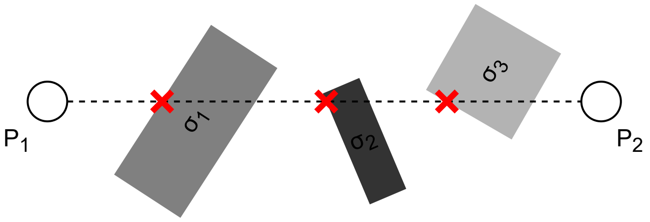


Figure 38: Simplified example of dampening factor calculation in the Attenuation-Factor-Model (AFM)

This edge represents the ability for an AGV to drive from V_s to V_e. One-way paths are fairly common in industrial applications. Therefore in contrast to the implementation in [14] the described model assumes, that any edge represents a one-way path from start vertex to end vertex and not in reverse. If a two way path is required, the reverse edge must be added to the graph manually.

Different levels of detail were possible for the representation. A high detail representation of the industrial environment enables high-precision simulation of the signal propagation, including reflection, refraction and scattering. However a high-precision representation also requires complete knowledge about the simulated factory and also entails high model maintenance cost every time something in the factory changes. Due to these disadvantages and the high cost of implementing such models, a more simplistic representation of the signal-attenuating obstacles was chosen. Each obstacle is present as a simple geometric shape (e.g. box, cylinder, sphere, etc.) and a specified signal attenuation factor σ_n. The model enables the propagation model to calculate a combined signal attenuation on the LoS path between two points P_1 and P_2 with:

$$\sigma(P_1, P_2) = \sum_{o}^{O_{LoS}} \sigma_o \tag{20}$$

Where $O_{LoS} \in O$ is a subgroup of all obstacles, with all obstacles, that intersect the LoS between P_1 and P_2. This process is shown in Figure 38.
This level of detail is appropriate to model local differences in the signal attenuation without incurring excessive overhead in model maintenance cost and computational complexity. Figure 37 presents the simulated communication range for direct and multi-hop communication with a client in an industrial application. The presence of walls changes both the direct and multi-hop communication range. In scattering-rich environments (e.g. warehouses) the inclusion of these obstacles is highly detrimental to the effective communication range.

4.2.4.3 Transmission model

The transmission model described in this work consists of two major parts. The first component is the path-loss of the transmitted signal, while the second component is interference and noise. The goal of this section is to determine the SINR of a network participant in order to estimate the probability of a successful demodulation and therefore a successful transmission of data. As previously described the SINR has three fundamental parts:

- **Signal** - The primary signal, which has to be decoded
- **Interference** - Other intentionally sent signals, inferring with the primary signal
- **Noise** - Unintentional interference in the frequency-band

When receiving signals from the wireless medium, multiple signals can reach a receiver at the same time. Only one of these signals can be decoded. This signal must be the strongest signal that was received, since all other signal can not be demodulated. Therefore in this model the strongest of all received signals is classified as the signal, while all other signals are part of the interference. Both the signal strength of the signal and the interference depend on positions of source and receiver and the signal propagation within the environment. There might also be interference, which is not caused by other participants, but by clients of other communication networks, which use the same or adjacent frequencies. Due to possibly different modulation and coding schemes or possible encryption these signal can not be demodulated, even if they constitute the strongest or only signal.
Which of the incoming signals is interference and which is the signal can be different from time-step to time-step. The signal is always the signal with the strongest remaining signal strength, while all other signals become interference. Let $S^{st} = [s_1, s_2, ..., s_n]$ be a set of the signals received in time step dt, sorted by the remaining signal strength. The only signal for which a demodulation might be possible is s_1, therefore $S = s_1$. All other signals constitute to the interference $I = \sum_{i=2}^{n} s_i + I^+(t, P_r)$, where $I^+(t, P_r)$ is a term for

additionally interfering sources. This term is time-variant and depends on the position of the receiver P_r. The received noise $N(t, P_r)$ depends on the same parameters. The Signal-to-Interference-and-Noise-Ratio (SINR) is therefore given by:

$$SINR = \frac{S}{I+N} = \frac{s_1}{\sum_{i=2}^{n} s_i + I^{+}(t, P_r) + N(t, P_r)} \tag{21}$$

The interference I is comprised of interference by other participants of the network and by other clients in other networks. Through effects like reflection and refraction a signal might also interfere with itself. Such self-interference can be either destructive or constructive. Since a multi-path propagation model is not scalable enough for the presented use case, this term is not available to us.

The wireless communication is not an isolated system. Other electrical systems can impact the wireless channel. This is expressed by the noise term N. In the industrial environment some sources of noise can be electrical and combustion drive systems, communication on adjacent frequency bands or other sources. The received power from this noise highly depends on the time and location at which the noise is received. The term N can also be used to model constructive and destructive interference by encompassing a random range, positive as well as negative.

The ability to transmit data depends on the ability to demodulate an incoming message. The Bit Error Rate (BER) directly depends on he SINR. A coding scheme can be used to recover packets with bit errors. This is only possible up to a certain amount of wrong bits. Therefore the Packet Error Rate (PER) depends on the BER. The probability for a successful demodulation is the same probability as not having a packet error:

$$P_{demod} = 1 - PER(BER(SINR)) \tag{22}$$

$BER(SINR)$ is a function, that depends on the utilized modulation scheme. For many common modulation schemes mathematical and empirical evaluations of these relation exist [219]. Determining the BER only from the SINR is always a simplification, as the real influence of interfering signals depends on the interaction of electro-magnetic waves. The same is true for the relation of PER and BER. Generally the coding scheme determines the robustness of a frame against error bits, but the bit-repair-success of different coding schemes also depends on the number of error bits per byte, the number of sequentially wrong bits and many more factors.

Many of the completed simulations used either IEEE802.11 a/g or Visible Light Communication (VLC). For IEEE802.11 a/g a simplified $PER(SINR)$-model was used [219]. For the VLC communication a simple threshold for the SINR was defined.

4.2.4.4 Robot mobility model

Many of the previously described models require position information about receiver or transmitter of a message or the distance between such a communication pair. Additionally the relative position to obstacles in the environment might be relevant. In simulations the positions and movement of mobile clients in network simulations are governed by so called mobility models. In Section 3.5 a number of these mobility models are described. The usage of mobility models stands in contrast to simulating the detailed robotic system.

The common section discusses the possibility to realistically model the movement and behavior of mobile robots in industrial applications. How realistic a model is of course depends on the examined parameters of the system. In our case the macro-view on the factory is most relevant. Therefore the models do not describe control loops and mm-scale errors. They are however meant to correctly predict and model the general movement of the mobile robots.

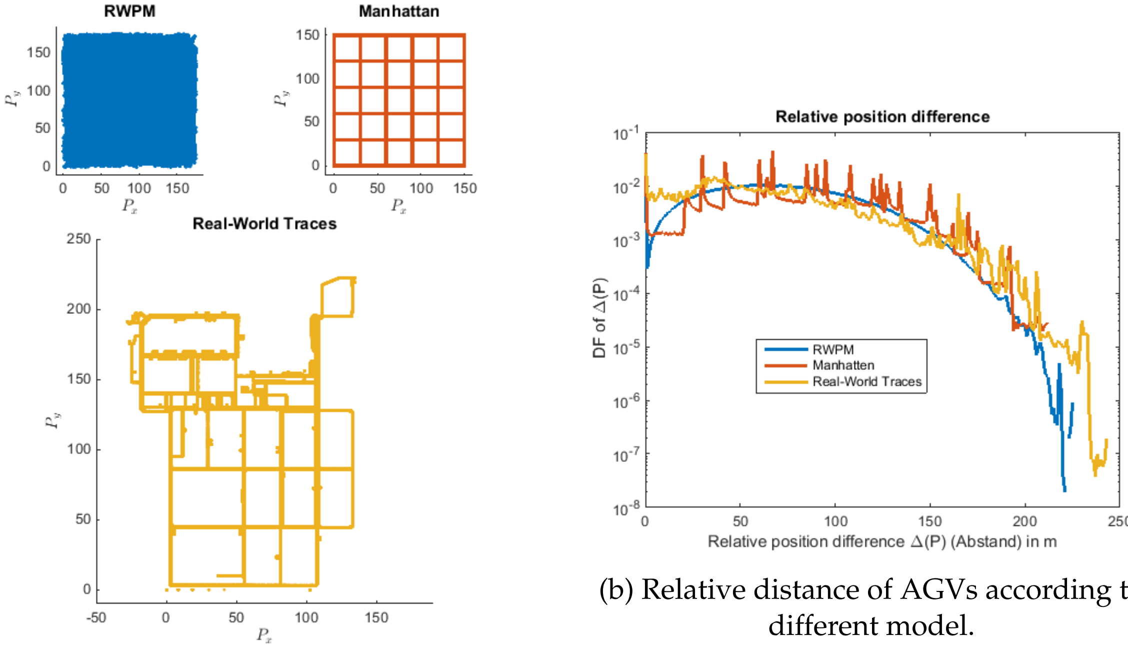
This approach has the advantage, that it is very scalable and easily reproducible. However these simulations are often not very realistic and sometimes not compatible with other aspects of the simulation models. For example simulating the attenuation of obstacles on wireless signals (see previous section), while using Random Way-Point Model (RWPM) (in which robots pass through walls) can lead to non-robust simulation results [14].

There are different ways to improve the modelling of specific use cases by a mobility model. Cavilla et al. [14] used a mobility model based on graphs to simulate the restricted movement in indoor scenarios. In the subsequent sections a similar graph-based mobility model is proposed. But in the following section it is examined if common mobility models, like RWPM and Manhattan-Model, can be changed to more precisely reflect the movement of AGVs on the factory floor.

The movement of 30 AGVs on the factory floor was observed and analyzed in terms of relative distances and speeds between clients [12]. The relative distance is a good indicator for the type of topology within the factory. The relative speed of the AGVs is an indicator for the mobility of the network and the frequency of changes in the topology. Parameters for RWPM and Manhattan model to replicate the observed industrial environment were chosen. The traces of the AGVs as generated by the two models and the real application can be seen in Figure 39a.

The parameters of RWPM and Manhattan model were chosen to represent a good fit to the existing tracks of the real AGVs. As seen in Figure 39b this also generates a good fit for the inter-node distance in the network, shown by the PDF of this distance. Especially distances above $40\,\mathrm{m}$ are very well matched by the two models. The Manhattan model shows the same spikes in inter-node distance, which are present in the real-world data and caused by the basic structure of the available paths. The probability for AGVs to be within close proximity was underestimated by both models. In reality the AGVs tend to gather at logistical hubs and charging stations. This behavior can not be replicated with simple models like the two presented here. In future sections, models are explored, that can simulate this behavior.

In all mobility models the default speed selection strategy was implemented. In RWPM a node selects a random speed from a defined range. This speed stays constant until the destination is reached. In the Manhattan model all nodes drive with the same constant speed. In reality the nodes generally strive towards using a specified default speed, but kinematics, safety concerns and traffic situation can lead to lower speeds. Addi-



(a) Tracks of moving AGVs according to RWPM, Manhattan model and reality.

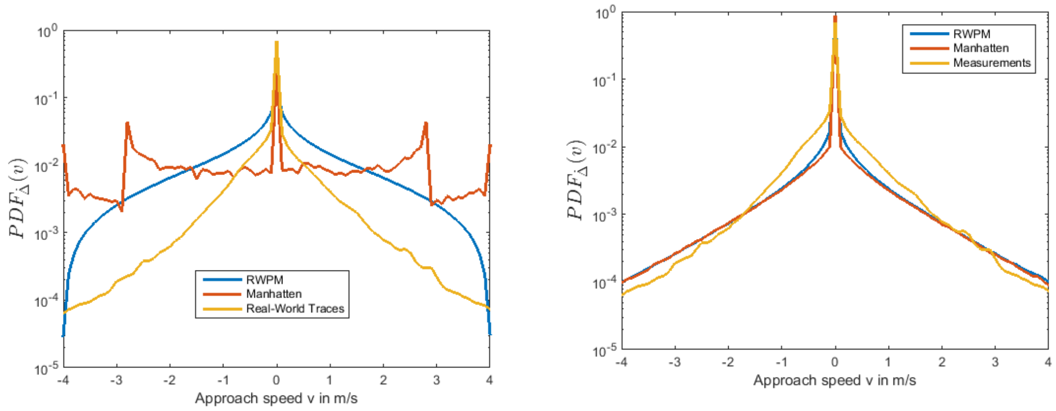
(b) Relative distance of AGVs according to different model.

Figure 39: Observations and simulations regarding AGV mobility.

tionally real AGVs do not move continuously during their operation. This is caused by the general over-capacity of the AGV fleet, charging times and durations in which the hand-over of goods is completed. The difference in speed distribution can be seen in Figure 40a.

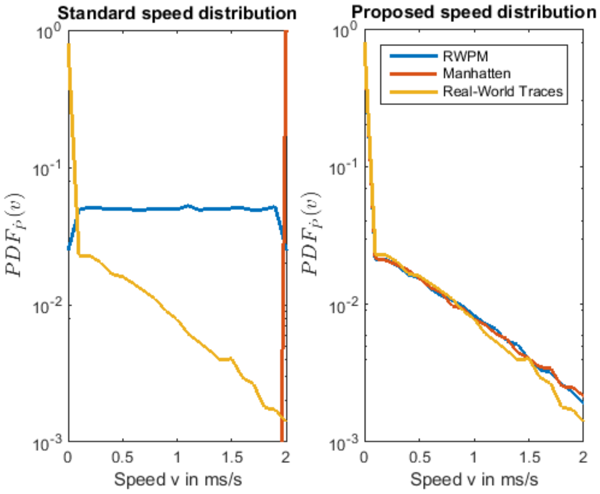
We propose a new speed (V) selection algorithm for RWPM and the Manhattan model in order to more precisely emulate the movement of AGVs on the factory floor (see Equation 23.

$$V = \begin{cases} 0, & \text{with probability } P = \phi \\ \Gamma(\alpha, \beta), & \text{otherwise} \end{cases} \tag{23}$$



(a) Inter-node speed in default models.

(b) Inter-node speed with newly proposed speed distribution.



(c) Old and newly proposed speed distribution.

Figure 40: Difference between real inter-node speed and examined models. Including the positive impact of a newly proposed speed distribution..

In this algorithm the speed of the AGV is set to $0\,\mathrm{m/s}$ with a probability of $\phi = 0.88$. This value was chosen empirically, in order to create the best possible fit between the real-world data and the model. In future work the correctness of this value can be determined, if more complete access to the AGVs fleet controller is available.

This represents the aforementioned scenarios in which an AGV does not move. If the AGV moves, then the speed is selected by a Gamma-Distribution Γ, where the shape parameter $\alpha = 1.17$ and scale parameter $\beta = \frac{v_r}{3}$ are chosen accordingly. The difference in node speed distribution can be seen in Figure 40c. The changed node speed impacts the relative node speed as inteded. Figure 40b shows, that appropriately selecting the node speed is also highly beneficial to the realism of simple mobility models in terms of relative node speed.

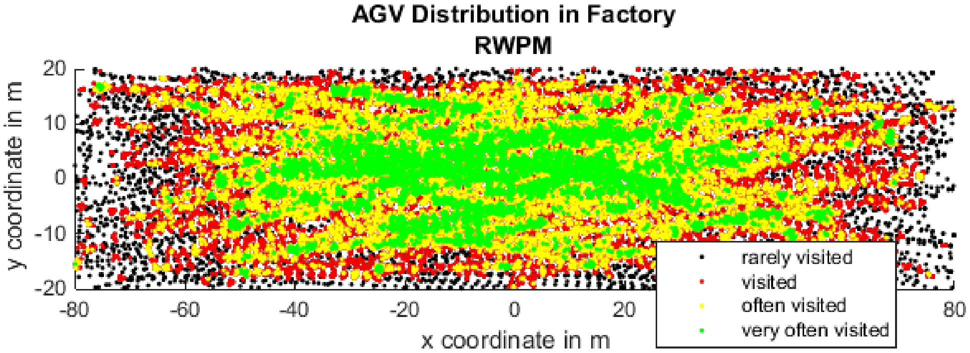


Figure 41: AGVs modelled by the RWPM.

As mentioned before, these models are improvements, but still not perfect. Two major differences persist. Firstly, the interaction of signals between clients with obstacles in the environment can not be emulated in these models. Secondly, typical behavior of AGVs on the factory floor can not be observed with these models (e.g. clustering at logistical hubs and sparse distribution within the production lines). In the subsequent section an improved model is presented, that addresses these weaknesses.

4.2.4.5 Production process based mobility model

The process of designing a more realistic mobility model for AGVs on the factory floor has two steps. Firstly, the model must emulate the restricted movement within the factory. The model must also emulate the typical distribution of AGVs observed on the factory floor [8].

In most network simulations the RWPM is used. This model is highly abstract and does not offer a good estimation of movement for most use cases. In a reference scenario an example factory with the outer dimensions of $40\,\mathrm{m} \times 160\,\mathrm{m}$ is presented. In Figure 41 the distribution of AGVs within the factory is presented, when simulated with RWPM. The AGVs move within all parts of the factory and disregard machines or walls and obstacles. The figure also shows, that the AGVs show a higher distribution to be at the center of the factory. This behavior was previously described by Bettstetter et al. [160].

Cavilla et al. [14] utilized a mobility model based on graphs to emulate the restricted movement within an indoor environment. In the utilized environment model a graph for this navigation is present (see Section 4). As previously described the graph consists of a number of vertices and a number of directed edges. Different policies can be used to control the movement of AGVs on the graph. In this section two strategies with different advantages are described:

The first strategy is, that once an AGV reaches a vertex the AGV can choose any of the connections of this vertex as the next path. The choice is random. This strategy enables the flagging of vertices and edges as occupied and removing them from the random selection process of other AGVs. With this simple strategy collisions between AGVs can

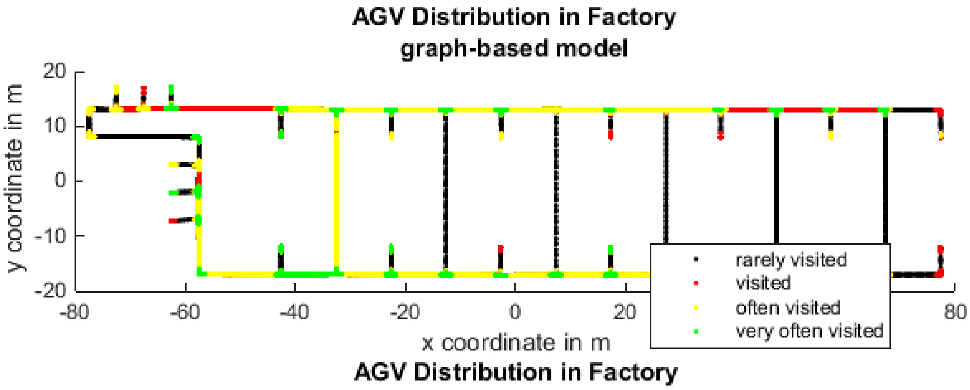


Figure 42: AGVs modelled by a graph-based mobility model.

be avoided. However the global movement of the AGVs becomes very unrealistic and random. Therefore this model is good for simulating local AGV behavior, but struggles with realism in the global AGV behavior.

Another strategy is to not randomly select a destination, that is connected to the current vertex of an AGV, but to select a random destination in the graph and calculate the shortest route to this destination. For this calculation an algorithm like Dijkstra can be used [220]. This leads to realistic global movement of the AGVs. However with this model AGVs can collide, since the presence of AGVs is not part of the route planning. The model does also not include detailed motion control loops or obstacle avoidance. Due to the high percentage of unidirectional paths in many industrial applications, the number of occurring collisions is relatively low. This model is able to realistically simulate the global movement of AGVs, but struggles with local realism.

Combining both methods is not easily possible. The combination would require the implementation complex fleet control schemes to avoid dead-lock behavior [47]. The distribution of AGVs on the factory floor, when simulated using a graph-based mobility model, is shown in Figure 42. The figure shows, that the AGVs now only move on the available paths within the factory. But the mobile entities still tend to gather at well connected nodes close to the geographical center of the factory. This is not realistic behavior. An improvement to the model is proposed to more precisely simulate the processes in a production facility.

The goal of the more precise mobility model is to emulate the production processes of a factory without simulating the complete material flow.

For this the vertices of the navigation graph are grouped according to their function with $V \ni [V_+, V_1, V_2, V_n]$. V_1 to V_n are vertices, at which specific tasks can be fulfilled. Some example tasks are:

- **Garbage collection** - AGVs take garbage from the production line
- **Garbage disposal** - AGVs dispose of previously collected garbage
- **Storage output** - AGVs pull material or goods from a storage facility
- **Storage input** - AGVs deliver goods or material to a storage facility

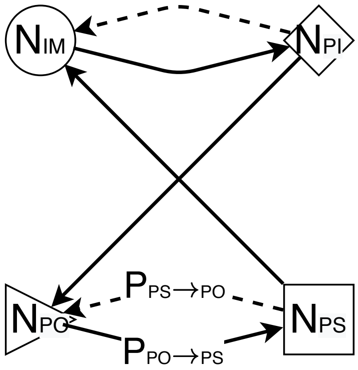


Figure 43: Markov-chain describing destination selection probabilities. Probabilities with $P = 0$ are omitted.

- **Production input** - At these points material or tools can be transferred to the production line
- **Production output** - Finished or partly finished products are transferred from a production line
- **etc.**

Any number of different types of tasks/positions can be classified by V_1 to V_n. A special type of vertex is V_+. These are cross roads and other vertices, that are not destinations for AGVs but rather part the the path layout.

The first step in creating more realistic movement for the AGVs is to eliminate all vertices in the sub-group V_+ from the random selection of destinations. In reality AGVs always have a specific destinations, and do not drive to every possible point on the navigation graph. The next step towards more realism is based on the following observation: Not all sequences of destinations are realistic/useful. An AGV driving from a storage input vertex to another storage input vertex, is for example very unlikely, since the AGV would not transport anything, that could be put into storage at the second vertex. We therefore define a function $P(V_p, V_d)$, which gives the probability for an AGV to drive from its current position of type V_p to a destination of type V_d. The sum of probability for all destination types must always be 1. This probability function can be expressed as a markov-chain. The markov-chain links the different types of destinations with the probabilities to drive from one of these destinations to the other. The example markov-chain for the use case presented in Figure 44 is given in Figure 43.

The denoted types of navigation vertices are: Input for material N_{IM}, input for production N_{PI}, output for production N_{PO} and product shipping N_{PS}. The normal transport process is denoted by the arrows between the types. Solid arrows signal high probability, while dotted arrows signal a lower probability. Probabilities of $P = 0$ are omitted from Figure 43.

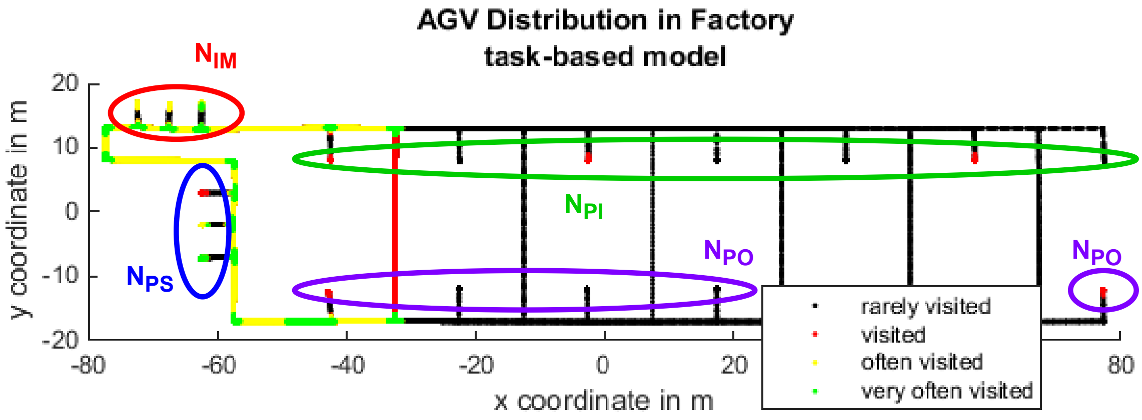


Figure 44: AGVs modelled by a task-based mobility model.

The AGVs show a very different distribution within the factory, when choosing their destination based on this markov-chain. The distribution is plotted in Figure 44. Since the markov-chain based model models the tasks of AGVs within the factory the model is further called task-based mobility model. In Figure 44 a very logistics-centric distribution can be seen. The AGVs tend to gather at the left of the factory, where the input and output of the factory is located. Within the production part of the factory (right side) the AGVs are distributed sparsely. This fits observations from real factories.
The presented models enable us to realistically simulate the speed and paths of AGVs in the factory environment. However the AGVs are not yet reactive. In the coming section we will explore the possibility to add the impact of wireless communication to the movement of these mobile robots.

4.2.4.6 Robot behavior

In reality AGVs communicate with machines and often a Central Control Unit (CCU) / fleet management. And this communication impacts the behavior of the AGVs. This work relies on correctly modeling the impact lost connections, insufficient channels and other communication characteristics have on the behavior of the AGVs.
Not all AGVs are the same and they react differently to the provided wireless network (see Figure 45). In the following segments the behaviors of different AGVs are described. This includes fully autonomous AGVs, centrally controlled AGVs and AGVs controlled according to the cloud robotics paradigm.
Fully autonomous AGVs do not require any communication to work properly. No central control is applied. Any used communication technology is either assumed to be ideal or has no effect on the behavior of the AGVs. This for example includes mobile assistance robots, that assist in the assembly of products. These are purely controlled by the employee within the production line and do not depend on any communication. Mobility models must not be modified to simulate this use case.

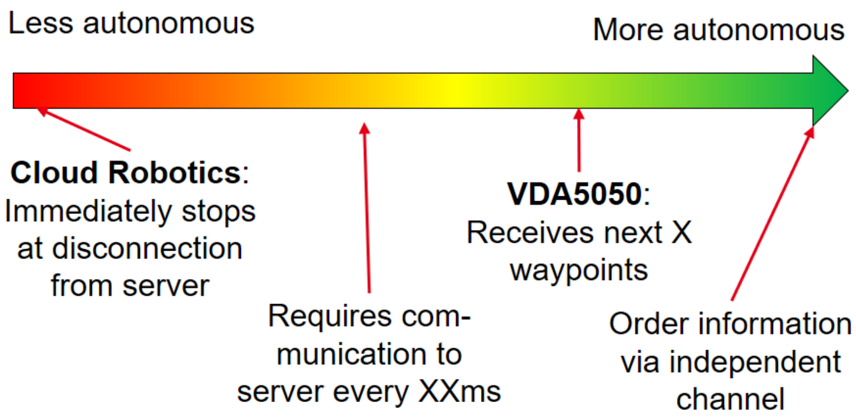


Figure 45: Autonomy levels of AGVs

Coordinated AGVs can act autonomously, but the actions of the fleet are controlled by a central control unit. Standards like VDA5050 [45] support this autonomy level. In this use case the AGVs regularly (e.g. every $3\,\mathrm{s}$) send status messages to the central control unit. The control unit issues orders to the AGVs. The AGVs do not start any transport tasks if they do not receive an order and the central control unit might issue a stop-order, if the control unit doesn't receive a status message within a certain time frame. In both cases the reactivity of the AGV can be implemented by setting the speed to $0\,\mathrm{m/s}$ if certain network conditions are present. If an AGV has no connection to the central control unit and no active order the AGV might autonomously return to a charging station with known / guaranteed connectivity.
Lastly AGVs can also be controlled according to the paradigm of cloud robotics. In this case the AGVs require constant connection to a server. The AGVs stops as soon as no sufficient connection is available. Additionally the requirement in regards to latency and throughput of the connection are much higher, since motor commands and sensor data must be transmitted over the link. This behavior can again be implemented by setting the speed of the AGV to $0\,\mathrm{m/s}$ if no sufficient link is present.
Not all AGVs can be described by these categories. Many manufacturers implement custom communication and control protocols, which might behave entirely different. However many of the systems relevant to this work can be described by this categorization of more or less autonomous.

4.2.4.7 Performance metrics

The developed modelling and simulation tools shall enable access to a wide variety of different metrics. The main task of these metrics is the comparison to set requirements for the network and the comparison of different networking approaches in the same scenario. Two central types of metrics can be defined:

1. **Network-related metrics**
   Network-related metrics are for example throughput, latency, path-loss, PER, packet-

loss and more. They are often required to determine if an applied communication solution is sufficient for an application or use case.

2. **Robot-system-related metrics**
The robotic system is impacted by the utilized communication technology. This impact can be observed, when observing the robotic system in the proposed model / simulation. The behavior of the robot system can be described for example in terms of transport tasks per hour per AGV ($T/h/AGV$), average continuous hours of autonomous operation, reliability of task completion and robustness to outside influence.

The following section describes, how these metrics can be extrapolated from the previously mentioned models.

The network metrics can be extracted from different parts of the network model. For example the path-loss and PER can be logged by the model of the physical network layer. The high level metrics, like throughput, latency and message delivery ratio can be extracted after the simulation from an extensive message log. Therefore all nodes of the simulated network log all generated and received traffic. Additionally data from the routing layer of the network can be logged to evaluate the topology of the communication network.

As described in Figure 36 the metrics regarding the robotic system can be best reported by the mobility model. In this case the mobility models also simulate the network-reactive behavior of the mobile robots. In the following sections a number of metrics and ways to calculate these metrics are described.

The number of completed transport tasks per hour $T/h/AGV$ is always given for the entire AGV fleet, but per number of AGVs n. This metric can be calculated as follows:

$$Tph \approx \frac{N_d}{T \cdot n} \tag{24}$$

Where N_d is the total number of destinations reached during the simulation of duration T.

When examining ad-hoc networks for AGVs observing the availability of links to the mobile clients is highly important. When considering AGVs, that for example move according to the VDA5050 standard, they cease movement, if no active order can be received. In a classical infrastructure network this will immediately require human intervention in order to restore connectivity. In an ad-hoc network the connectivity can be restored automatically through the mobility of the other clients. However observing the number of AGVs that are simultaneously inactive due to missing connectivity is therefore interesting. Theoretically permanent connection loss of all AGVs can also happen in ad-hoc networks. The probability of this occurrence can also be an important metric in the examination of the autonomy of an AGV fleet.

In [8] we observed these metrics and the impact of different mobility and signal propagation models on them. The selection of a suitable model is very important when simulating specific use cases.

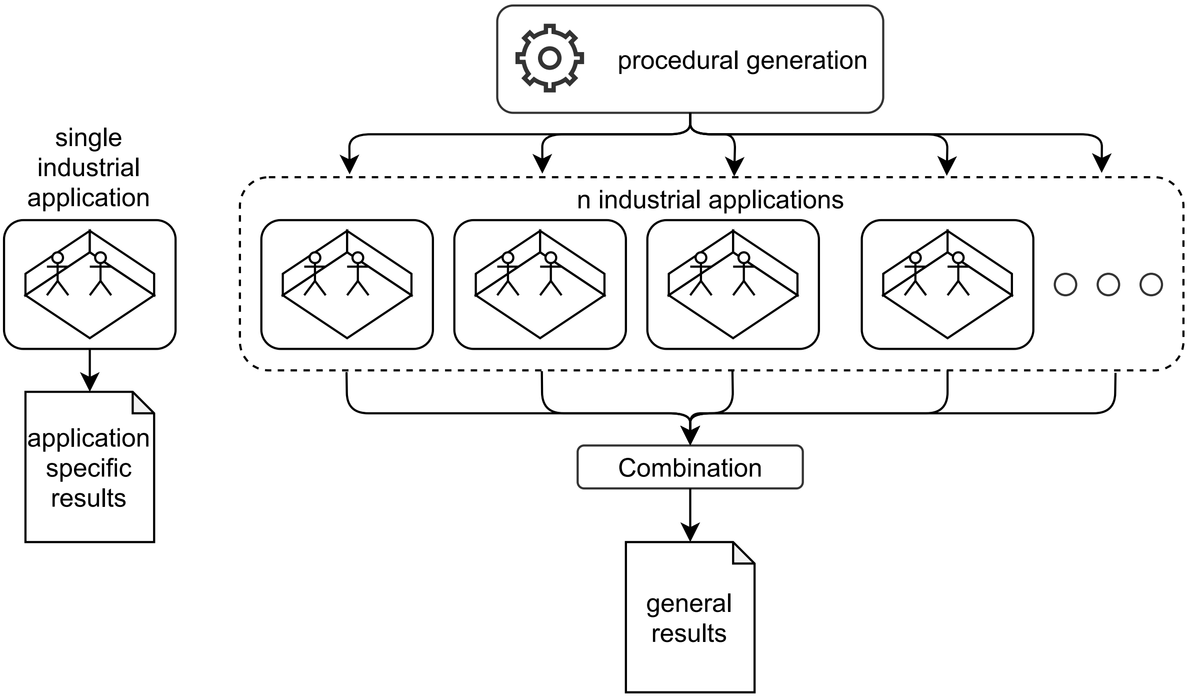


Figure 46: Concept of combining multiple simulation results to generate generalized results about observed system.

4.2.4.8 Procedural generation

The previously described models can be used to accurately recreate any industrial application or environment. However, sometimes such recreations of specific applications are not useful. If a new AGV control method, networking protocol for communication technology must be implemented, then general statements about the performance and applicability of these things might be more relevant than statements regarding specific use cases. In this case even very precise models are not helpful, as they can only lead to application-specific statements.

The goal of this section is to introduce a method, which enables the extraction of general performance and applicability information for industrial MANETs, while utilizing the previously described models. The general idea is inspired by Arnold et al. [194]. Instead of simulating a single factory for results, hundreds or thousands of factories are simulated, the results are combined and general results can be obtained. Like [194], procedural generation is used for the creation of the hundreds and thousands of factories. The complete process of application generation, simulation and result combination is shown in Figure 46.

As show previously different aspects of the industrial environment impact the performance and characteristics of a wireless network. The procedural generation generates an application model, which must cover all of the following aspects:

- **Factory size and boundaries**
  A factory is defined by the general shape and size of the factory floor.
- **AGV mobility and movement patterns**
  Throughout the factory the AGVs move on a specific layout throughout the factory
- **Signal attenuation**
  The signal of wireless communication technologies is attenuated by certain obstacles in the factory environment.
- **Network infrastructure**
  Depending on the examined communication technologies, network infrastructure must be present.

The procedural generation must therefore generate models which contain the necessary details. The steps in the procedural generation are chosen based on these aspects.

```
Generate factory floor space
Generate AGV navigation graph
    Generate basic manhattan graph
    Erode regular grid
    Place task points
    Define parking points
Place AGVs
Place obstacles
Place access points
```

The process starts by selecting a size A for the factory in m^2. A shape parameter r_S is selected. This shape parameter describes the relation of the lengths of the factory in x-direction (L_x) and y-direction (L_y) as $r_S = \frac{L_x}{L_y}$. With this shape parameter the sizes of the factory can be determined ($L_y = \sqrt{\frac{A}{r_S}}$ and $L_x = r_S L_y$). This creates rectangular factories, which is the most-common geometric form for factories.
Afterwards a navigation graph is placed within the factory. The generation of the graph starts with a Manhattan graph, which spans the factory from edge-to-edge. The number of lanes of the manhattan graph is the same in x- and y-direction. The distance of two adjacent, parallel lanes in the manhatten graph are determined based on the lane distance D_g. The number of lanes per direction n_l is selected in a way, that no two adjacent lanes are further apart, than D_g. The number n_l is determined by:

$$n_l = \left\lceil \frac{max(L_x, L_y)}{D_g} \right\rceil \tag{25}$$

This creates a standard regular manhattan grid. However, most factories do not fully consist of regular grids (see Figure 39a, page 89). Therefore, the grid is eroded. This refers to removing a certain percentage P_{nd} of vertices from the grid and all edges, which connect to these vertices. Removing vertices has, in contrast to removing edges, the advantage, that no unconnected vertices are created. However, the graph can split.

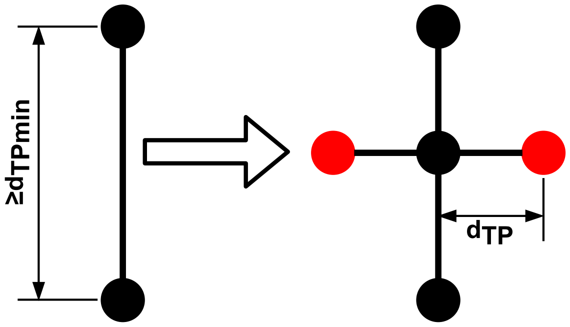


Figure 47: Basic process and geometry of adding a task-point to a lane.

In the presented implementation, if such a gap is created, then the used path planing algorithm can cross the gap only, if no other path is available.

The next step is to add task-points to the navigation graph. AGVs usually do not stop and fulfill tasks directly on a lane. Instead they drive into crate pedestals or crate hand-over-points. These are directly adjacent to the navigation graph, but the drive lane stays unoccupied, while the AGV is on this point. These points are added to a certain percentage P_{TP} of all lanes in the eroded manhattan graph. Their geometry and the process of adding them to a lane is shown in Figure 47. Task Points can only be added to lanes of at least length d_{TPmin}.

The vertices of the navigation graph have a position and a type. All vertices in the original graph are of *default* type. Vertices, which are added as task points are of *task* type. A third type of vertex in introduced. Sequentially all task vertices are examined. If another vertex of type *task* is within a range defined by d_{minP}, then the examined vertex is changed to type *parking*. The *parking* vertices can be described as redundant *task* vertices. This means, that blocking a *parking* vertex, does not block any processes within the factory, since there is another, equivalent *task* vertex close by. *Task*- and *parking*-vertices can both be destinations for AGV tasks. For the AGV fleet knowing, that a *parking* vertex can be blocked for a prolonged duration of time, while a *task* vertex must be freed as soon as possible, is important to note. Defining the parking vertices concludes the process of navigation graph creation.

On this navigation graph AGVs are placed. The number of AGVs is defined by the percentage P_{AGV}. The percentage describes, that on P_{AGV} percent of the *task* and *parking* vertices an AGV is placed. Therefore, the number of AGVs automatically scales with the size of the factory and the density of the factory in terms of task destinations. P_{AGV} can be understood as being comparable to the AGV density.

Furthermore, obstacles are placed within the factory. The number of obstacles n_O as well as the size of the obstacles S_O is randomly selected. The obstacles have a specific signal attenuation factor. They are placed in such a way, that they do not intersect the previously placed navigation graph. The number of obstacles does not scale with the size of the factory. In larger factories, there are often not more obstacles, but larger

Figure 48: Legend to Figure 49

obstacles. This is also the case in this procedural generation
Lastly the Access Points (APs) are placed, if a communication technology is examined, that requires APs. There are two modes for the placement:

1. **Sparse placement**
   The sparse placement mimics common factory environments with non-complete coverage. In this case a number of APs is randomly placed within the bounds of the factory. The actual number of APs n_{AP} depends on the number of AGVs n_{AGV} and is defined by the relative percentage P_{AP} with $n_{AP} = P_{AP} \cdot n_{AGV}$. The random placement causes high variance in the size of the actually covered factory area. The number of APs scales with the number of AGVs, since the APs are often installed to service these AGVs.
2. **Complete coverage**
   The procedural generation is also able to create factories with complete network coverage. For this the APs are placed in the very dense regular grid. Signal attenuation is avoided, by placing the APs on the vertices of the navigation graph.

The previously described procedural generation process relies on a number of parameters. These parameters are summarized in Table 12. The table shows the parameters and short descriptions. Additionally, for each parameter a value or value range is defined. These are the values for the simulations subsequently used (see section 5.4). If a value range is defined, then the actual value for the specific generated factory is chosen from an equal distribution between the lower and upper bound.
The ranges for A, r_S, D_g and P_{nd} were chosen based on experience and observations in several real factory buildings. From a specific factory for electrical drive systems the values for P_{TP}, d_{TP}, d_{TPmin} and d_{minP} were extracted. P_{AGV}, n_O, S_O and P_{AP} are again experience values from several industrial applications. Other parameters for the simulation, like path-loss exponent or signal dampening, were empirically determined [8].
In Figure 49 seven different procedurally generated factories are shown. They were all generated using the parameter set shown in Table 12. The selection of the random parameters is based on a seed. This seed is equivalent to the generated factory. Based on this seed the same factory can be recreated for further tests.
After generating the factory models the factory is simulated for a certain duration and data points are collected. This simulation can be repeated for each generated factory and the data points can be combined.

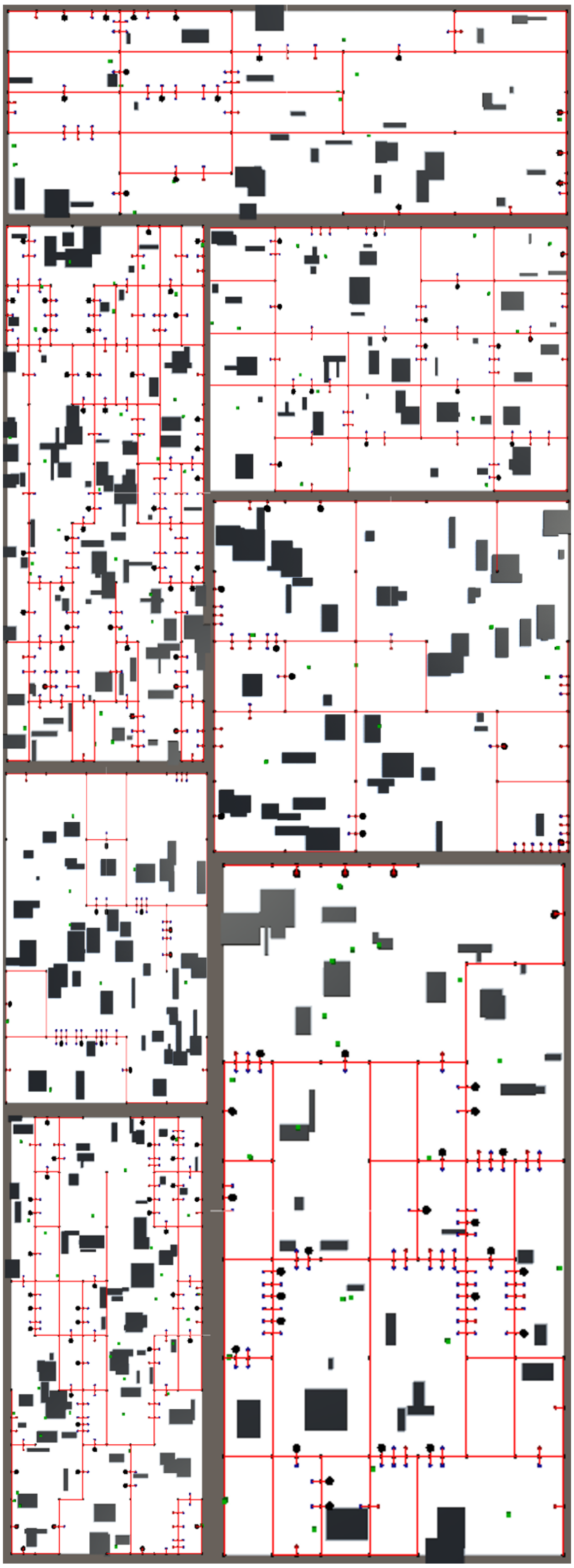


Figure 49: 7 example factories

Table 12: Table of subsequently used parameters

Parameter	Value	Unit	Description
A	$7000 < A < 150000$	m^2	Factory floor size
r_S	$0.33 < r_S < 1$		Ratio of x and y length of the factory
D_g	$7 < D_g < 20$	m	Distance between paths in navigation graph
P_{nd}	$10 < P_{nd} < 30$	$\%$	Irregularity percentage of navigation graph
P_{TP}	100	$\%$	Number of edges to which task points are added
d_{TP}	2	m	Distance of task points to original graph edge
d_{TPmin}	5	m	Minimal length for edges to add task points to
d_{minP}	5	m	Maximum distance of two task points for parking point classification
P_{AGV}	50	$\%$	Number of AGVs in relation to number of task and parking points
n_o	$10 < n_o < 100$		Number of obstacles
S_o	$1 < S_o < 10$	m	Size of obstacles
P_{AP}	75	$\%$	Number of APs, expressed as ratio to number of AGVs

4.2.4.9 Simulation tool

A simulation tool was developed, that encompasses the precise modeling of industrial applications, including network reactive AGVs and procedural generation.The simulation tool is meant for professionals to estimate the applicability and performance of different wireless communication solutions to a variety of industrial use cases.

The tool was developed based on the Unity game engine, like previous robot simulation tools [195]. The tool consists of three major parts:

1. **Level** - The level is the three dimensional representation of the robots environment.
2. **Robots** - A number of mobile entities moving in the environment. Each robot containing a model for a wireless communication interface and a model for the mobility and behavior of the robot.
3. **Management and Utilities** - A number of software modules fulfilling different tasks in the simulation tool, like setup, timing, logging, etc.

The level consist of a ground plate, a set of obstacles and a navigation graph. The ground plate defines the geometrical size and shape of the factory. Additionally the

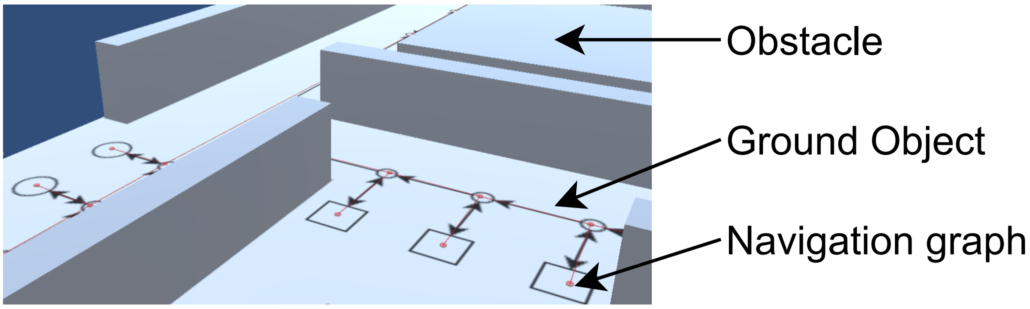


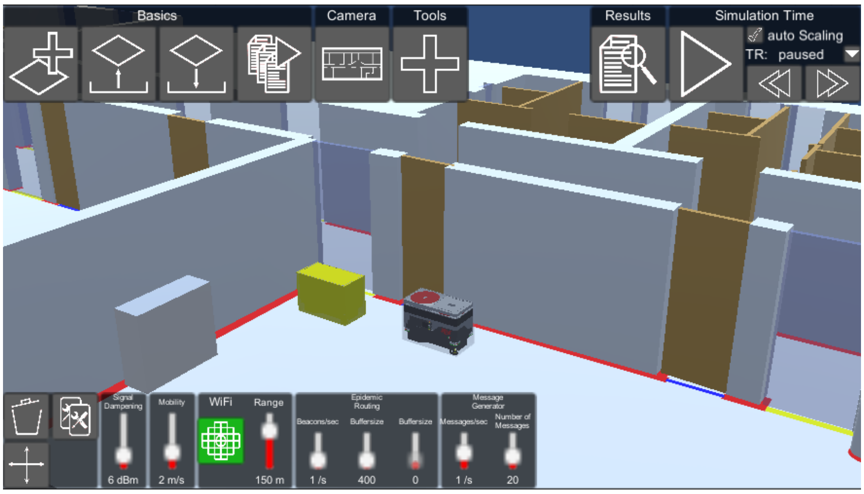
Figure 50: Example industrial environment within the simulation.

ground plate can display the floor-plan of a building or factory. This simplifies the placing of the obstacles and the navigation graph. The obstacles are simplified three-dimensional representations of any kind of object within the factory, that can interact with the wireless signal propagation between the mobile devices. These objects / obstacles are added with a simple geometric shape and a dampening factor. The 3D models are purposefully simple in order to maintain scalability in the simulation. Another element in the environment is the navigation graph. The navigation graph consists of vertices representing specific positions within the factory and unidirectional edges connecting these vertices. Each vertex has a specific type describing if a task can be fulfilled at this vertex and what kind of task can be fulfilled. The ground floor, obstacles and navigation graph objects can be seen in Figure 50.

The robots are another important component of the simulation seen in Figure 51. They have the central components mobility and communication. The mobility model controls both, the movement of the robots but also their reaction to the state of the network or incoming messages. The model encapsulates both, the previously proposed mobility and behavior models. Additionally the network model for this client runs as a component of these robots. The network model of each robot encapsulates the incoming messages, demodulation, parsing to the upper network layers, message generation, parsing to the lower network layers, media access control and signal propagation modelling of outgoing messages. Participants like APs are also part of the level and classified as non-moving robots for the purpose of simulation. They are connected to the AGVs CCU, which is not part of the level, but part of the management tools.

Some parts of the simulation tools, do not encapsulate the previously proposed models, but rather manage the correct execution of the models and the accessibility of the extracted results / metrics.

The first management tool has the central task to setup the simulation scenarios and execute them. This includes loading a particular configuration of environment and mobile robots, setting up simulation parameters, executing the simulation and logging the results. This tool is also able to execute simulation series with different parameters and configurations. An example for such an simulation series is to simulate a factory with a



Signal Dampening 6 dBm
Mobility 2 m/s
Range 150 m
Beacons/sec 1 /s
Buffersize 400
Buffersize 0
Messages/sec 1 /s
Number of Messages 20

Figure 51: Robot with parameters in simulation.

DTN with different buffer sizes for this DTN and to do a certain number of repetitions per buffer size in order to obtain statistically relevant results.

A particular challenge during the execution of the simulation was the timing. Most network simulation tools are discrete event simulators, which offer precise timing for each event within the network. The used Unity game engine does not offer such precise timing. The engine executes steps within the simulation synchronously to the rendering of the simulation. A time management tool was therefore implemented. The tool observes the timing of the frames within the simulation and adjusts the time scaling to guarantee a precise simulation.

Another important tool within the simulation is the logging. The logging can be either event discrete or continues. Continues logging constantly logs the value of certain parameters over time with a specified frequency. The event discrete logging logs the occurrence of certain events, for example message generation or the receiving of messages. The logged data is saved in the form of *.csv*-files. These files can subsequently be analyzed by external programs like Matlab, Excel or Python scripts.

In the following section this tool is used to examine different industrial ad-hoc systems.

5 Industrial Ad-Hoc Systems

In this section different types of ad-hoc systems are implemented in the industrial reference use case. The performance, behavior and applicability of these systems is examined and described. The goal of the implemented systems is to fulfill some of the most pressing needs for ad-hoc communication in industrial applications. The first Subsection (5.1) observes the P2P channel between AGVs in industrial environments. Different characteristics of a resulting MANET are reviewed and lessons for the following systems design are extracted. The two following subsection 5.2 and 5.3 describe two very heterogeneous ad-hoc communication systems for the AGVs. The first system focuses on highly time-critical communication, while the second one concerns delay-tolerant communication. In subsection 5.4 a control system for the AGVs is introduced, which has the goal to optimize the communication conditions in an ad-hoc network.

Many of the methods, which were proposed and described in Section 4 are used in the design and implementation of the subsequently described systems. The methods presented in section 4.2.1 are applied in section 5.1. The implementation of the time-critical communication was supported by the simulation methods and models developed in 4.2.4. The delay-tolerant communication and the applicability of the developed method was checked with the method proposed in 4.2.3. Lastly, one of the main reasons to develop the proposed model and simulation tool was to examine reactive robot behavior, this enables the research regarding the adaptive positioning of the robotic clients described in section 5.4.

All of the presented systems continue to concern the use case of AGVs in industrial environments. However, some of the proposed systems can also incorporate other mobile devices like tablets or smartphones. Additionally the insights provided in section 5.1 are relatable to any kind of mobile communication in industrial environments.

5.1 Properties of the industrial ad-hoc channel (2)

In [64] firsts insights into the latency properties of industrial ad-hoc channels were gained. This knowledge was deepened in [9] with a detailed examination of ad-hoc channels and networks based on empirical investigations.

Wireless communication channels are highly heterogeneous. They depend on the applied technology, the used frequencies, movement of clients, weather conditions and much more. The characteristics of these channels also highly impact the applicability and performance of different networks and network types. Examining the characteristics of industrial ad-hoc channels was important to the presented work, in order to design and select more effective technologies and routing strategies for this application. The following are some of the questions answered by the examination and the reasoning behind these questions:

- *How interconnected is an industrial MANET between AGVs? Is the network fully connected?*

  This questions concerns the applicability of different routing schemes (proactive vs. reactive routing) and the applicability of DTNs. If the network is fully connected, DTNs can not offer any additional connectivity or advantage.

- *Are the base assumptions of routing protocols fulfilled by the available channels?*
  Many routing algorithm assume certain channel or network qualities / characteristics. For example bidirectional channel, connectedness of the network, minimum life time for connections, etc. The goal of this examination is to give an overview over which assumptions are true for the industrial use case, and which are not.
- *Which general advantages can be offered, by incorporating an MANET or other multi-hop ad-hoc networks to the industrial use case?*
  The offered advantages of industrial MANETs are described within this section. Both in terms of increased connectivity and longer route life time by utilizing redundant channels. This motivates the implementation of the systems proposed in the coming section.

In the following a measurement method is introduced, which enables us to answer the presented questions. Afterwards different metrics for the ad-hoc network are examined and lastly a number of lessons learned summarize the future design considerations for industrial ad-hoc systems.

5.1.1 Methods of measurement(2)

The goal(1) for these measurements was to record the time-variant topology of the MANET. Recording the Nodal Encounter Pattern (NEP) of the AGVs in the industrial application enables us to evaluate this topology. In this section the basics of this recording and the difference to existing literature is summarized.

Section 4.2.1 described, that Nodal Encounter Patterns (NEPs) are normally extracted from network traces based on the following assumption:

> "If two users associate with the same location (i.e., switch port in the USC trace, access point (AP) for all other traces) for overlapped time intervals, they are assumed to encounter (i.e.,being able to communicate) with each other." [214]

This assumption describes, that if two participants are registered at the same AP in a infrastructure network then the connectivity of these two network participants in an equivalent an ad-hoc network is assumed. This assumption is the best / only possible assumption to extract NEPs from network traces. But as shown in Table 8 there are many scenarios in which this assumption is not true.

In [9] we have shown, that this assumption heavily depends on the number and distribution of APs on the application area of the ad-hoc network. Defining an algorithm to correct possible errors caused by this assumption was also not possible. Therefore the conclusion is, that in the presented use case implementing the proposed method to record NEPs (see Section 4.2.1) is the more promising solution.

Recordings were done with the parameters described in Table 13. The main goal(1) was to observe an ad-hoc network between AGVs in an industrial environment. Other configurations were executed in order to test the method and to generate a basis to compare the industrial MANET to.

Table 13: Measurement parameters in chennel observations [9]

Parameter	Values
Environments	Office / Outdoor / Industrial
Movement	static / group / AGV
Number of nodes	5 - 10
Communication Technology	IEEE 802.11
Send Power	$20\,\mathrm{dBm}$
δt	$0.2\,\mathrm{s}$

The three different environments were chosen due to their prevalence in literature or their relevance to the examined use case. The office environment is the most common test environment in scientific literature [136, 137, 221]. This use case is highly relevant to many use cases including ours. Many real factories also contain office segments. The outdoor environment is again very common in literature but of lower relevance to the industrial use case. Lastly examining the industrial environment was the central goal of this section. Different types of mobility were tested in order to identify the sources of possible changes in the topological structure of the network. In the static and group mobility configuration only interference between participants and with other communication networks can be sources for disconnections, while the individual movement of the AGVs will cause additional disconnections. Lastly different time resolutions δt of the NEP recording were tested. Generally a very high time resolution is beneficial, but recording at higher resolutions also causes increased traffic. Therefore $\delta t = 0.2\,\mathrm{s}$ was the best possible time resolution for measurements in the industrial environments.

The measurements were done with small battery-powered Single Board Computers (SBCs). These SBCs are equipped with a WiFi interface in accordance to the IEEE 802.11 b/g/n standards and ran an Linux image. The NEP recording protocol was implemented within the click-router-framework [222]. This framework abstracts the handling of packets with connected elements. The structure of the resulting router is presented in Figure 52.

The central element of the configuration is the *Tracer* element. This element generates the beacons for the participant and logs the incoming beacons of other participants. The remaining elements are required for the operation of the *Tracer* element. The source code for the protocol implementation is fully published [9]. A short description follows:

```
Tracer(STICK ,RTICK ,ADD)
```

STICK and *RTICK* are the send and receive interval of the element, while *ADD* is the simplified address of the participant. The element can run in two modes: single mode

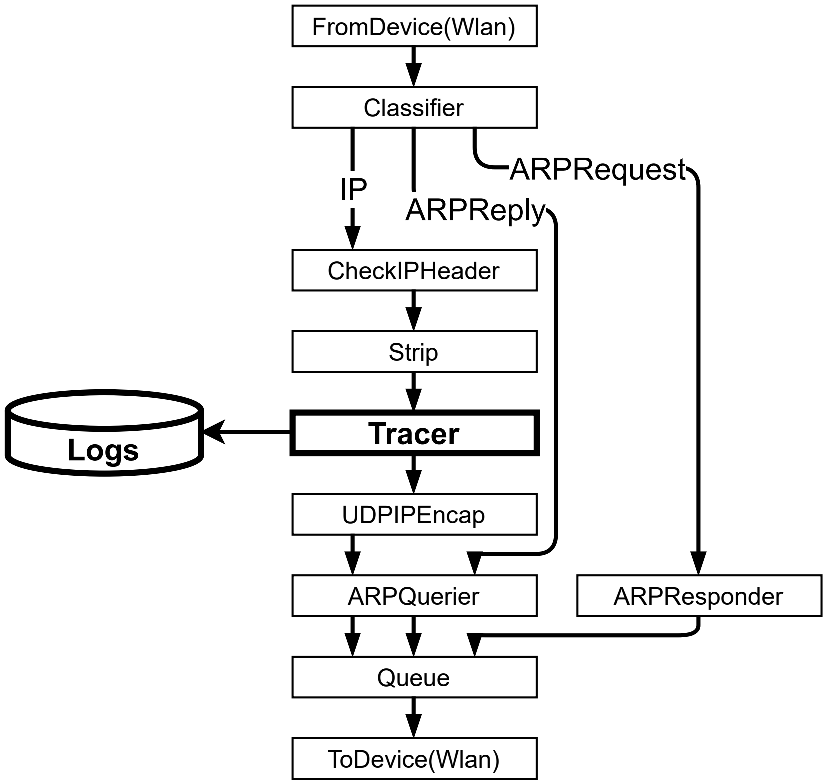


Figure 52: Implementation of the NEP recoding protocol (Element: Tracer) with the click router framework.

and summary mode. In single mode every single incoming message is logged. In summary mode all incoming messages during one *RTICK* interval are summarized. The mode is automatically set to single, if *RTICK* is set to 0. Using the summary mode is recommended, if a very low *STICK* is used. The value of *STICK* is equivalent to the previously mentioned δt. Once the router configuration is active, the activity of the network is logged into persistent storage. The recording can be stopped at any time without losing any data.

After the recording the logged files are pulled from all participants and then processed to a single NEP. This processing is described in section 4.2.1.

5.1.2 Measured channel characteristics

The created NEPs can subsequently be compared using different metrics. In the following sections different networks are compared in terms of these network metrics. In particular we compare:

- A static ad-hoc network in an office environment
- A group-mobile ad-hoc network in an industrial environment
- A mobile AGV-based ad-hoc network in an industrial environment

For these three scenarios the following test parameters were chosen:

Parameter name	Unit	Reference test	Static industry test	Mobile industry test	Description
dt	s	$0.2\,\mathrm{s}$	$0.2\,\mathrm{s}$	$0.2\,\mathrm{s}$	Time resolution of the NEP
T	s	$>11\,800\,\mathrm{s}$	$>8800\,\mathrm{s}$	$>10\,400\,\mathrm{s}$	Run time of measurement
N		6	7	8	Number of nodes
Mobility	Type	None	Group	AGV	Type of mobility
Environment	Type	Office	Industry	Industry	Environment description

Table 14: Measurement parameter description and values for measurements [9]

The main focus of these examinations are the effects of network configurations and environments on the resulting networks, and particular properties of the mobile industrial ad-hoc network, that are relevant in the design of planned ad-hoc systems.

5.1.2.1 Network connectedness

The first examined metric is the network connectedness. This metric describes the number of connections within the network as the percentile of the maximum number of possible connections. The maximum number of connections in an ad-hoc network of n participants is n^2-n. As described previously the NEP describes the connections within the network as $C(\theta,\rho,t)$, with θ being the transmitter and ρ the receiver on a communication link. The function gives either 1, if a connection between transmitter and receiver is possible at time t or 0 if a connection is not possible. The network connectedness is subsequently defined as:

$$N(t) = \frac{1}{n^2-n}\sum_{\theta}\sum_{\rho} C(\theta,\rho,t) \tag{26}$$

Figure 53 shows the network connectedness of ad-hoc networks in the three previously described scenarios. The graphs show the median and standard deviation (2σ) of the network connectedness. The network connectedness exhibits short-term (noise-like) changes and long-term changes. In the static office environment no long-term changes occurred. Short-term changes are caused by interference between nodes and interfer-

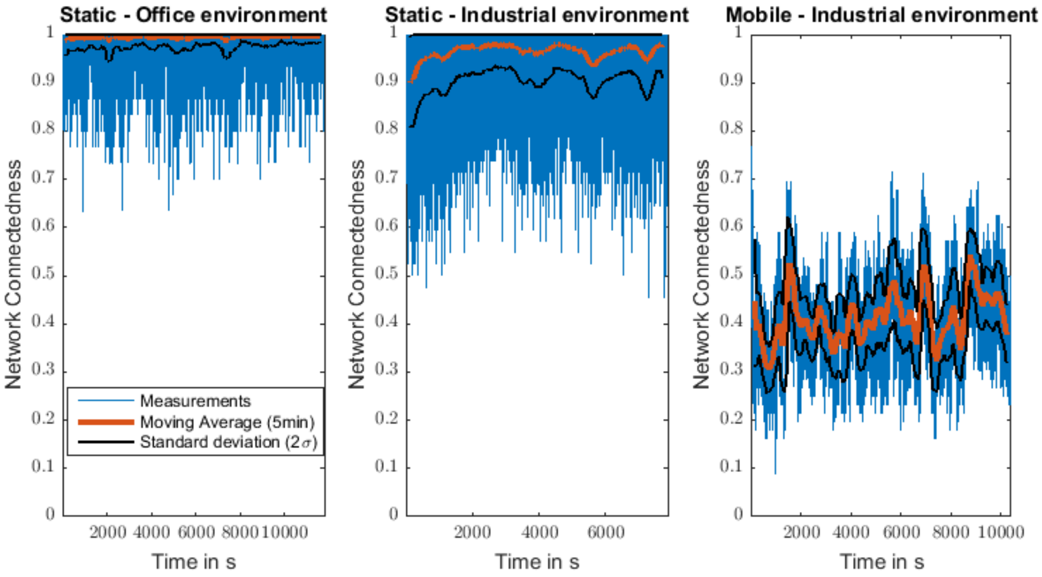


Figure 53: Network connectedness calculated from NEP [9]

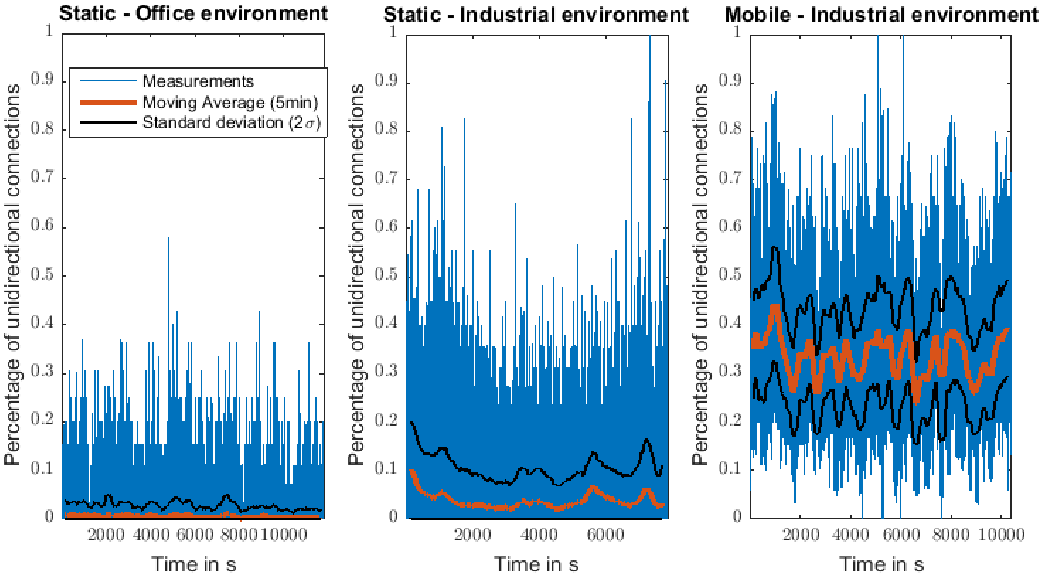


Figure 54: Percentile of unidirectional connections calculated from NEP [9]

ence with other wirelessly communicating clients. For the measurements the 2.4 GHz-channel was used. Therefore interference by non-participating communicating clients is unavoidable.

5.1.2.2 Presence of unidirectional connections

Changes in the topology of an ad-hoc network require the search for new routes. This route search is often based on the ring-flooding of the network with route requests. Almost all routing schemes assume, that if a request was received from a transmitter at a receiver, that the receiver is also able to send messages to the original transmitter. Therefore, the routing schemes assumes bidirectional links.

When looking at the physical propagation path between the transmitter and the receiver, the loss in signal strength stays the same regardless of the propagation direction. However there are still reasons, why the transmission might be possible in one direction, but not the other. Firstly there is third-party interference. Either transmitter or receiver might experience high channel noise, which prohibits sending due to the MAC or prohibits receiving due to destructive interference, which prohibits demodulation. Another important factor is time. Almost always both clients do not send at exactly the same time. Therefore the channel characteristics can change between these two points in time.

Using NEPs enables to observe if, within one time-step δt, a pair of network clients is unidirectionally or bidirectionally connected. The percentage of unidirectional connections within the NEP can be described by:

$$P_u(t) = \frac{\sum_\theta \sum_\rho |C(\theta,\rho,t) - C(\rho,\theta,t)|}{2 \cdot \left(\sum_\theta \sum_\rho C(\theta,\rho,t) - n\right)} \tag{27}$$

The percentage describes the percentile of connections in the network, which do not have a reversed counter part. In an example network, three nodes A, B and C exist. Nodes A and B are connected with $C(A,B,t) = 1$ and $C(B,A,T) = 1$. Node C is only connected with $C(A,C,t) = 1$. All other $C(\theta,\rho,t)$ are equal to 0. The percentile of unidirectional connection is $P_u(t) = \frac{1}{3}$. As one of the three existing connection has no reverse connections.

Most routing schemes assume bidirectional connections, therefore $P_u(t) = 0$. But most routing schemes might also still be effective with a very small number of unidirectional connections $P_u(t) \leq 0.05$.

Figure 54 presents the percentile of unidirectional connection in the previously introduces scenarios. The figure shows, that the assumption of no or very little unidirectional connections is true for a static ad-hoc network in the office environment. However, the presence of these unidirectional links becomes much more prevalent in the industrial environment. The static ad-hoc network only experiences between $2\,\%$ and $10\,\%$ of unidirectional connections, but short-lived spikes of up to $50\,\%$. However unidirectional connections become omnipresent in the industrial MANET. On average between $30\,\%$ and $40\,\%$ of all connections are unidirectional.

In the context of routing algorithms, bidirectional connections are often a base assumptions. Many routing algorithms drastically suffer in performance or are not operable. Alternations to existing routing protocols are possible but worsen their overall performance [223].

5.1.2.3 Route life time (RLT)

The RLT in an ad-hoc network is again important to characterize its usefulness. If the RLT is very low, then the increasing number of route requests and other overhead traffic worsens the network performance. At the same time any change in the route is an opportunity to lose packets and negatively contributes to the reliability of the network. A high RLT generally has no disadvantages.

The RLT can be analyzed based on recorded NEPs. But, as described in Section 4.2.1 a filter must be applied before examining the RLT. This filter eliminates very short connections and very short disconnections from the data. Very short connections are not relevant, as the route search and establishment requires some time before the route is usable. Once a route is found th route is often not discarded immediately if one message can not be transmitted. Instead a timeout is applied. The route is only discarded, if no reconnection is possible within this timeout, the route is then disabled or deleted. Therefore disconnections shorter than this timeout are not relevant.

For the presented examination a connection and disconnection timeout of $300\,\mathrm{ms}$ is chosen. In terms of route life time the directionality of the route is not relevant. A route and its reverse route are independently analyzed in this section.

In Figure 55 the probability of a route persisting for a certain duration is plotted. As an example about $10\,\%$ of all connections reach a RLT of $100\,\mathrm{s}$ or more in the static network in an office environment. Additionally the average RLT is presented. The figure shows, that both the mobility and also the raised interference in the industrial use case negatively influence the RLT.

A very short RLT requires more overhead by the routing protocol to establish new routes and results in lower reliability and worse performance for the application layer. Preceeding the route deletion with long time-outs may be beneficial to the performance of the industrial MANET.

5.1.2.4 Benefits of multi-hop networks

The NEPs can also be used to calculate the topology of a possible multi-hop network in the same application. The method to calculate the resulting topology was introduced in Section 4.2.1. Such a multi-hop ad-hoc network can have two positive influences on the ad-hoc network:

1. **Increase in connectivity**
   A multi-hop network naturally increases the number of available destinations for any participant in the network.
2. **Increased RLT through redundant routes**
   Multi-hop network also enable the usage of redundant routes. In these routing schemes multiple routes to a destination are determined and if one faults, the routing can automatically switch to the other.

In the following the advantages of multi-hop networks for AGVs in industrial applications are explored. The calculation of the network connectedness and RLT can be applied to $C^n(\theta, \rho, t)$ in the same way as to $C(\theta, \rho, t)$.

Figure 56 presents the network connectedness for a multi-hop industrial MANET. The

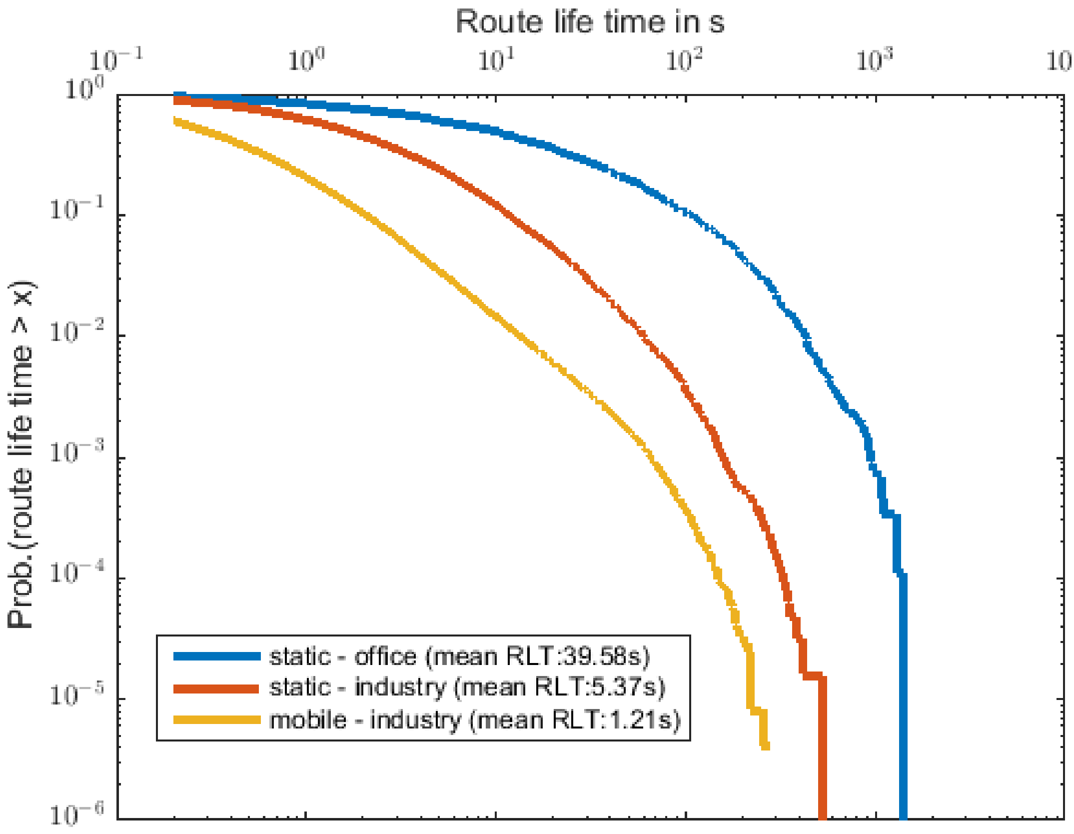


Figure 55: Route life time calculated from NEP [9]

figure is based on the same NEPs of a single-hop ad-hoc network that was previously presented. The method previously described was used to calculate the potential network connectedness, when using a 1, 2 or 3-hop network under the same conditions. The figure shows, that the network connectedness increases drastically, be adding only a single additional hop. This drastic increase is particularly interesting if networks with side-link capability are considered, which are equivalent to this single hop. In the observed application the second hop only offers slight improvements, while the third hop does not show any higher network connectedness, than the 2-hop network.

A similar relation between number of hops and performance gain can also be observed, when examining the RLT. The RLTs of connections in multiple multi-hop networks can be seen in Figure 56. Of note is the high benefit of the second hop in terms of average RLT. However, for the RLT, as for the network connectedness, the third hop show no real benefit.

The general conclusion for the examined use case is, that the inclusion of a 1 to 2-hop network is highly beneficial. Any more hops barely affect the communication availability and stability while increasing the networks overhead.

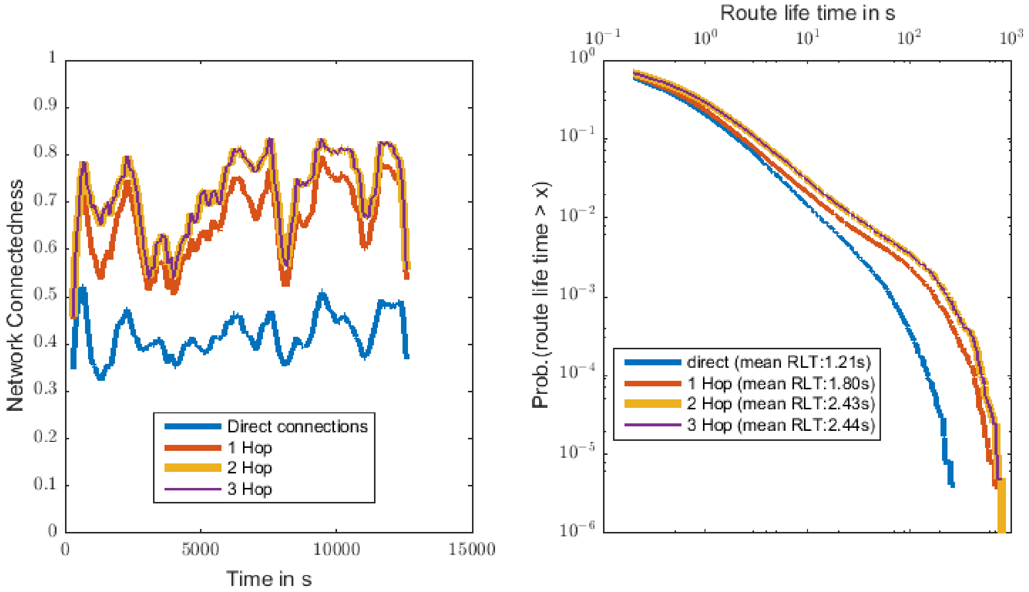


Figure 56: Multi-hop benefit in terms of connectivity and route life time [9]

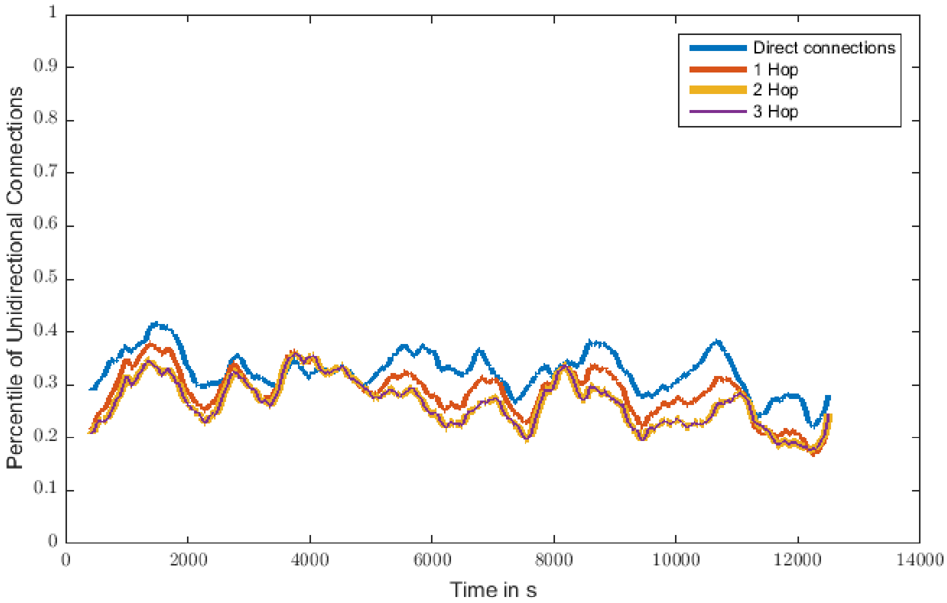


Figure 57: The percentage of unidirectional connections, and the effect on including redundant multi-hop routes of certain lengths.

5.1.3 Lessons learned for industrial ad-hoc system design

From the observations, described in the previous sections, certain lessons regarding the design and implementation of ad-hoc systems can be extracted. Some of the observations are only true for the examined combination of application area, number of clients, communication technology and other factors. However some general lessons regarding the design and applicability of ad-hoc networks can be extracted.

First of all, the observations confirmed, that the implementation of a multi-hop ad-hoc network is beneficial to the available connectivity in the network and to the RLT of connections within this network. Even a small number of hops can improve the number of available communication destinations by up to $100\,\%$ and the RLT of connections by the same percentage.

The presence of unidirectional connections was observed. Bidirectional connections are often an assumption by many routing strategies. Therefore this observation is quite critical. Another observation was, that the inclusion of redundant multi-hop routes only slightly lowers the percentage of these connections. This reduction is shown in Figure 57. Therefore, a theory is, that even routing schemes with robustness against unidirectional connections might not be very effective. This assumption must be tested in future work. The percentage of unidirectional connections might also depend on the chosen δt. A higher time resolution for the NEPs (lower δt) might reduce the number of detected unidirectional connections. Tests with these parameters were not within the scope of this work.

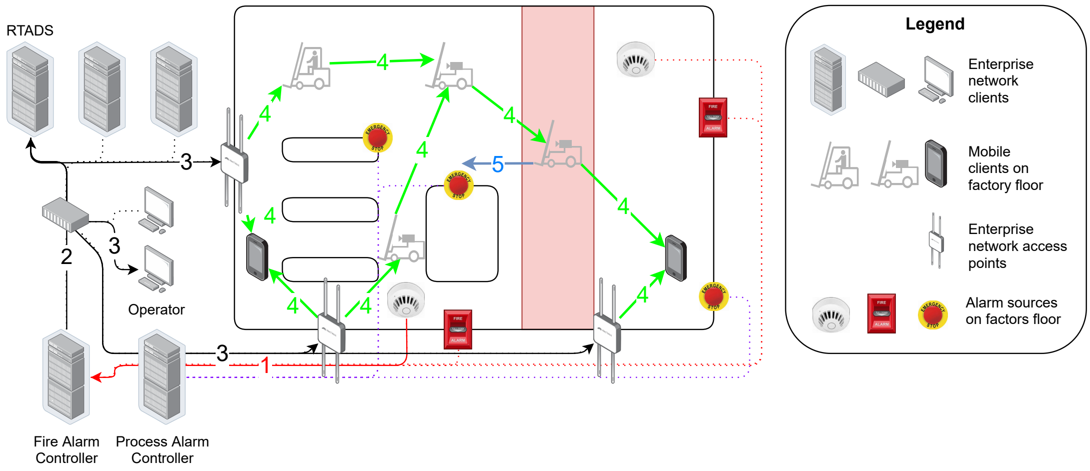


Figure 58: Scenario for real-time communication in the factory of the future.

5.2 Time-critical communication

The central contributions to this section were published in [64] and [10]. The protocol proposed in [10] is an extension to the base given in [64]. [11] further added the possibility to use multiple incompatible communication technologies.

The industrial trends towards flexibility and mobility lead to a shift towards wireless communication for any kind of communication. This does include safety-critical communication like alarms and warnings. For the transmission of these messages real-time transmission requirements are applied. For real-time transmission a transmission within a specified time must be guaranteed. The guaranteed transmission within a certain time frame is the basis for a guaranteed execution of reactions to the transmitted data / alarm.

A use case for the real-time alarm dissemination for AGVs will be introduced in the coming section. Followed by the description of two ad-hoc communication system enabling this use case. Lastly some characteristics of the utilized ad-hoc channels are examined, which enhance the benefits of the proposed system.

Two systems are proposed in regards to the real-time alarm dissemination.

1. **Flooding-based Network Monitoring (FBNM) [5]**
   The FBNM is a system with the goal to observe the connectivity in a mobile ad-hoc network via network flooding.
2. **Real-Time Alarm Dissemination (RTAD) System [10]**
   The RTAD system is based on the FBNM. The system is utilized as a watchdog-like mechanism of the RTAD and also enables the transmission of safety-relevant alarms.

5.2.1 Use Case Description

The use case environment is the industrial environment (see Figure 58). Within this environment mobile entities (humans with hand-held devices, fork-lifts and AGVs) move throughout. Parts of the industrial environment can be categorized as specific zones, for example production cells or emergency exits. Within the industrial applications different types of alarm can be captured (e.g. fire-alarms, process-alarms, etc.). Each alarm might require a different type of reaction by the AGVs and other controllable devices.

- A fire-alarm might require all AGVs, which currently move over emergency routes, to leave these routes and position themselves in a non-obstructive way.
- A process-alarm must stop all AGVs within a certain range around the machine, which issued the alarm.

Real-time requirements are often specified for these safety-critical reactions. In order to enable timely reactions to the alarm, these alarms need to be transmitted with the same requirements towards real-time. In the presented application an infrastructure-based wireless network is used, which is expanded by multi-hop relaying. The main task of this ad-hoc network is to offer enhanced coverage within the building and to enhance reliability by using redundant routes.

The requirements for the proposed communication system are:

1. A network size of up to 10 hops must be supported.
2. An alarm message must be guaranteed to reach every network participant within $\leq 100\,\mathrm{ms}$.
3. Multiple non-compatible communication technologies must be incomparable.
4. Network must adapt according to the mobility of the clients
5. The system must have a minimal impact on other wireless communication systems

The system was designed with the following basic idea: In a mobile wireless network within an dynamic environment static channel characteristics can not be guaranteed. An alternative is to guarantee to the mobile entity, that the entity will be informed of either the alarm or a disconnection within the real-time time-frame.

5.2.2 System Description

The system implements a watchdog-like mechanism in an industrial MANET. This mechanism floods the network from one source to all other participants with test-messages. These test-messages test the availability of one or multiple redundant routes, the one-way latency on this route and the combined reliability of the redundant routes. Due to the correlation in latency and reliability of sequentially sent messages the system enables the prediction of delay and reliability for alarm-messages, which replace the test-messages in case of an alarm. If a test-message is not received or if the latency or reliability requirements are not met a disconnection alarm can be issued for the client. In these cases the assumption must be made, that an alarm-message can not be received in a timely manner.

The envisioned system leads to a very specific topology for the dissemination network. A single source (possibly via multiple APs) needs to disseminate a message to all participants of the network. This topology enables the usage of a very controlled variant of network flooding. The flooding happens from only one source, is loop-free and happens at specific intervals.

Parameter	Description	Value for reference scenario
n	Number of nodes in the network	≈ 10
t_{max}	Maximum Delay for alarm-messages / maximum timeout for disconnection	$100\,\mathrm{ms}$
N	Maximum number of supported hops	10
P_{min}	Minimum transmission probability / reliability	$90\,\%$

Table 15: FBNM parameters

The operation of the system has two phases. During normal operation the FBNM is used. After an alarm is issued the RTAD system is active.

5.2.2.1 Flooding-Based Network Monitoring

A number of central parameters must be decided, for the operation of the FBNM. These parameters are described in Table 15.

For the following description a single source for the alarm messages is assumed. One source with multiple interfaces or multiple redundant sources are also possible, details of this follows the initial description.

The basic function of FBNM is to inform mobile clients of their ability to receive alarm from a specified source. But additional functionality can be implemented. For example the routes from source to clients can be recorded, this way all clients know a return route to the source. This return route can additionally be used to transmit data (status, connection feedback, etc.) to the source. This enables an operator to quickly see the complete status of the network. This functionality is beneficial, but not a core part of the FBNM. A central argument against their inclusion is the additional overhead and frequency band usage.

The flooding of the network is effective due to the very controlled manner of its implementation. Only exactly one participant of the network can initiate a flood and this participant does this with a very specified frequency. The flooding is implemented in a loop-free manner. Part of the test-messages and alarm-messages is a sequence number, which increments with every test-message. A message is only forwarded by a participant, if the sequence number of the message is higher, than the highest previously encountered sequence number. The created topology is a tree. The alarm-source represents the roots and the clients are spread along the branches of the tree. Any client can be connected to multiple branches. This creates redundancy for the transmission of safety-critical messages to the receiver.

For the implementation of the network only two types of messages are required and one is optional. The two required types are additionally largely identical. In order to assume correlated channels for sequential messages the messages must have the same length. Therefore the test- and alarm-messages have the same length and nearly identical content:

1. **4-bit** - Message identificator
   Specified bit-sequence to filter messages, that are a part of FBNM
2. **8-bit** - Checksum
   Checksum to ensure message integrity
3. **32-bit** - Sequence number
   Incrementing number to keep flooding loop-free
4. **64-bit** - Time of Sending
   Time of Sending of the message by the source
5. **8-bit** - Number of hops
   The number of hops, which this message experienced, incremented by each relaying node.
6. **8-bit** - Message-type
   The type of the message (test, alarm, type of alarm)
7. **8-bit** - Additional alarm info length (optional)
   bit length of additional alarm information l_a
8. **8-bit** - Additional route info length (optional)
   bit length of additional route information l_r
9. l_a**-bit** Additional alarm information (optional)
   Additional information about alarm (e.g. restrictions, severity, etc.)
10. l_r**-bit** Additional route information (optional)
    Information appended by relays about the taken route

The length of the message can vary, depending on the implementation and the maximum possible l_a and l_r. The total length of the message should be below the Maximum Transmission Unit (MTU) of the used network with the lowest MTU. This means that the message must not be partitioned and the added overhead in the medium and processing overhead for the receivers is minimized.

The proposed system can be used to flood a network with a reach of ≥ 10 hops in $\leq 100\,\mathrm{ms}$ (see Figure 59). MAC issues can raise the delay and lead to delays of $\geq 100\,\mathrm{ms}$. These delays are recognized as disconnections in the FBNM. These occurrences of increased delay are more common if a congested wireless medium must be used.

In such highly-utilized networks a prioritization mechanism will be necessary to fulfill the targeted delay requirements. This prioritization can apply to the test-messages and especially to the later mentioned alarm-messages. Since the messages are only propagated through broadcasting no additional routing is required. The mechanism can also automatically filter any kind of message sequence change.

The frequent flooding of the network is equivalent t broadcasting by all connected devices. The utilization of test-messages as hello-messages or vice-versa can reduce the

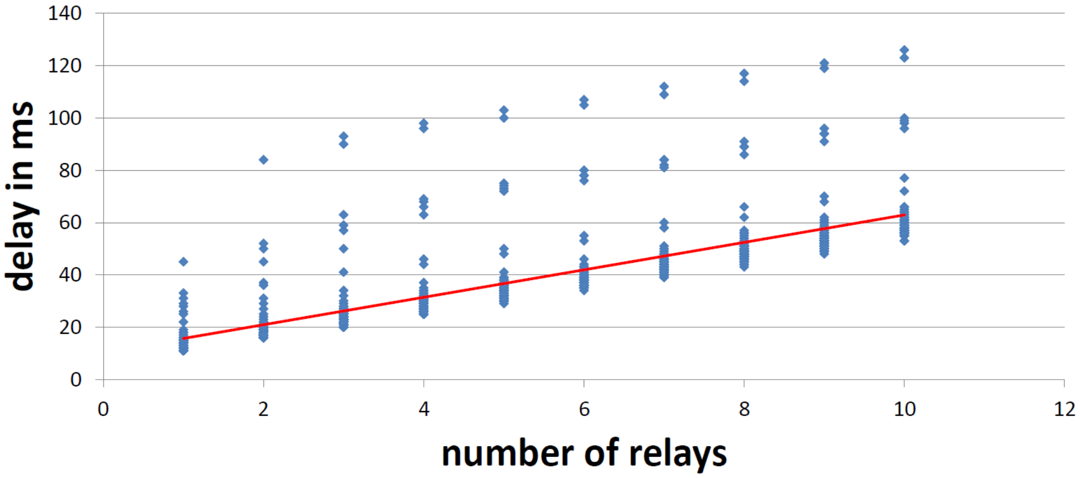


Figure 59: Linearly increasing delay per hop in FbNM. [64]

overhead, if in addition to FBNM systems routing mechanisms like AODV are in place. Now, that every client can determine its connection state within a guaranteed timeframe, the transmission of alarm-messages within the same time guarantee can be enabled.

5.2.2.2 Real-Time Alarm Dissemination

FBNM running with a test-message interval of t_{tmi} is the base assumption for the following description. Therefore at any point in time a test-message has been received at most $\leq t_{tmi}$ ago. Another assumption is, that a alarm-message send at the current time experiences a latency and route reliability similar to the previously received test-message.

In the following section a Real-Time Alarm Dissemination (RTAD) system based on the FBNM is described. Firstly, observations regarding the latency correlation of sequential messages are described, which form the basis for the developed system. Afterwards the types of available alarms and reactions by the mobile devices are described. Lastly the system is compared to other system in terms of complexity expressed by the number of produced messages and length of messages.

A wireless channel can be assumed as unchanging within the coherence time. The coherence time of the used channels can be estimated via the Doppler spread. For communication standards like WiFi or 5G a coherence time of about $9.7\,\mathrm{ms}$ to $24.2\,\mathrm{ms}$ can be assumed (see Table 6). A realistic test interval for FBNM is between $50\,\mathrm{ms}$ and $1\,\mathrm{s}$. This raises the question, if the latency of sequential messages in an industrial MANET is correlated outside the expected coherence time. This question was examined by running FBNM for a prolonged period of time and analyzing the measured latencies.

Figure 60 presents the results of three latency measurements with three different industrial wireless communication solutions. The figure presents the PDF of latency differences of sequential messages. The time between the sequential messages was randomly

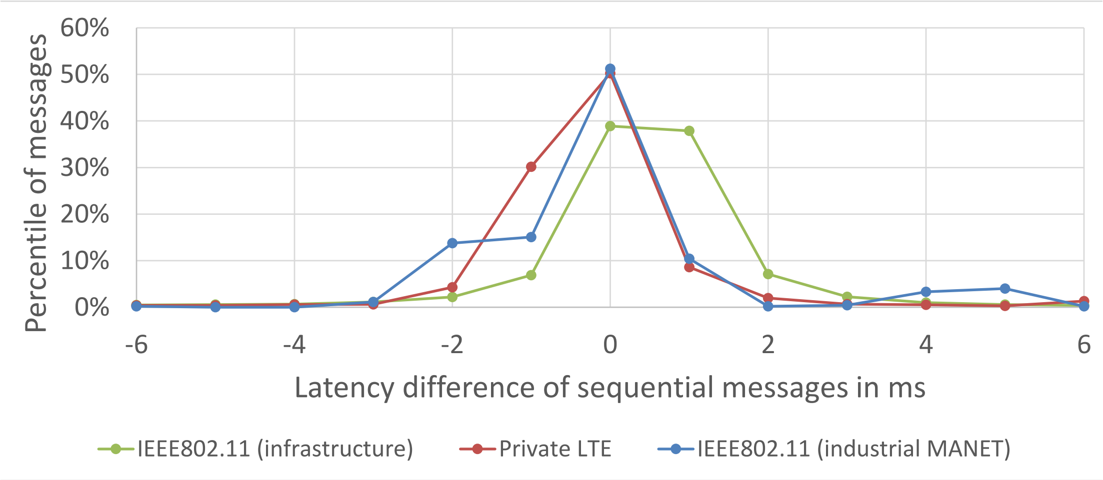


Figure 60: Similarity in sequential latency for different communication technologies [10]

selected from an interval between $100\,\mathrm{ms}$ and $1\,\mathrm{s}$. An observation is that $91\,\%$ to $95\,\%$ of all sequential messages have a latency of $\pm 2\,\mathrm{ms}$ to the previous message. Based on these observations an assumption is, that the latency of previous test-messages can not only be used to characterize the connectivity state but also to predict connectivity loss due to mobility. Connectivity loss due to interference can not be predicted with this method.
Figure 58 presents a reference implementation of the RTAD system. The central architecture has been extracted from the scenario in Figure 61. The figure presents the most important steps in the process of disseminating an alarm:

1. Based on a smoke-detector or a panic button an alarm is issued and transmitted from the correspondig system to the RTAD system. Which is also the test-message source for the FBNM.
2. The RTAD system forwards the alarm to the operator of the AGV fleet. And broadcasts the alarm over all available APs.
3. The alarm is relayed between the AGVs.
4. The AGVs can react to the alarm. This might require the AGV to for example stop or to leave a specific zone.

In the following a number of example alarms are defined and a number of possible reactions by the AGVs are specified. Both, the types of alarms and the types of reaction heavily depend on the type of application and are not representative for all possible types of alarms and reactions.
Different sources can issue different types of alarms. Smoke detectors or manual emergency switches can be sources for fire alarms. An expectation is, that these alarms are issued by a central fire alarm source. Fire alarms are most often universal and not limited to specific parts of the factory. In case of a fire alarm humans must leave the vicinity. Therefore AGVs must not block paths and especially not block emergency exits. Such critical zones must be left immediately.

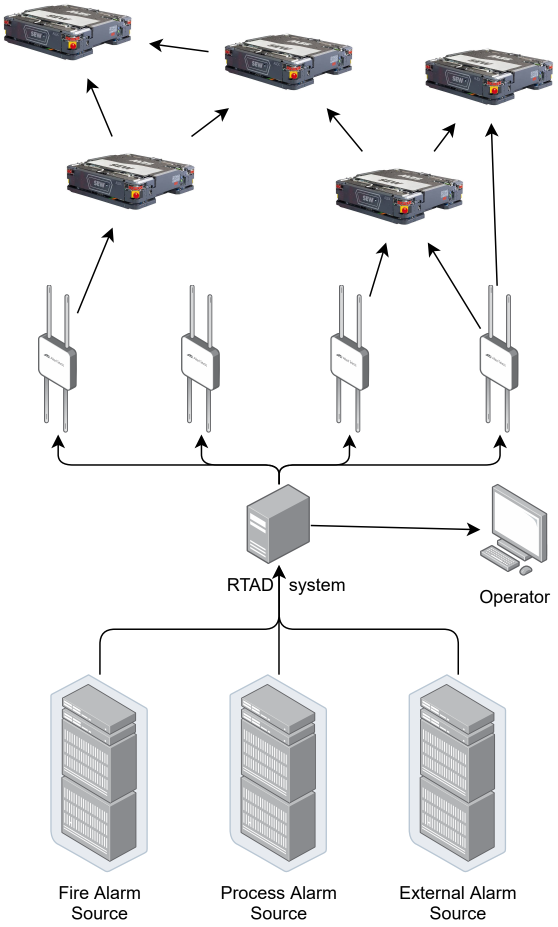


Figure 61: Extracted architecture of the RTAD system

Other alarms might indicate emergencies, accidents or machine malfunctions. These alarms are mostly relevant to mobile machines in the direct vicinity of the incident. Local machine must stop their movement, in order to minimize the risk for further accidents or malfunctions. At the same time machines at the other end of the production facility do not need to stop, since their unavailability would negatively impacts the factories efficiency, while not improving the safety of the workplace.

A very specific type of alarm is the disconnection alarm. This alarm is not issued by any source, but by the client side of the RTAD system. The disconnection alarm indicates that no connection to the alarm source is possible with sufficient characteristics (latency, reliability). This alarm can be automatically resolved once a test-message with sufficient latency and reliability is received.

Other alarms in contrast must be resolved / acknowledged by human operators. Depending on the type of alarm this might either be a remote operator for the AGV fleet or by an employee in the vicinity. This must be done in order to guarantee, that the source of the alarm is no longer a threat to the human workers or that moving AGVs do no longer pose a risk to them.

Connectivity State	non critical area	critical area
Connected	normal operation	cautious operation
Disconnected	cautious operation	stop operation, leave area, reconnect

Table 16: Connectivity and position-aware robot operation [10]

As previously described different types of alarms require different types of reactions by the AGVs. This reaction might also depend on the current position of the AGV. Both, leaving a critical zone and not moving in the vicinity of an accident depend not only on the type of received alarm, but also on the current position. The combination of connectivity state and current position might lead to combined behavior, which is described in Table 16.

An important step in the implementation of RTAD is the time synchronization of the clients. The test-messages are evaluated in terms of one-way latency. This latency can be calculated by subtracting the time of sending from the current time, at the time of receiving the test-message. This calculation only leads to meaningful results, if the clocks of the alarm source and all clients are synchronized. Since delay is the range of 0 ms to 100 ms are measured a synchronization accuracy of ±2 ms is targeted. Such an accuracy can be achieved with the Network Time Protocol (NTP). This protocol is easy to use and can also effectively run via direct links in and ad-hoc networks. Tests showed that the clock drift of commercial hardware during a workday was ≤2 ms. A process is proposed in which a reference clock is placed at the charging stations of the AGVs. Every time a direct connection to this clock is available via the ad-hoc network the synchronization is initiated. This also benefits other processes on the AGV, which utilize the system clock.

5.2.3 Comparison to other systems

There are other systems, which can offer similar functionality. Therefore defining the benefits of the proposed systems in comparisons to these alternatives is highly important. The systems are evaluated in terms of characteristics and complexity. Characteristics describe the suitability of the systems to the examined use case. The complexity characterizes the overhead of the systems in relation to specific system parameters. As previously mentioned keeping the overhead as low as possible is very relevant in industrial applications.

Protocol	Number of packets Complexity	Size of Packets Complexty	Characteristics
RTAD	$\mathcal{O}_m(n)$	$\mathcal{O}_l(1)$	state-less no global knowledge supports unidirectional connection
TBD APR Liao01 QMPR [224] Liao02 Lin-Liu OP-MP	$> \mathcal{O}_m(n)$	$> \mathcal{O}_l(1)$	
FA [184] CHEN [226]	$\mathcal{O}_m(n)$	$\mathcal{O}_l(1)$	no high mobility support
AQOR [184]	$\mathcal{O}_m(n)$	$\mathcal{O}_l(1)$	state-full requires bidirectional connections

Table 17: FBNM parameters

Typically relevant characteristics are for example the systems ability to handle mobility. At the same time a stateless systems has the advantage to be quickly deployed and to be able to quickly add new nodes to the network. The number of messages send by the different systems is denoted by $\mathcal{O}_m()$ as a function of different system parameters, most notably the number of participants n of the network. The size of the sent messages $\mathcal{O}_l()$ is another complexity parameter for the expected size of the transmitted messages. The complexity often depends on the diameter d of the network in hops.

The proposed system offers a number of message complexity of $\mathcal{O}_m(n)$. This means, that the number of messages send in the network is identical to the number of participants of this network. The size of this messages is constant, therefore $\mathcal{O}_l(1)$. To the best of our knowledge this is the minimal impact, that such a system can offer. At the same time the RTAD is applicable to highly mobile networks. The state-less architecture can also be beneficial in the examined use case. The system can also monitor transmission routes within the network. In this case the length of messages increases to $\mathcal{O}_l(d)$ and the number of messages to $\mathcal{O}_m(2n)$. But the same functionality can also be used with smaller messages (by using link state routing instead of source routes) and fewer messages (by reducing the number of sent feedbacks).

In [184, 224, 225] and [226] different comparable systems are introduced. We analyzed these works in terms of the aforementioned complexity terms.

The protocols TBD, APR, Liao01, QMPR, Liao02, Lin-Liu and OP-MP create more overhead, than the proposed RTAD system [224]. The protocols Forward Algorithm (FA), ad-hoc QoS on demand routing (AQOR) [184] as well as the the Chen-Heinzelman protocol (CHEN) [226] remain with the same messages complexity of $\mathcal{O}_m(n)$ and packet size complexity of $\mathcal{O}_l(1)$. FA and CHEN are not designed to handle high mobility. In the examined use case the clients are highly mobile. This worsens the performance of these two protocols. AQOR in contrast can handle a higher node mobility, but AQOR has two disadvantages. Firstly, the route consists of state-full devices once the route is discovered and secondly the protocol is designed for bidirectional communication, which RTAD does not require and which might not be given in mobile industrial application [9]. Available alternatives are summarized in Table 17.

5.3 Delay-tolerant communication

The observations and results presented in the following section expand upon the ones first first published and discussed in [7].

Delay Tolerant Networks (DTNs) transmit information via the store-and-forward principle. They effectively use the mobility of the clients to disseminate messages. This greatly enhances the coverage of a network, but at the cost of much higher delays. In addition to the coverage advantage the inclusion of a DTN can also be used for load-balancing. If the wireless medium is highly utilized low-priority messages can be buffered and sent once the medium utilization decreases. In this case the delay might be much smaller than minutes, but the messages must still be delay-tolerant.

In the following sections a use case for the delay-tolerant communication is described, followed by the application of a model previously described in section 4.2.4. The model is validated and statements regarding the applicability of the network type are extracted.

5.3.1 Use Case Description

In most industrial applications low-latency communication is highly important. This can for example be seen in the development of URLLC technologies in the context of 5G. However, there is also data, that is delay-tolerant. Examples for this delay tolerant data can be the order data defined by the VDA5050 standard. The VDA5050 standard defines orders as messages sent from a central fleet management to the AGVs, which define start points and destinations for a transport task, as well as the route between the two points. The tasks of AGVs in a production facility are usually planned hours ahead of time, therefore the task can be transmitted with minutes of delay. Other sets of data, like map updates or software / firmware updates are also delay-tolerant.

However, there are also types of messages and even architectures for AGV implementations, that do not support DTNs. The trends of edge computing and cloud robotics for example do not support DTNs. In contrast the trend towards more and more autonomous mobile machines supports DTNs. In the context of cloud robotics, the processing of sensor data and the control of the robot is moved to the cloud. Therefore the sensor data and control commands must be moved through the network. Both types of data are very sensitive to transmission latency. Their transmission through a DTN link is not practical. Previously the order message within the VDA5050 standard was mentioned as being delay-tolerant. The status messages within the same standard in contrast are not delay tolerant. They must regularly be transmitted from the AGVs to the CCU. If the system is implemented within a DTN the consequences of non-acknowledged status messages must be changed or the handling of these situations must be improved.

Determining which range of delays can fit which types of messages is important in order to determine, to which scenarios the DTNs are applicable. In the following sections the reference number ① to ④ are used to reference different use cases.

Reference Number	Scenario Description	Required Range	Acceptable Latency
①	Disseminating navigational information about short-term changes in the environment to optimize route search and selection	Locally $\leq 50\,\mathrm{m}$	$1\,\mathrm{min}$
②	Dissemination of VDA5050-like order information. Information contain start-positions and destination	Globally, Complete network	$10\,\mathrm{min}$
③	Distributing navigation maps and other bigger data-sets between the AGVs.	Globally, Complete network	$1\,\mathrm{h}$
④	Share software and firmware updates via the DTN. This supports the process of continuous and sequential roll-out.	Globally, Complete network	$1\,\mathrm{day}$

Table 18: Use cases for industrial DTNs for AGVs

5.3.2 Model Validation

In order to validate the previously described model, operational validation [142] was used. For this validation a networked system was created in the real-world and replicated using the model. The behavior of the models and the performance predicted by the model is subsequently compared to the real world implementation.

As a reference routing scheme Epidemic Routing (ER) [94] was implemented using the click modular router framework [222]. ER is often used for reference DTN implementations. If a non-saturated wireless channel and sufficient DTN storage is assumed, then ER is an optimal routing solution with minimal packet loss and delay.

In [7] two scenarios were implemented in the real-world and the results generated by the real-world measurements and the model were compared. The two scenarios were an industrial scenario and an outdoor scenario. The scenarios are presented in Figure 62. Subfigure 62a presents the outdoor scenario. Four static clients were placed on a campus while one node was moved between the static clients. The speed of the mobile node was measured. This scenario of very controlled propagation characteristics (and therefore communication range) and node speed was chosen to evaluate, if the statistical model correctly reproduce the speed dependent network characteristics. In terms of the parameters r and v this scenario is far more controlled than the following industrial scenario. The industrial environment of the scenario is presented in Figure 62b. The en-

(a) Outdoor DTN implementation

(b) Industrial environment of implementation

(c) Paths of AGVs in industrial implementation

Figure 62: Real-world implementations for the validation of the statistical model [7]

vironment is scattering-rich due to the high number of conductive obstacles. The AGVs in the scenario were used for the transport of goods and tools throughout a production facility for electrical drives and gear boxes. The AGVs drove along the path given in Figure 62c. The speed and distribution of the 6 used AGVs can not be controlled or tracked during the measurement.

In both scenarios every participant generated one message per second for a random other participant. This created a required throughput far lower, than the band-width offered by the used IEEE 802.11 b/g/n standard. Congestion on the medium is therefore unlikely. The storage size of the nodes was chosen sufficiently large to not overflow during the tests. Packet loss due to buffer overflow can not occur during the tests. Therefore, through combination of these two assumptions ER can present the optimal performance possible by any DTN.

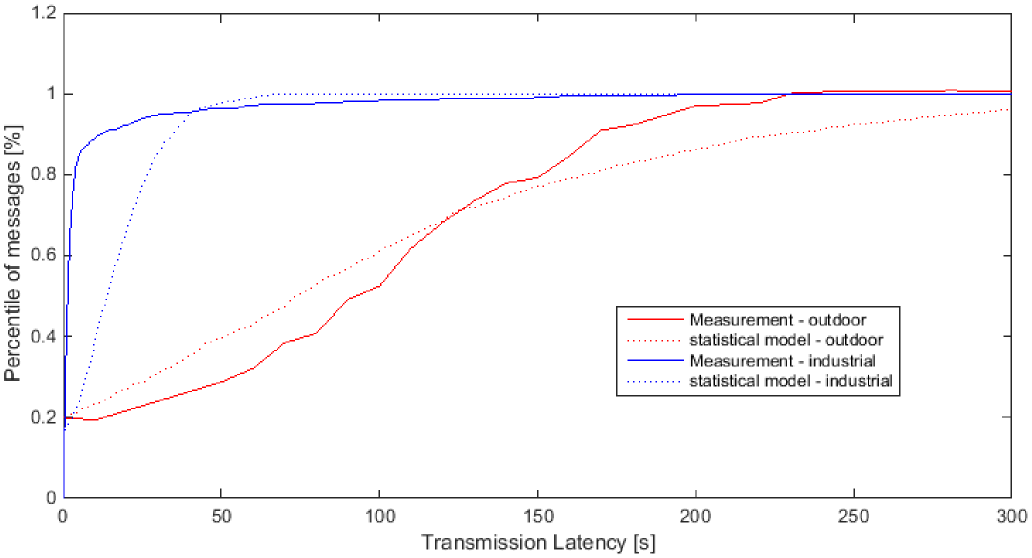


Figure 63: Delay CDF as predicted by statistical model and real-world implementation. Outdoor and industrial scenarios are shown.

Figure 63 compares the CDF of DTNs. The four combinations of outdoor and industrial scenario and real-world implementation and statistical model are shown. Firstly, the higher latency in the outdoor scenario compared to the industrial scenario can be seen. This higher latency is both predicted by the model and measured in the real-world. Secondly, the predictions and real measurements can be compared. The statistical model predicted the outdoor scenario well. The probability for very low latency transmission is slightly overestimated, as well as the probability for high latency transmission. The average and median latency however are very well estimated. The industrial use case generally overestimates the latency of transmissions. In the real-world implementation many messages were transmitted with delays $\leq 1\,\mathrm{s}$, while the average predicted delay according to the statistical model is $\approx 15\,\mathrm{s}$. The most likely cause is the non-random distribution of the AGVs on the factory floor. The statistical model assumes, that the clients are randomly distributed and moving on the factory floor. This is not true for real factories [8] .

In general the observation is, that the proposed models behave very similarly to the real-world applications. However, some model parameters must be customized if specific use cases shall be modelled. The results of the model can be used rather as estimations, than as predictions.

5.3.3 Applicability of Delay Tolerant Networks

In section 4.2.3 a model for the description of DTNs is proposed. This model enables the estimation of latencies in DTNs. The determined latency can be compared to the defined requirements. The required ranges from Table 18 can be expressed in terms of

Parameter	Symbol	currently typical range	envisioned range for future applications
Application area	A	$900\,\mathrm{m}^2$ to $4000\,\mathrm{m}^2$	$400\,\mathrm{m}^2$ to $1 \times 10^6\,\mathrm{m}^2$
Number of participants	n	1 to 200	1 to 20000
Communication range	r	$15\,\mathrm{m}$ to $50\,\mathrm{m}$	$1\,\mathrm{m}$ to $100\,\mathrm{m}$
Movement speed	v	$0\,\mathrm{m/s}$ to $2\,\mathrm{m/s}$	$0\,\mathrm{m/s}$ to $7\,\mathrm{m/s}$

Table 19: Current and future application parameters for DTNs with AGVs

percentage of AGVs which must receive the message within a certain time frame. Multiple parameters remain, which affect the performance of the DTN and its applicability. These parameters are the number of mobile participants n the speed v at which the participants move, the size of the applications area A and the average communication range r of the mobile devices. Many of these parameters show the simplifications of the model. The communication range r for example depends in reality on other parameters, like the position of the transmitter, the direction, in which to send or the time. Selecting an appropriate average communication range is highly important to the quality of the results. Using the maximum communication range, which is often the range given for available communication technologies, must be avaioded. The speed v of the mobile entities must also be selected appropriately. The model assumes that all participants move at all times, which is not realistic. Therefore a speed lower than the real movement speed must be selected. The number of participants n must not be determined, since this parameter is often given for any application. The area A is often of a very complex shape, therefore the used area A might differ from the real size of the application.

In [7] certain ranges for the described parameters are given. These ranges describe:

1. Typical parameter ranges for current applications.
2. Expected parameter ranges for future applications according to trends.

The application parameters given in Table 19 are expected for current and future applications. These parameter explicitly describe indoor AGV applications. Outdoor applications (e.g. container terminal see Figure 13b) present different challenges with larger application areas but also increased communication range. However, the proposed model is also applicable to outdoor applications, as shown previously. While there are applications with only one AGV, these applications are not relevant to scenarios in which DTN are applicable. Therefore a lower bound of $n \geq 2$ is used.

In [7] we varied the four parameters, while holding the other three parameters at reference values within the predefined ranges (see Figure 64). The average delay of messages, as predicted by the model, was analyzed. In this analysis the requirements for ②, ③ and ④ were fulfilled for every value of the parameters. The requirements of ③

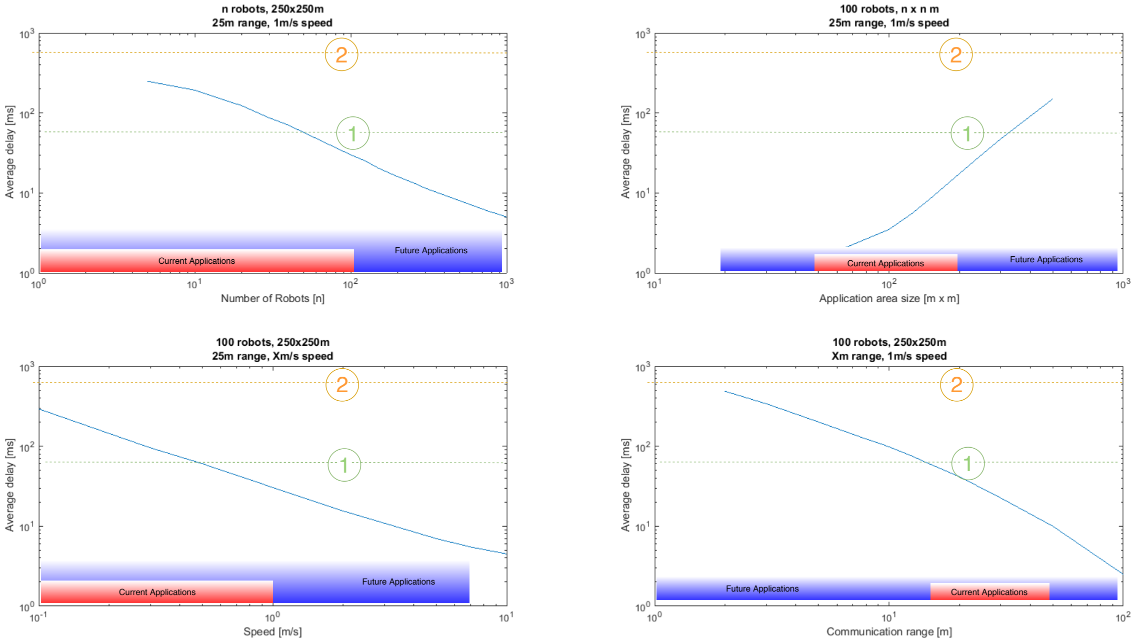


Figure 64: Average delay using a DTN in different application. The performance in compared in regards to the use cases 1 to 4. The ranges are marked according to the current and expected future ranges [7]

and ④ are outside the plotted area in Figure 64 and fulfilled in all examined use cases. The requirements for ① were not fulfilled, if the number of participants, speed of participants or communication range was to low or if the application area was to large. Even for ① all participants must be reached, which is a worst-case assumption of the requirement given in Table 18.

The performance and fulfilled requirements in regards to the parameter ranges of today's applications and expected future applications are compared. The trends in industrial AGV systems either support the inclusion of DTNs or if they contradict their inclusion. The trends towards faster AGVs and higher number of AGVs both improve the performance of the DTN in terms of latency. The used model does not include effects of interference. An expactation is, that if much higher number of AGV are used within the same application area, that the interference increases due to the network density. This development requires efficient algorithms for the message forwarding in the DTN. On the other hand, if the network density is high, the probability for disconnections form the network are low and a DTN might not be necessary.

There are certain weak points in this analysis. For example, only one parameter changes between applications. The likelihood, that if the application area increases, that either the number of participants or their speed also increases, is very high. At the same time it is very unlikely, that an AGV has only one communication interface with a range of

$1\,\mathrm{m}$. In this case the AGV most likely also has other interfaces with a higher range.
In the following section a more precise evaluations of the relation of multiple parameters is presented.
Four model parameters create six possible combinations of two-parameters. For each combination the two combined parameters are varied while the others are chosen randomly from the range given in Table 19. This Monte-Carlo approach enables the examination of the combined parameters. The median delay of messages was observed on n messages during d days of DTN operation.
The transmission of more than $2.8 \cdot 10^5$ messages during > 300 days of DTN operation were observed. The median delay of the messages is classified according to the previously defined use cases. A green dot (·) represents a message delivery with a median delay sufficient for use case ①. Messages, that were transmitted sufficiently fast for use case ② are shown as a yellow dot (·). Use case ③ requires a delay of $<1\,\mathrm{h}$. A measured message is shown as a red dot (·) if this requirements was meat. All measurements fulfilled the requirements for use case ④, therefore they were not specifically marked.
For each measured message another network configuration was tested. Every configuration is specified by the four parameters n,A,r and v. For each tested message these four parameters were randomly selected from the ranges given in Table 19 for the future applications. The four parameters lead to six possible combinations of two parameters. For each of these combinations a scatter plot or all $2.8 \cdot 10^5$ messages with different colored dots (·,· and ·) are created.
All scatter plots are combined in Figure 65. These plots show expected behavior, but also unexpected observations. The single dots create more or less clear areas of network configurations, which can fulfill certain requirements. The expectation was, that the number of AGVs and the size of the application are the central parameters, that determine the performance of the DTN. In Figure 65 shows, that the communication range is even more crucial to the success of the DTN. Even in configurations with beneficial parameters (e.g. medium application size and high number of AGV) high delay transmissions regularly occur. This can happen due to the other two parameters.These cases of high performance variation in normally beneficial network configurations do not occur, if the variations in communication range are accounted for. A very low communication range ($\leq 20\,\mathrm{m}$) drastically worsens the performance of all DTNs. A small exceptions is, that applications with a size below $10000 \cdot r$ are not highly affected by this. This shows, that a DTN based on VLC is not feasible if a random distribution of AGVs is expected.

5.3.4 Message Ferry

In Section 2 an example for the application of DTN technology to the industrial use case was given. This use case consisted of an AGV with a technical problem in a zone within the factory, without network coverage. By chance a status message from this AGV was transmitted via an DTN to the operator. In the use case the zone without coverage was not easily reachable for the human operator, therefore the operator sent a firmware update via the DTN to the faulty AGV.

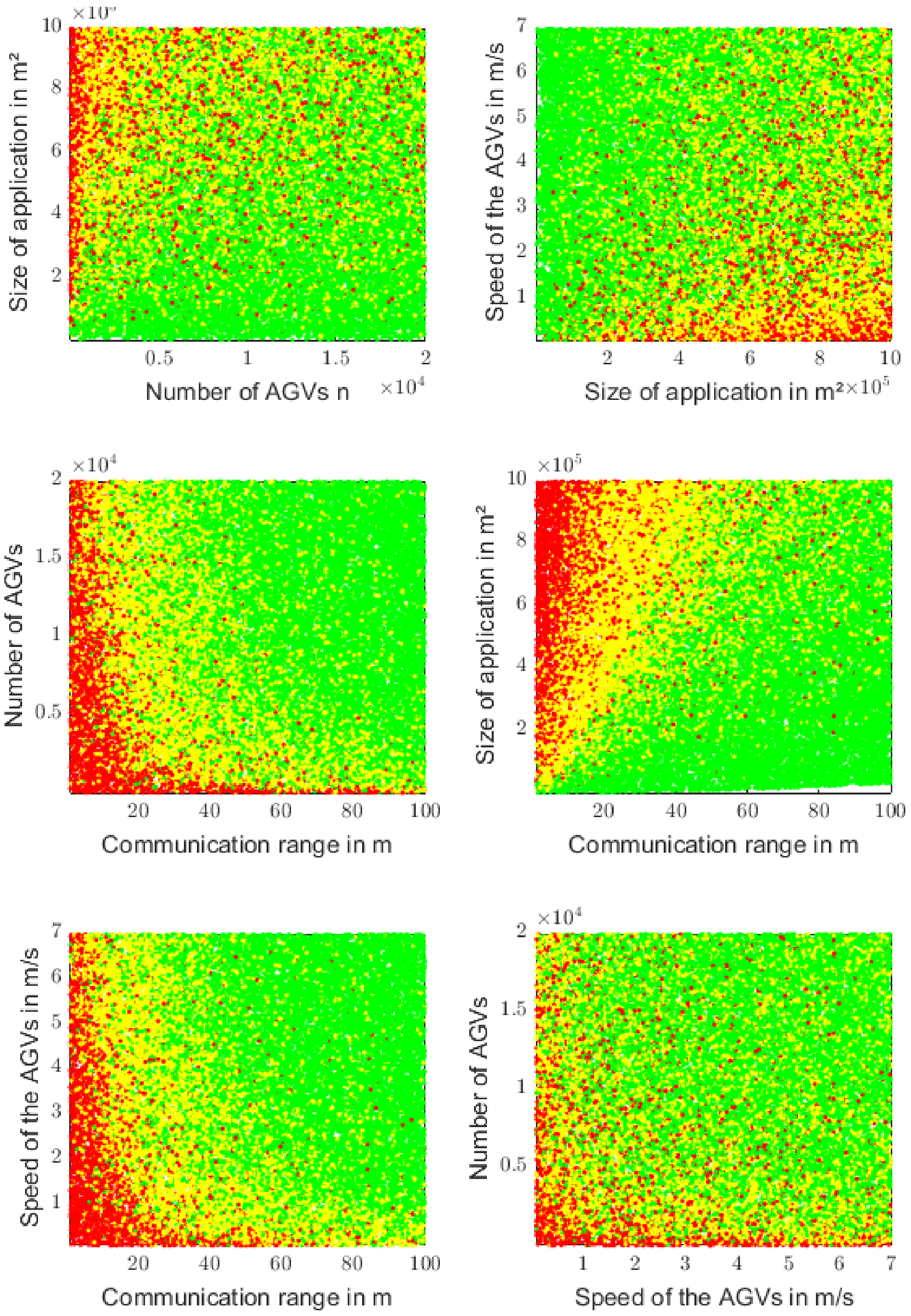


Figure 65: Variation of all parameters. Six plot of all possible combinations of the 4 parameters. Green dot (·) median delay $\leq 60\,\mathrm{s}$; Yellow dot (·) median delay $\leq 600\,\mathrm{s}$; Red dot (·) median delay $\leq 3600\,\mathrm{s}$

This process can use the normal DTN and transmit the message by chance or since the geographical position of the receiver is known an AGV can be instructed to transport

the message to the receiver, decreasing the time until the AGV is operational again. This active control of mobile clients to disseminate or collect messages in an DTN is often referred to as a message ferry [91, 92, 93].
In the industrial context such ferrying approaches have some specific challenges and specific chances. The challenges for example concern the limited mobility of the mobile clients and the obstacle-rich environment. However the chances are, that the main task of the AGVs is the transport of objects. The messages / the data can be classified as an object and be transported with the usual orders, issued by the CCU. This strategy is for example applicable in the previously discussed use case.

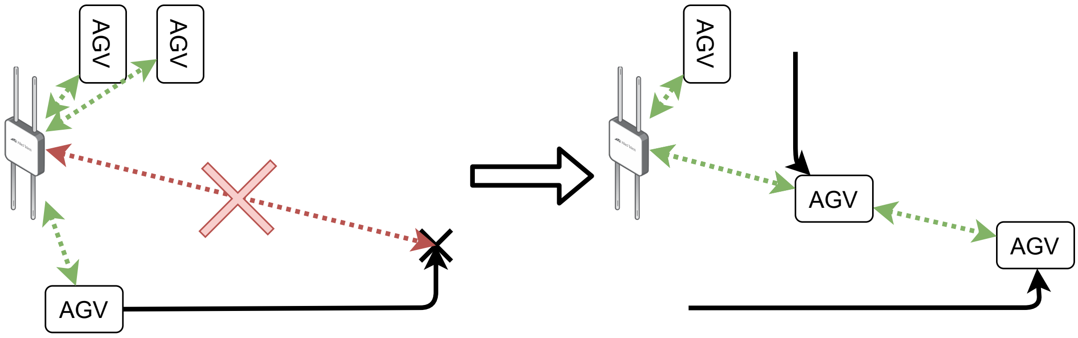


Figure 66: Concept of the cooperative network.

5.4 Cooperative robot network

[13] was the first article to publish the results presented in the following section.

The availability of communication channels in challenging industrial environments can often not be guaranteed. A lack of connectivity can negatively impact the behavior and performance of intralogistics systems, like AGVs. The last section proposed to use the movement of AGVs to transport messages throughout a DTN. This section shows, that the movement of AGVs can also be used to repair the topology of an industrial MANET and improve the transport performance of an AGV fleet.

The basic concept is, that an AGV receives an order with a destination. This destination might be outside the coverage zone of the used wireless communication technology. If the AGV detects, that the destination is outside of the coverage zone, the AGV concludes, that receiving new orders is unlikely, while at this destination. The AGV therefore requests assistance from the AGV fleet. One or more other AGV/AGVs from the fleet assist the first AGV by positioning themselves between the closest AP and the task destination. The AGVs communication operates as a MANET. This enables them to relay messages from one to another. The relaying of the messages effectively enhances the range / coverage of the closest AP. Therefore, the fist AGV can now receive the next order at the destination and resume continuous operation.

In the following sections the process is described in high detail, followed by a description of the investigative method. This method is used for preliminary investigations, before the method is used to characterize the benefits gained by the adaptive positioning method. In these section three types of networks are compared:

1. An infrastructure network (non ad-hoc network)
2. An industrial MANET (ad-hoc network)
3. An industrial MANET, including adaptive positioning of AGVs (adaptive network)

5.4.1 Process

There are several characteristics, that were important in the design of the adaptive positioning system. Firstly, the system is designed to the decentralized. Most AGV fleets have a central controller, but the proposed coverage optimization process might need to be performed without a connection to this controller. Therefore, the requesting AGV and assisting AGVs can operate independently from any other systems. The designed system respects the industry specific requirements. For example the movement of the AGVs is highly restricted to certain paths and the AGVs must avoid to block any paths or resources in the factory environment. Additionally the wireless spectrum is a sparse resource in industrial application. Any communication within the adaptive positioning system must only use minimal band-width. Lastly, the system must be easy to configure, use and maintain.

The basic process has three important steps:

1. **Learn wireless coverage**
   The AGVs must be able to determine if the destination of a task will have coverage or not, before driving to this destination. The industrial environment is very dynamic and the coverage of a MANET is hard to predict. A pre-configured coverage map or similar solutions are therefore not suitable. Additionally, these pre-configured solution do require additional work in the setup and in the maintenance of the system. The proposed alternative is to learn the coverage of the system during the normal operation of the AGVs. This has the additional advantage, that the adaptive positioning can react to changes in the environment or defects in network infrastructure.
2. **Determining relay positions**
   The optimal positions of the relay-AGVs are determined by the AGV, that requires assistance. The relay-positions are selected from a set of parking positions in the factory. These parking positions are defined as positions at which an AGV can park for a prolonged period of time without blocking any paths or access to resources (see definition in Section 4.2.4).
3. **Select suitable relay-AGVs**
   The relaying task might require one or more relay-AGVs. These AGVs must be selected from the complete fleet. An auctioning system is used as a decentralized method to accomplish this selection.

Some previous setup is required before the system can be used. All AGVs must be informed about all parking positions and all APs. The first step in the operation of the adaptive system is learning the network coverage in the industrial environment.

5.4.1.1 Learning network coverage

The goal of learning the network coverage is to understand the relation of an AGVs position X_{AGV} to the probability for this AGV to be able to connect to the central controller $P_{Con}(X_{AGV})$. A resolution for the AGV position is defined in order to limit the amount of data, that must be stored.

The reduction in resolution starts with the selection of a set of points of interest within the factory. In this application the points of interest are the parking points within the factory. A Voronoi diagram is generated from this set of points using the euclidean distances. Each Voronoi cell is related to the point of interest within this cell. If an AGV is within a Voronoi cell of a point of interest, the position is processed as if the AGV is at this point of interest.

The AGVs repeat the following process with a predefined interval. For the presented implementations this interval is set between 1 and $3\,\mathrm{s}$. For each point of interest two counters are maintained on each AGV. The first counter N_p^{PoI} is incremented in each interval, in which the AGV is within the Voronoi cell of PoI. The second counter N_{cp}^{PoI} is incremented, if the AGV is within the cell of PoI and if a connection to the Central Control Unit (CCU) is available. Since $N_p^{PoI} \geq N_{cp}^{PoI}$ must always be true, we can define the probability P_p^{PoI} of connection availability at PoI as:

$$P_p^{PoI} = \frac{N_{cp}^{PoI}}{N_p^{PoI}} \tag{28}$$

Due to this process AGVs can only know the probability to connect from a point / zone, which they have previously visited. If no data is available for a task destination ($N_p^{PoI} = 0$), then $P_p^{PoI} = 0$ is assumed. The number of PoIs, for which a probability is known increases over time. A faster increase in this probability is desirable.

A decentralized cooperative learning approach is proposed, to increase the speed of learning connection probabilities. For this approach the industrial MANET of the AGVs is used. The AGVs exchange data with a certain periodicity (e.g. the same as the periodicity of the learning process). Each AGV sends the counters N_p^{PoI} and N_{cp}^{PoI} of a random PoI with $N_p^{PoI} \geq 1$ via broadcast. Each AGV that receives this broadcast can add the received counters to the locally stored counters of the same PoI.

The coverage learning was tested with and without the cooperative aspects. From all AGVs the probabilities to know a destinations connection probability was recorded and is presented in Figure 67. The figure shows, that the learning of destination connection probabilities is much more reliable and much faster, compared to the non-cooperative method.

If specific communication technologies, like VLC are of interest, then the proposed learning algorithm might be enhanced to better fit the needs of this technology. VLC is only possible with LoS-connections. This for example enables the creation of a map based on the availability of the connection. Such a system can be implemented, if all clients regularly broadcast their positions via the VLC channel.

5.4.1.2 Determining relay positions

The first step is complete. The AGVs are able to predict, if there will be coverage at the destinations of tasks. The next step is to determine, if assistance of other AGVs is required. In this implementation a threshold is used. If the expected connection probability is below this threshold, assistance is required, if the expected connection probability is above the threshold, no assistance is requested and the AGV drives to the tasks destination.

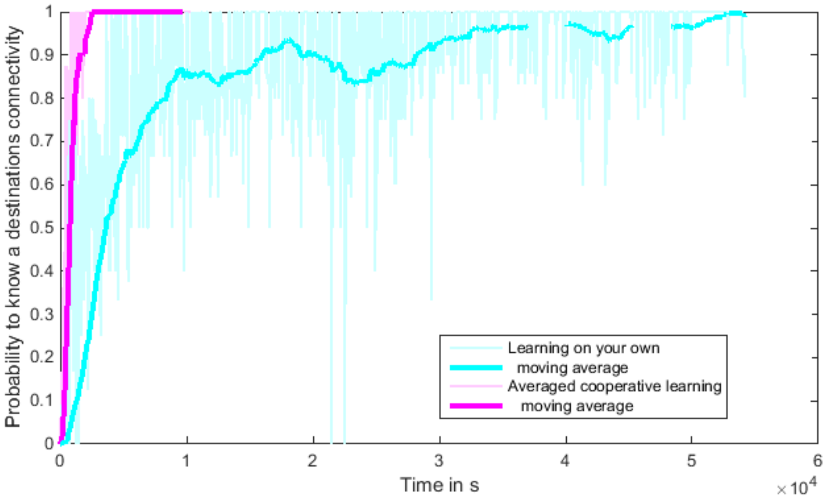


Figure 67: Speed to learn network coverage in a factory.

The process of requesting assistance is decentralized and coordinated by the AGV that requires the assistance. The requesting AGV first needs to determine the positions at which other AGVs must be positioned. The relay position can not be freely chosen, since freely chosen positions can block paths or resources in the factory. Instead the relay positions are selected from the set of parking positions.

In this section the term *relay-route* refers to a collection of positions, that connects P_{AP} and P_{TD}. The relay-route starts with the position of the AP closest to the task destination P_{AP} and ends at task destination P_{TD}. The algorithm must select a number of parking positions, which connect these two positions. For the algorithm a maximum distance, d_{max} between two positions on the relay-route is defined. For the industrial use case d_{max} $=20\,\mathrm{m}$ is a suitable value. Furthermore, $|P_1 - P_2|$ defines the euclidean distance between the positions P_1 and P_2.

The minimum number of required relay-AGVs can be determined using:

$$n_{min} = \left\lceil \frac{|P_{AP} - P_{TD}|}{d_{max}} \right\rceil \tag{29}$$

The process to search for a relay-route starts by sorting all parking positions according to the following distance:

$$D_p = (|P_p - P_{AP}| + |P_p - P_{TD}|) - |P_{AP} - P_{TD}| \tag{30}$$

Initially the $n_{min} + s$ parking positions with the smallest D_p are selected as a relay-route. In the beginning of the process $s = 0$. Different operations are required to determine the relay-route:

- **Sort route**
  The elements of the relay-route are sorted from closest to the AP to farthest from the AP.

- **Check route**
  All distances between sequential positions in the relay-route are checked. The relay-route is valid if no distance exceeds d_{max}.
- **Expand route**
  Expands the searched relay-route by increasing s by 1.
- **Optimize route**
  Remove all elements from the relay-route, whose removal shortens the relay-route but does not invalidate the relay-route.

These operations are used to determine a relay-route using the following algorithm:

```
    if(Check route):
        Optimize route
        Return route
    else:
        n_park = number of parking points
        if(n_min + s < n_park):
            Expand route
        else:
            Optimize route
            Check route?
            if(Check route):
                Return route
            else:
                No route found
```

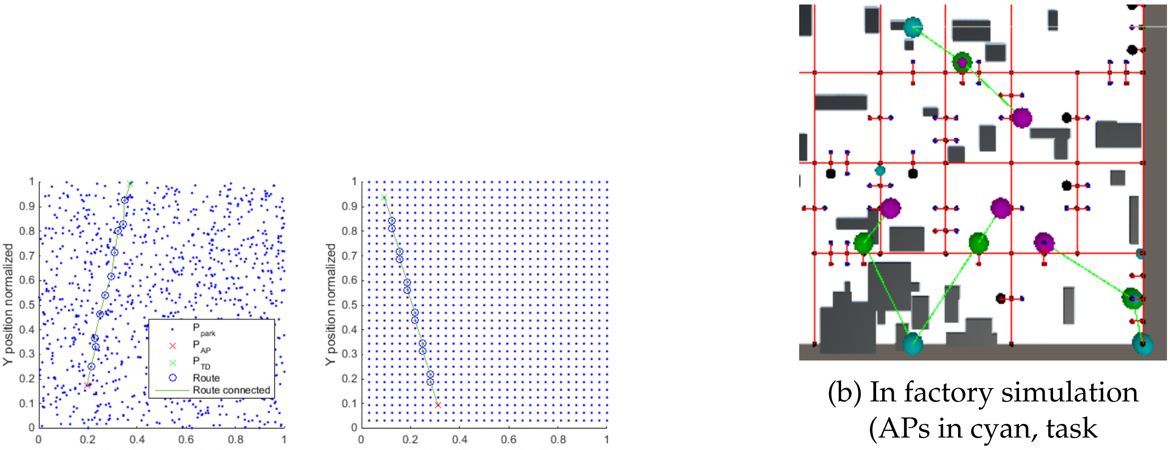
Routes found using this process are shown in Figure 68. The figure presents the algorithm being used in an abstract scenario and in a simulated factory. In the abstract scenario regular grids and irregular sets of parking positions are examined. In both cases the algorithm was fast to determine a suitable relay-route. In the factory simulation the figure shows, that several AGVs have determined relay-routes to connect an AP and a task destination.

In rare scenarios the algorithm might not be able to determine a valid relay-route. However, this was not observed in the calculation of $\geq 10^5$ relay-routes during all following simulations.

5.4.1.3 Selecting AGVs from the fleet

The last step before assistance can be given to the requesting AGV is to select, which AGV from the fleet to position at which position of the relay-route. The process must again be decentralized.

An auctioning system is proposed. In this system the requesting AGV offers all positions of the relay-route via the industrial MANET. All receiving AGVs start by determining, if they are currently available to relay. If they have active transport tasks, or if they are charging, they might not be available. In this case they do not respond to the offer. If an AGV is available the AGV sends the current location, battery state and more



(a) In regular and irregular abstract scenario

(b) In factory simulation (APs in cyan, task destinations in magenta and relay positions in green)

Figure 68: Finding relay-routes with the described algorithm.

back to the requesting AGV. The requesting AGV can then determine the most suitable relay-AGVs and signal their selection to them. Once all relay-AGVs are selected the requesting AGV can drive to the task destination. The communication with in the industrial MANET during this process is presented in Figure 69.

In special cases a beneficial strategy can be to wait until all relay-AGVs are at their parking positions. This guarantees, that a connection is available as soon as the requesting AGV reaches the task destination.

5.4.2 Method of investigation

A collaborative networking scheme, such as the one proposed in the previous chapters is highly affected by the application environment. The placement of parking positions, task destinations and APs and also the general layout of the factory have a very high impact on the benefits gained by the implementation of the adaptive network.

A best-case and worst-case example are described. In a worst-case example the factory has a very dense networking infrastructure. Therefore relaying is never required and the adaptive networking does not improve the communication of the AGVs. Instead the adaptive networking actually decreases the transport performance of the AGVs, because the system will still request assistance until the system has learned, that coverage is universally available. This blocks some AGVs from fulfilling transport tasks. In a best case scenario there is only a sparse network of APs. Additionally there are many parking positions, while the task positions are outside of the range of the APs. In such a scenario the benefits of the adaptive network can be disproportionately high.

One must not rely on the observations from single industrial applications in order to get a realistic picture on the actual benefits gained by the adaptive networking. Instead the observations from hundreds of industrial applications were combined in order to make more reliable predictions about he applicability and benefits of this networking

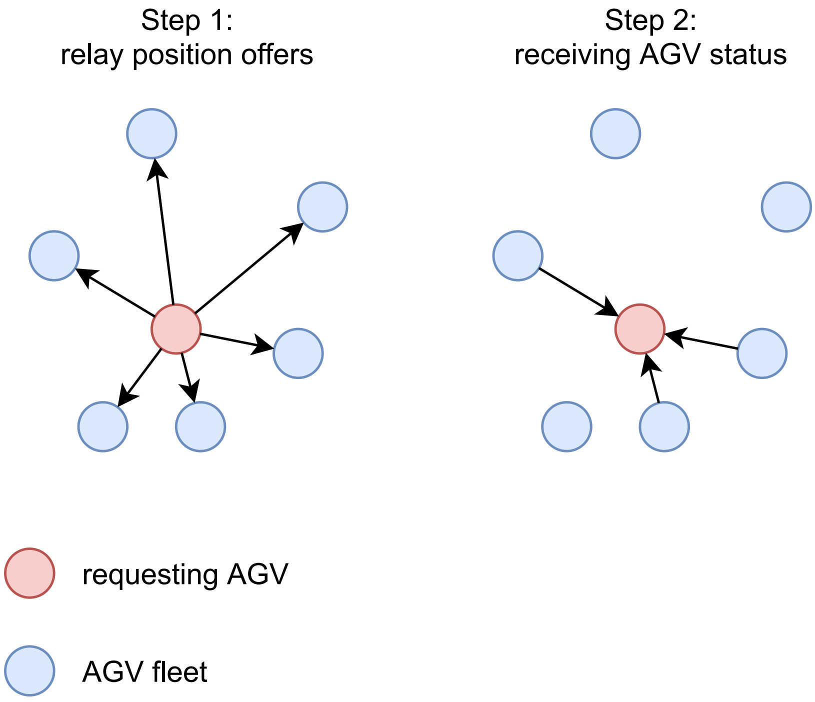


Figure 69: Communication during selection process.

method. In section 4.2.4.8 we introduced a method to procedurally generate industrial applications for network simulation. With this method hundreds of environments are generated, simulated individually and their observed results are combined.

In the following section investigated metrics are introduced and the simulated scenario is described in more detail. Additionally two scenarios are introduced, which are used to observe the behavior of the adaptive networking system.

5.4.2.1 Simulation method

As previously described the simulation is based on the procedurally generated factory environment. Within this environment the AGVs are coordinated by a CCU. The communication between the CCU and the AGVs is implemented according to the VDA5050 standard. Orders are generated at the CCU and send to the corresponding AGV. Each order consist of the AGV that must fulfill the order, the destination at which the task must be fulfilled and the time that is required to fulfill the task.

The order is send to the AGV via a wireless network. The CCU can communicate using all APs in the factory environment. The wireless network can be either a non ad-hoc network, an ad-hoc network or an adaptive network. The same network is used by the AGVs to send status updates to the CCU. The CCU uses these status updates to determine the connection state of the single AGVs and acknowledges them via the wireless network. The AGVs use the acknowledgements to determine their own connection state.

The wireless network uses IEEE802.11 b/g/n as the simulated standard. The signal propagation is simulated using the multi-wall-model, which includes the signal attenuation by obstacles. The movement is simulated using the task-oriented graph mobility model described in [8]. However, the destination are centrally determined by the CCU. The AGVs only move if they received an order otherwise they stay stationary.

5.4.2.2 Investigated metrics

During the simulation two main metrics are recorded for later analysis. These metrics are:

1. The percentage of AGVs connected to the CCU
2. The number of completed transport tasks per hour per AGV

The connectivity of the network is given in terms of percentage of AGVs that are registered at the CCU. The CCU knows the number of AGVs that are in the factory and can compare this number to the number of AGVs from which status messages were received. This metric mostly informs about the density of the networks topology. However, since the AGVs do not move if they do not receive tasks from the CCU a hypotheses is, that this metric is connected to the transport performance of the AGV-fleet.

The transport performance of the AGV-fleet is measured in terms of completed transport tasks per hour per AGV. Once a AGV has completed a task the AGV will signal this to the CCU. The CCU registers all of these messages and logs them.

5.4.2.3 Investigated scenarios

Two different scenarios are investigated. The first scenario concern factories with non-complete network coverage. In this scenario the APs are randomly placed in the simulated factory environment. This results in a non-complete coverage for the wireless network.

In contrast the environment changes in the dynamic environment scenario. In this scenario the APs are placed in the factory in such a way that complete coverage is achieved. However during the simulation the environment is changed. Obstacles are moved and some APs experience faults.

5.4.3 Preliminary investigations

Two research question from previous work were investigated using the methods described in this section:

1. Are ad-hoc networks able to increase the connectivity in industrial applications?
2. Is the connectivity in an AGV-fleet correlated to the transport performance of this fleet.?

With the methods introduced in this section answering both of these questions independently from specific industrial applications is possible. For this purpose 300 different factories were simulated using either a non ad-hoc network or an ad-hoc network. Both previously described metrics, the connectivity and the transport performance, were recorded and are plotted in Figure 70.

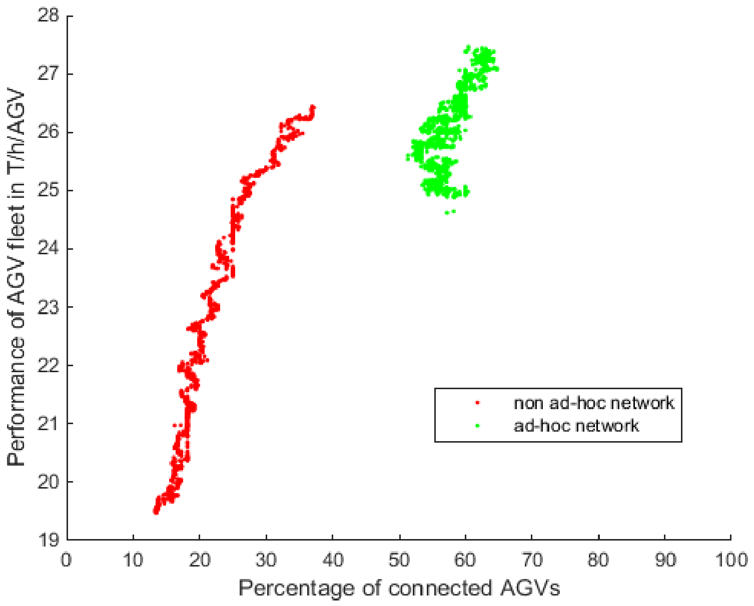


Figure 70: Correlation of connectedness in AGV-fleet and transport performance for non ad-hoc and ad-hoc networks.

Figure 70 shows, that generally ad-hoc networks are better connected than non ad-hoc networks in the simulated industrial applications and that a higher connectedness generally also leads to a better AGV-fleet performance in terms of completed transport tasks per hour per AGV (T/h/AGV).
The utilization of industrial MANETs benefits both, the network and the underlying robotic application.

5.4.4 Benefits of adaptive positioning

The adaptive networking scheme can be used to further improve the availability of communication channels in industrial applications and increase the performance of the AGV-fleet. The system is tested in the two previously described scenarios. An expectation is, that the adaptive network performs better than the ad-hoc network, which in turn performs better than the non ad-hoc network. Performing better means, in this case, that a higher connectivity and transport performance is achieved.
For the dynamic environment scenario an expectation is, that all three types of network perform identically, while full network-coverage is still available. However, once the environment changes the non ad-hoc network should be most drastically impacted, while the adaptive network can recover the fastest.
The results of a single simulation (for non ad-hoc, ad-hoc and adaptive network) are shown in Figure 71. The figure shows that the connectivity of the ad-hoc network and adaptive network show a high variance, but generally stay within a certain range. In contrast the non ad-hoc network continuously loses in connectivity. This happens, be-

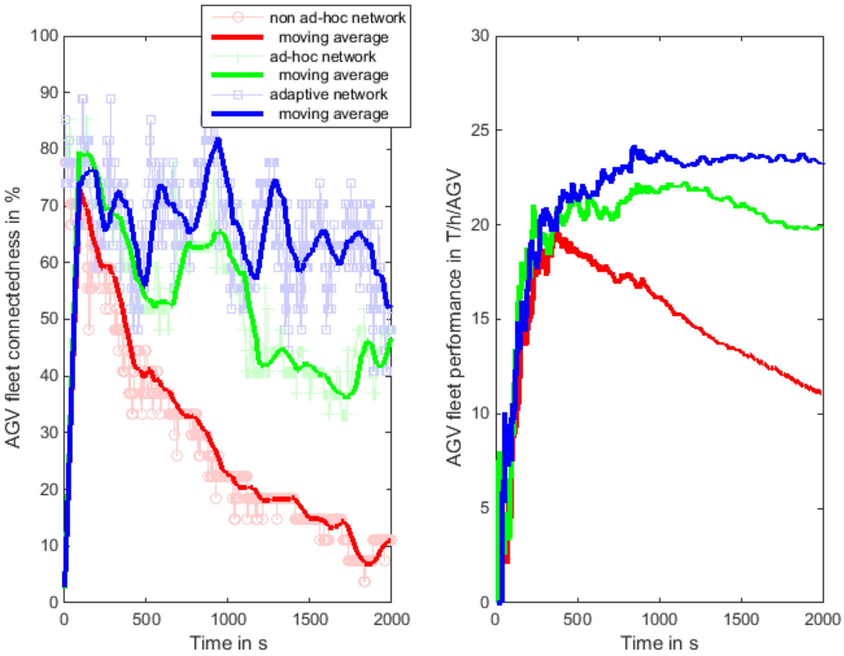


Figure 71: Change over time in network connectedness and transport performance.

cause AGVs leave the coverage of the APs and have no system to return to the coverage zone, if the task destination has no coverage. This steady decline in connectedness can also be seen in the transport performance of the non ad-hoc network. Every AGV, that leaves the coverage zone is lost to the AGV-fleet and can not be used for future transportation tasks, effectively reducing the performance of the system. The ad-hoc and adaptive network by contrast experience a stable performance over time, once they reach a certain value. In the presented example the expectation of

$$\text{non ad-hoc} \leq \text{ad-hoc} \leq \text{adaptive} \tag{31}$$

was fulfilled. However in the following sections the analysis is done for hundreds of factories in order to represent a more accurate picture of the very heterogeneous industrial application.

In the following scenarios results form hundreds of simulations are summarized, therefore Probability Density Functions (PDFs) of the connectivity and performance are a tool of choice.

5.4.4.1 Scenario: non-complete coverage

In Figure 72 PDFs for the network connectedness and transport performance in the non-complete coverage scenario are presented. In terms of connectedness the expected result of adaptive outperforming ad-hoc and ad-hoc outperforming non ad-hoc is clearly visible. The non ad-hoc network has a high probability to have less the $30\,\%$ of the AGVs

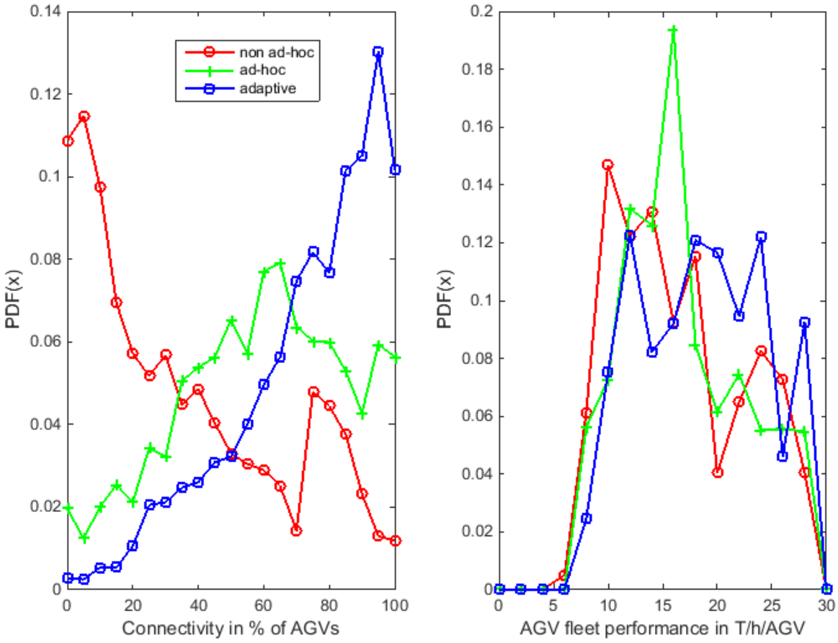


Figure 72: Resulting connectedness and fleet performance in the non-complete coverage scenario.

connected to the CCU, while the adaptive network has more then $70\,\%$ of all AGVs connected at most times.

The benefit of the ad-hoc network and adaptive network are not that clearly visible in terms of completed transports per AGV per hour. The ad-hoc network achieves an average performance of $17.35\,\mathrm{T/h/AGV}$, which is slightly higher than the average performance of the non ad-hoc network at $16.89\,\mathrm{T/h/AGV}$. Examining the mean values of both systems with moving block bootstrapping revealed that these two distributions only deviate lightly. The average performance of the adaptive system by contrast was $18.69\,\mathrm{T/h/AGV}$, which is a $7.7\,\%$ improvement over the non-adaptive ad-hoc network. The average observation was, that the adaptive approach can further improve upon the ad-hoc network.

5.4.4.2 Scenario: dynamic environment

In the dynamic environment scenario the environmental conditions majorly change at the mid-point of the simulation. This is summarized in Figure 73. The plot of the average performance (in terms of T/h/AGV) and the observed ranges of this performance. For the first half of the simulation we see the expected behavior of all three networks. They all perform very similarly. In the second half we see, that the performance of the non ad-hoc network is affected the strongest. Ad-hoc network and adaptive network perform identically in the beginning. After some time the adaptive network begins to

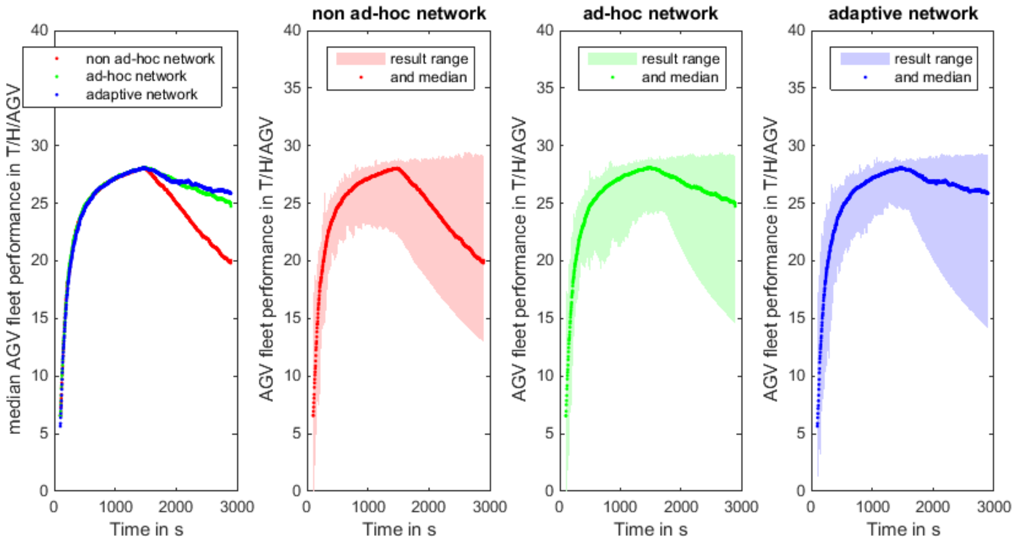


Figure 73: Impact of environmental change on non ad-hoc, ad-hoc and adaptive networks.

Table 20: Performance of networks in dynamic environment

Network type	Pre-Change performance in $T/h/AGV$	Post-change performance in $T/h/AGV$	Change
Non ad-hoc	27.67	20.52	$-25.8\,\%$
Ad-hoc	27.73	25.41	$-8.6\,\%$
Adaptive	27.68	25.93	$-6.3\,\%$

perform slightly better than the ad-hoc network. This small delay is caused by the required learning of the AGVs in the adaptive network. In the next three plots the average performance, but also the result ranges are plotted. The result ranges are quite similar regardless of the used networking strategy. There were non ad-hoc networks that were barley affected by the change in the environment, while some adaptive networks were very highly affected.

In Figure 74 PDFs of the AGV-fleet performance are shown. One set of PDFs (dashed lines) shows the performance before the changes in the environment, while the other set (solid lines) shown the performance after he environmental change. The plot shows, that the performance of all AGV-fleets, regardless of network, decreases. Especially visible is the decrease in performance by the non ad-hoc network. The performance of the non ad-hoc network drops by more than $25\,\%$. The performance drop for the ad-hoc and adaptive networks are much smaller with $8.6\,\%$ and $6.3\,\%$ respectively.

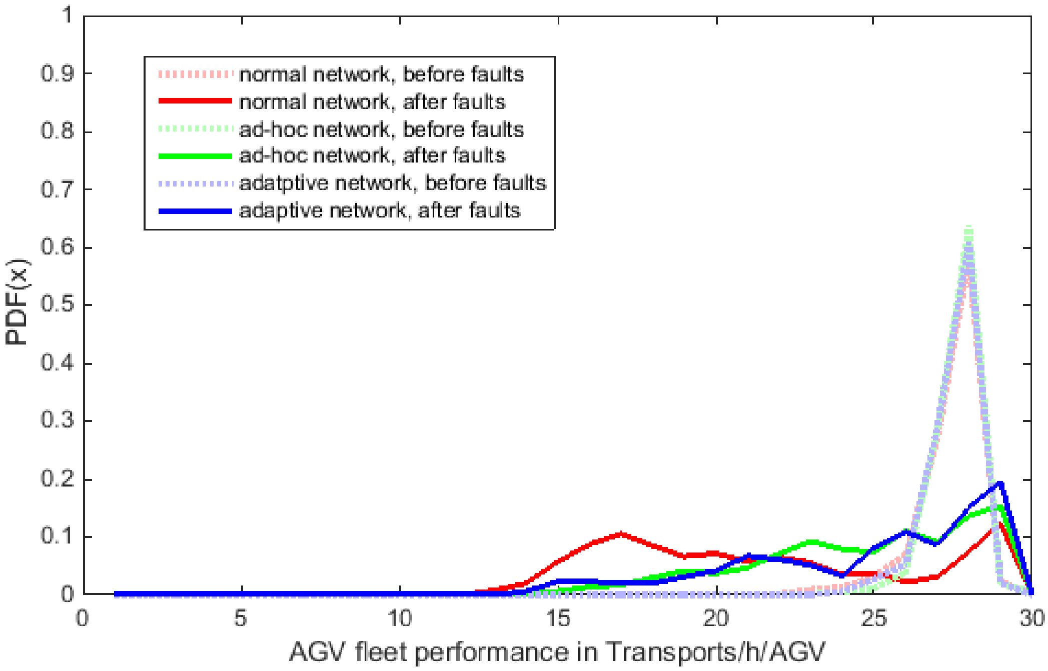


Figure 74: PDFs of AGV-fleet performance before and after change in the environment

5.4.5 Experimental implementation

The system was implemented with a small group of robots using VLC. In this implementation reliably forming relay structures was possible. The usage of communication technologies like VLC leads to additional challenges. For example the AGVs did not only need to control their position for the relaying, but also their orientation. In this case solving the challenge was possible by orienting the AGV towards the mid-point between the previous and following station in the relay-route. However, this solution is very specific to the used VLC implementation.

6 Conclusion

This work showed, that ad-hoc networking solutions are able to provide a valuable set of benefits to the field of industrial automation, especially in the context of mobile clients. This work contributed to the state of the art in two main ways. Firstly, new methods for the investigation, modelling and simulation of industrial MANETs are described. Secondly, these new methods were used and verified in three applications of ad-hoc technologies to the industrial use case.

The models and methods introduced in this work concern the examination of industrial ad-hoc systems, their simulation and the simulation of the impact of these systems on the underlying automation solution. A new method for the observation of the time-variant topology of MANETs is proposed, which is specifically designed to fulfill the requirements of industrial applications. This method enables the empirical observation of dynamic ad-hoc measurements, while the measurements only require minimal bandwidth. This method will improve the ability of engineers and scientists to optimize ad-hoc networks for specific industrial environments.

A new simulation architecture is proposed to model the interaction of mobile automation systems and the used wireless communication. This simulation architecture also includes a number of newly proposed and modified models from the field of network simulation. The focus of these simulation tools is to accurately simulate communicating AGVs in industrial environments. Additionally statistical models are proposed that enable applicability checks for certain types of networks, without implementing these networks. They main goal of this simulation tool is to allow users to estimate the performance of industrial ad-hoc systems and to facilitate a more wide-spread adoption of ad-hoc topologies for industrial wireless networks.

The developed methods and models are used to implement industrial ad-hoc solutions. Three different ad-hoc technologies are implemented and examined. The first is a system for the real-time transmission of safety relevant data via an industrial ad-hoc network. These messages require a reliable low-latency communication. This communication was achieved using a flooding-based approach. With this system transmitting messages over up to 10 relaying nodes within less than $100\,\mathrm{ms}$, or to detect a disconnection within the same time frame, was possible.

The second system, in contrast to the first, was meant for delay-tolerant communication. In industrial applications certain types of data (e.g. orders, software-updates, etc.) can be transmitted with delays of minutes or hours. This enables the usage of Delay Tolerant Networks (DTNs). In this work the applicability of these networks to different use cases and types of data is examined. A conclusion is, that many application can benefit from the resilient nature of DTNs. Results showed, that even with a low node density of ≤ 5 nodes on $30\,000\,\mathrm{m}^2$ $90\,\%$ of all messages were transferred in $\leq 3\,\mathrm{min}$.

The last system is specifically used to combine the technologies of ad-hoc networks and AGVs. In the proposed system AGVs actively change their positions in order to optimize the coverage and topology of an ad-hoc network. This proposed networking has shown to be not only beneficial to the AGVs communication, but also improve the transport performance of the AGV-fleet. Using this adaptive positioning system improved the performance of the AGV-fleet by 7.7 % compared to an AGV-fleet communicating via an infrastructure network. Additionally the resilience of the fleet against changing communication conditions is improved.

Over all this work improves two things. Firstly, the ability of engineers and scientists to create and adapt networks to the industrial use case in improved by supplying new simulation tools and evaluation metrics. Secondly, ad-hoc systems can improve upon the status quo, by proposing a number of different industrial ad-hoc systems.

6.1 Contributions

In Section 1 a number of related research fields and open research questions were described. The contributions to the research field and the questions answered by the research that was carried out are presented in this section.

This work contributed to three different field.

1. **Industrial automation**
   To the field of industrial automation new types of networks are introduced. These new wireless networks enable communication in challenging scenarios and are specialized to offer novel functionality an fulfill application-specific requirements. Additionally new tools for the simulation and modelling of these networks are provided. Such tools are necessary, since the decision to implement certain communication technologies often hinges on the predictions made by such models. The developed tools and methods enable these predictions.
   Lastly new control methods for mobile devices are proposed. These control methods enable he mobile devices in assisting the network infrastructure or other networked devices and providing communication opportunities in cases of incomplete network coverage. These control methods are specifically designed to fulfill the requirements of industrial applications and environments.
2. **Mobile ad-hoc networks**
   The field of MANETs is a very well established research field. In the last years MANETs have been applied to more and more specialised application (e.g. underwater networks or vehicular networks). The proposal to use this type of network in the industrial context is a new type of these specialised networks. In this work methods and systems are introduced, that regard the implementation of MANETs in industrial applications but also methods and tools that enable further and more efficient research regarding this application. This especially includes tools, methods and models to simulate industrial MANETs.
   Additionally novel observations were made in industrial applications, which can help shaping the nature of future industrial networks. The methods of these observations were specifically developed for the industrial use case.
3. **Network simulation and modelling**
   Network simulation and modelling is a wide and challenging field. In the context of this work the simulation and modelling of mobile wireless networks is particularly relevant. Many of the commonly used tools and models are not suit-

able for the simulation of special applications. This includes models for the signal propagation and the node mobility. A specific focus was on providing a novel model architecture, which enables the simulation of mobile nodes, whose mobility behavior can react to the simulated wireless network. The models and model parameters provided in this work were validated using operational validation.

A number of open research questions were asked in Section 1. Answering some of these research questions in great detail and to provide solutions to the related challenges was possible within this work.

The questions "*What metrics can represent the impact of communication technologies and their effect on the effectiveness of mobile robots?*" and "*Which methods are suitable to simulate/estimate/predict the effects of the communication technology?*" were answered by developing new simulation models and tools. These tools enable the investigation of industrial MANETs and DTNs. They are able to analyze these systems in terms of other metrics that are specifically relevant to the industrial application and the use case of AGVs, for example the number of completed transport tasks per hour per AGV.

Novel systems were proposed as answers to the questions "*Can ad-hoc networks provide a real-time channel for inter-robot communication*" and "*How can the mobility of the clients be controlled to optimize the coverage of the network in a factory environment.*". These systems are not perfect, but a first step in answering these questions. In the process of developing these systems new methods were introduced and requirements and conditions were defined, which will help future researcher to further improve upon these systems and propose more efficient and effective ways to answer these research questions.

Lastly the question of "*How can mobile robots in industrial applications effectively utilize ad-hoc networking technologies?*" could only be answered in parts. Different networking strategies and communication technologies were investigated, but the most effective way to utilize ad-hoc communication is highly dependent on the application and the framing requirements, therefore a final and full answer to this question seems unlikely. We hope, that the provided tools, methods and insights enable future researchers to find more answers to this question.

6.2 Future Work

The future of ad-hoc communication in the industrial use case can hardly be predicted. New use cases, technologies and trends emerge daily. In the different sections of this work we gave visions on future improvements to the discussed systems and methods. In this section however a more general view on the development of wireless ad-hoc communication in industrial use cases shall be discussed.

Current trends in industrial communication are Time Sensitive Networks (TSNs) and for example 5G. The inclusion of these technologies to different industrial plants and systems and design recommendations for these systems are currently very present in academical literature. Ad-hoc system mostly gain in importance in the context of Wireless Sensor Networks (WSNs), which are used for condition monitoring and predictive maintenance in industrial applications. Another trend is the inclusion of more powerful communication technologies to the factory floor.

These new technologies often use very high carrier frequencies ($\geq 50GHz$) this limits the range of the communication technology due to signal attenuating obstacles. The challenge of guaranteeing coverage will become increasingly difficult. The number of required APs for full coverage of the industrial plant would be impractical. P2P communication solutions will likely be required for communication technologies like Visible Light Communication (VLC) and radar.

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Affidavit

I hereby confirm that my thesis entitled "Development, Simulation and Evaluation of mobile wireless Networks in Industrial Applications" is the result of my own work. I did not receive any help or support from commercial consultants. All sources and / or materials applied are listed and specified in the thesis.

Furthermore, I confirm that this thesis has not yet been submitted as port of another examination process neither in identical nor similar form.

Würzburg, the 12.07.2022 Christian Sauer

Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, die Dissertation "Entwicklung, Simulation und Bewertung vonmobilen kabellosen Netwerken in Industriellen Anwendungen" eigenständig, d.h. insbesondere selbständig und ohne Hilfe eines kommerziellen Promotionsberaters, angefertigt und keine anderen als die von mir angegebenen Quellen und Hilfsmittel verwendet zu haben.

Ich erkläre außerdem, dass die Dissertation weder in gleicher noch in ähnlicher Form bereits in einem anderen Prüfungsverfahren vorgelegen hat.

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