
Karl Christian Lautenschläger

Suitability of Modern Wi-Fi for Wireless-Infield-Communication of Agricultural Machines

Diploma Thesis in Information Systems Engineering

30 March 2023

Please cite as:

Karl Christian Lautenschläger, "Suitability of Modern Wi-Fi for Wireless-Infield-Communication of Agricultural Machines,"
Diploma Thesis (Diplomarbeit), Faculty of Computer Science, TU Dresden, Germany, March 2023.

Suitability of Modern Wi-Fi for Wireless-Infield-Communication of Agricultural Machines

Diploma Thesis in Information Systems Engineering

vorgelegt von

Karl Christian Lautenschläger

geb. am 29. Juni 1998
in Magdeburg

angefertigt an der

**Technischen Universität Dresden
Fakultät Informatik
Networked Systems Modeling**

Betreuer: **Christoph Sommer**
Gutachter: **Christoph Sommer**
Burkhard Hensel

Abgabe der Arbeit: **30. März 2023**

Erklärung

Ich versichere, dass ich die Arbeit ohne fremde Hilfe und ohne Benutzung anderer als der angegebenen Quellen angefertigt habe und dass die Arbeit in gleicher oder ähnlicher Form noch keiner anderen Prüfungsbehörde vorgelegen hat und von dieser als Teil einer Prüfungsleistung angenommen wurde.

Alle Ausführungen, die wörtlich oder sinngemäß übernommen wurden, sind als solche gekennzeichnet.

Declaration

I declare that the work is entirely my own and was produced with no assistance from third parties.

I certify that the work has not been submitted in the same or any similar form for assessment to any other examining body and all references, direct and indirect, are indicated as such and have been cited accordingly.

(Karl Christian Lautenschläger)

Dresden, 30 March 2023

This template is for use with `pdflatex` and `biber`. It has been tested with TeX Live 2020 (as of 25 Oct 2020).

Abstract

about 1/2 page:

1. Motivation (Why do we care?)
2. Problem statement (What problem are we trying to solve?)
3. Approach (How did we go about it)
4. Results (What's the answer?)
5. Conclusion (What are the implications of the answer?)

The abstract is a miniature version of the thesis. It should be treated as an entirely separate document. Do not assume that a reader who has access to an abstract will also have access to the thesis. Do not assume that a reader who reads the thesis has read the abstract.

Kurzfassung

Gleicher Text (sinngemäß, nicht wörtlich) in Deutsch

Contents

| | |
|--|-----------|
| Abstract | iv |
| Kurzfassung | v |
| 1 Introduction | 1 |
| 2 Fundamentals | 3 |
| 2.1 Wireless-Infield Communication | 3 |
| 2.2 Use Cases for Wireless-Infield Communication | 5 |
| 2.3 Wireless Lans according to IEEE 802.11 | 8 |
| 2.4 Related Work | 21 |
| 3 Analyzing Corn Harvest Process Data | 25 |
| 4 Field Measurements | 33 |
| 5 Simulation | 39 |
| 5.1 Data Rate | 41 |
| 5.2 Robustness | 48 |
| 5.3 Platooning Services | 59 |
| 6 Evaluation | 67 |
| 7 Conclusion | 68 |
| Bibliography | 76 |

The table of contents should fit on one page. When in doubt, adjust the tocdepth counter.

Chapter 1

Introduction

- general motivation for your work, context and goals.
- context: make sure to link where your work fits in
- problem: gap in knowledge, too expensive, too slow, a deficiency, superseded technology
- strategy: the way you will address the problem
- recommended length: 1-2 pages.

With the growing demand for increased efficiency and autonomy in the agricultural domain, Wireless-Infield Communication (WIC) has emerged as a key technology to increase the automation and digitalization of agricultural processes. WIC describes a wireless connection between agricultural machines in the field that enables the exchange of process data.

Given that there are many different agricultural technology companies worldwide, and a mix of their machines often cooperate in the individual agricultural company, demand for interoperability between agricultural machines of different brands has emerged. In 2008, the Agricultural Industry Electronics Foundation (AEF) was founded to develop and standardize this interoperability ¹.

The AEF has defined a binary unit system, the ISO 11783 standard, for agricultural machinery communication, mainly tractors and implements [1]. According to Schlingmann and Benishek [2], the ISO 11783 standard is known as the ISOBUS system.

The authors mention that the AEF is currently working on other issues. Among them is also WIC. The associated project group WIC develops and standardizes solutions for Machine-To-Machine (M2M) wireless communication between cooperating agricultural machines.

¹<https://www.aef-online.org/about-us/about-the-aef.html>

In order to implement WIC, the WIC project group has been searching for a suitable technology that can realize the required data rates, latencies, robustness, and high transmission range. The plans to implement WIC are written down by members of the WIC project group in [3]. The authors consider the fundamental use of cellular networks as very problematic because, according to [4], only 30 % of the land surface has network coverage. For this reason, one major concern is that the required data cannot be exchanged because there is no network connectivity around many fields. Nevertheless, the authors want to leave the future WIC system open to cellular standards.

The authors' current focus is on Wi-Fi technologies, which must first be evaluated for use in the agricultural environment.

In my final thesis, I intend to support the progress of the WIC project group and investigate how modern Wi-Fi can enable WIC. In particular, I will focus on the current Wi-Fi standard, IEEE 802.11ax. During my research, I will study the use cases of WIC in agriculture and the requirements and challenges for WIC in agriculture. In order to analyze the suitability of IEEE 802.11ax to enable WIC, I will concentrate on the example use cases Agricultural Platooning Service and Video Streaming Service. Agricultural Platooning Service enables the exchange of process data to guide a vehicle in a platoon with a lateral and longitudinal offset to a leading vehicle. Video Streaming Services exchange video data to enable the driver to see the remote content of screens and cameras of other vehicles in the field.

In the beginning, I will analyze agricultural process data to find the requirements and challenges of the mentioned use cases. I will complement these with insights from past research on WIC in agriculture and wireless technologies in the agriculture domain in general.

The suitability of IEEE 802.11ax for WIC depends on whether the required data rates, latencies, robustness, high transmission ranges, and robustness in the harsh agricultural environment can be achieved.

By understanding past limitations of Wi-Fi technologies for outdoor communication networks and exploring how IEEE 802.11ax addresses these limitations, I will investigate how IEEE 802.11ax can be configured. For this purpose, I will first simulate how the capabilities of IEEE 802.11ax affect the data rate and the robustness of the wireless connection. After learning suitable parameter settings for the physical and MAC layer of IEEE 802.11ax, I will simulate the use cases Agricultural Platooning Service and Video Streaming Service to determine whether the requirements and challenges of the WIC use cases can be met by IEEE 802.11ax.

Add Field experiments to the thesis plan.

Chapter 2

Fundamentals

- describe methods and techniques that build the basis of your work
- include what's needed to understand your work (e.g., techniques, protocols, models, hardware, software, ...)
- exclude what's not (e.g., anything you yourself did, anything your reader can be expected to know, ...)
- review related work(!)
- recommended length: approximately one third of the thesis.

2.1 Wireless-Infield Communication

Since 2014, the WIC project group has been working on the development of a for WIC standard, which covers a standard for machine-to-machine communication, encryption, and security ². Schlingmann and Benishek [2] summarize the goals of the WIC project team as follows:

- Define use cases for WIC in agriculture
- Evaluate the suitability of communication technologies
- Find suitable communication protocols
- Standardize the WIC common software library
- Develop functional and security requirements and concepts
- Test first prototypes in regards of cross-brand comformance

²<https://www.aef-online.org/about-us/teams.html>

- Write a application guideline

First steps have already been taken in this direction. The use cases and key scenarios are defined and explained by the authors as follows:

- **Real-Time Machine-to-Machine Control** is the exchange of control data under real-time conditions with defined latency policies. This use case enables leader-follower scenarios where agricultural machines follow a leading agricultural machine at a lateral and longitudinal distance. Throughout this thesis, I will refer to Real-Time Machine-to-Machine Control as Agricultural Platooning Service.
- **Streaming Services** are communications that stream video from remote cameras and monitors at a high data rate and low latency. The authors estimate the distance between the communication participants to be less than 100 m. As a result, this data is available on another agricultural vehicle and can be analyzed and processed there. I will refer to Streaming Services as Agricultural Streaming Services in this thesis.
- **Process Data Exchange** describes the exchange of process data. One example is the exchange of already sprayed field areas to prevent multiple spraying of fertilizers and pesticides on the same field area by different machines. According to the authors, this WIC use case requires long-range technologies because agricultural fields worldwide can be vast.
- **Fleet Management & Logistics** is the potential retrieval of data from the ongoing agricultural process. This information can influence economic or agronomic decisions of agricultural enterprises or service companies and is therefore required in a Farm Management Information System (FMIS). Since not all agricultural machines may be connected to the FMIS, the WIC project group is looking at how to use M2M communications to bridge the missing communications infrastructure until the data reaches a machine that can connect to the FMIS.
- **Road Safety** describes a use case which is already a project between the European Telecommunication Standard Institute and the AEF. Since agricultural vehicles are repeatedly underestimated in their size and speed by other road users when they suddenly turn off the field onto the road, the other road users need to be warned in this situation. In this way, smart technologies in cars and motorcycles can brake these vehicles in advance and prevent possible accidents.

Considering that I investigate the Suitability of modern Wi-Fi for Wireless-Infield-Communication and modern Wi-Fi like Wi-Fi 6 is no long range technologies, I

will focus on investigating the suitability of these two Wi-Fi standards for the WIC use cases Real-Time Machine-to-Machine Control and Streaming Services. Throughout this thesis, I will refer to real-time machine-to-machine control as Agricultural Platooning. An example how farmers can benefit from Streaming Services or Agricultural Platooning Services is the corn harvesting and loading process.

2.2 Harvest and Loading Processes as Use Cases for Wireless-Infield Communication

The Forage harvester has proven to be an essential agricultural machine for harvesting and loading forage. Seifert, Grimm, and Schurig [5] define a forage harvester as an agricultural loading machine for nearly all types of animal feed. According to the authors, a forage harvester can load the following animal feed by mounting different cutting and loading devices: Hay, Straw, Corn, Grass and Clover.

In the harvesting and loading process, a Transport Machine (TM) typically drives alongside or behind the Forage Harvester (FH) so that the FH can load the harvested goods onto the trailer of the TM using the spout. Drivers operate both machines and try to keep the speed and distance so that the spout only throws the harvested goods into the trailer of the TM. An image of a corn harvesting and loading process can be seen in Figure 2.1.

Taking a corn harvest scenario as an example, some key figures are represented in [6], a standard reference book in agricultural literature. This book contains key figures of agricultural processes, which 80 experts have compiled. The key figures, which are shown in Table 2.1, are dependent on the Plant Density (PD) and show the large amount of forage harvested by a FH every hour.

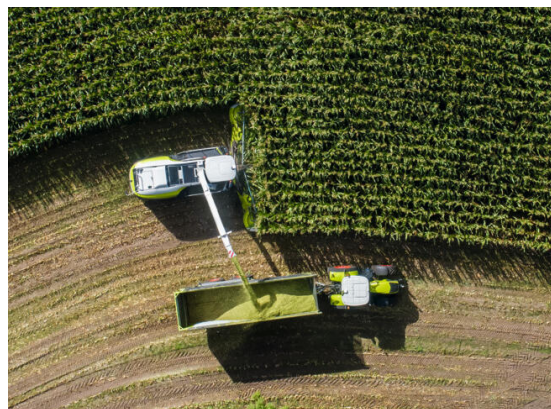


Figure 2.1 – Forage Harvester (FH) and Transport Machine (TM) in a corn harvesting and loading process

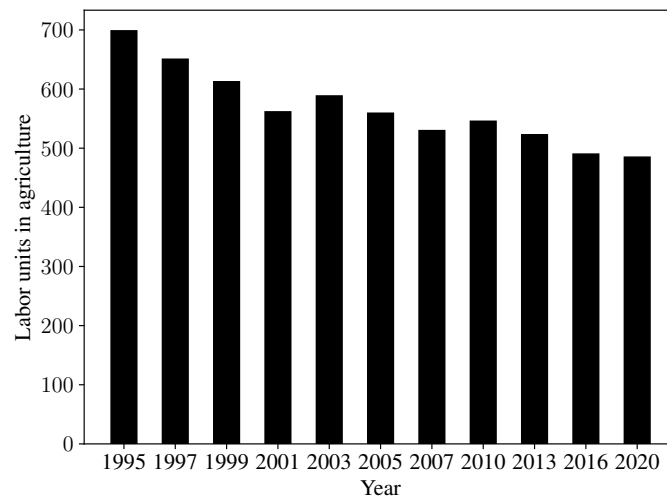


Figure 2.3 – Decrease in the agricultural labor force in Germany based on the data from [9]

Smolnik and Lücke [10] adds that platooning services at the platoon level can reduce FH drivers' workload so that they can focus on optimally adjusting the machines. In addition, TMs can be guided to the FHs in a targeted manner so that logistics processes in the field can be improved.

At the same time, the harvest and loading processes are examples of the video streaming WIC use case, where a video of the TM's filllevel is available at the FH and could be transmitted to the TM in order to inform the TM driver about the machines filllevel. During these harvest and loading processes, the spout of the FH must be controlled to set the loading position of the forage into the trailer of the TM.

According to Murcia [11], different spout guidance and control systems have been developed to automate the filling of the trailer. Spout guidance and control systems use a camera attached to the spout to determine the fill volume at each point of the trailer via machine vision and set the spout to fill the empty parts accordingly. The author describes Autofill - systems from Claas and Intellifill - systems from CNH Industrial as examples of spout guidance systems.

Streaming the video of a camera at the spout from the FH to the TM would be a practical application of the video streaming use case in the harvesting process. If the TM driver can watch a live stream of the trailer's fill level, he will always be informed and knows when the trailer is full and can drive the forage back to the farm.

2.3 Wireless Lans according to IEEE 802.11

According to Kauffels [12] the first version of the Standard IEEE 802.11 was published in 1999 to enable a wireless alternative to Ethernet - or Token-Ring - networks. Sauter [13] considers IEEE 802.11 also to be an implementation of Ethernet with the help of wireless radio technologies. The author lists the extensions to the original standard, which range from 802.11b, 802.11g, 802.11a, 802.11n, 802.11ac to the latest enhancement 802.11ax. The different IEEE 802.11 standards can operate in the 2.4 GHz - , 5 GHz and 6 GHz - frequency band. IEEE 802.11n is also known as High-Throughput (HT) Wi-Fi, IEEE 802.11ac as Very-High-Throughput (VHT) Wi-Fi [14] and IEEE 802.11ax as High-Efficiency (HE) Wi-Fi [15]. The standards are known by these names. In addition, they are also called Wi-Fi 4, Wi-Fi 5 and Wi-Fi 6 respectively. Jacob et al. [16] fügt dazu noch hinzu, dass es zusätzlich noch die zwei Erweiterungen IEEE 802.11p und dessen Nachfolger IEEE 802.11bd gibt. Diese operieren in einem reservierten Frequency spectrum for Vehicle-to-everything (V2X) nach den Autoren im 5.9 GHz frequency spectrum

Kauffels [12] defines the following three basic architectures for IEEE 802.11.

If two or more stations communicate directly without an AP, they form an ad hoc network. According to the author, this can be set up quickly and easily and is also called Independent Basic Service Set (IBSS).

The Infrastructure Basic Service Set (BSS) mode allows all stations within the range of defined range around the Access Point (AP) to communicate via a central AP. Within the area of the BSS, all stations can move freely and communicate with one another.

Since an AP has limited range and can only cover a certain area, the Extended Service Set (ESS) was introduced. It contains a distribution system, which links several BSS with each other.

Thereby, the BSS coverage areas can physically overlap so that continuous connection of stations within the ESS can be provided. For a better performance the BSS can be placed physically on top of each other. One can also have physically separate BSSs so that these BSSs can be linked together over long distances. According to the author, the standard does not specify a distance limit for such connections.

He also mentions, that the standard defines the following three mobility types for station in an ESS, where a station can do no-transition and thereby stay within a BSS, BSS-transitioning and move from one BSS to another BSS within the same ESS and ESS-transition, where the Station moves from a ESS to another one but no stable connection can be guaranteed.

Sauter [13] adds, that usually Ethernet is used to link APs in within an ESS. But according to the author this can be replaced by a wireless connection, which is called wireless bridge.

To enable communication between Wifi devices, the IEEE 802.11 standard defines the following layers of the OSI model. The first layer is the physical layer.

Wi-Fi Physical Layer

A constant change of the physical layer accompanies the further development of IEEE 802.11. Sauter [13] mentions that all new enhancements of the physical layer of IEEE 802.11 are backward compatible with previous definitions of the standard.

According to the Author, IEEE 802.11 initially used DSSS and FHSS as modulation methods. Since IEEE 802.11g the modulation method Orthogonal Frequency-Division Multiplexing (OFDM) can be used in the 2.4 GHz frequency band. The author explains OFDM as follows. OFDM divides the transmission channel into subcarriers with different amplitudes, frequencies and phases. Each subcarrier is orthogonal to another one, as they send the information “Low“, where only one other subcarrier is sending the information “High“.

Symbol length

The data is then sent as OFDM symbols over the individual OFDM subcarriers. The distance between the “Highs“ of the subcarriers is specified as subcarrier spacing and corresponds to the reciprocal symbol length. IEEE 802.11ax increased the OFDM symbol length from 3.2 μ s for IEEE 802.11n to a maximum of 12.8 μ s [13]. This corresponds to a subcarrier spacing of 312.5 kHz and 78.125 kHz respectively [13].

For the IEEE 802.11p and IEEE 802.11bd standards, a symbol length of 6.4 μ s applies, corresponding to a subcarrier spacing of 156.25 kHz [16].

The Fast Fourier Transform and Inverse Fast Fourier Transform are used to modulate and demodulate the transmitting bits. With the reduction of subcarrier spacing, more subcarriers are created in the transmission channel, so the Fast Fourier Transform size must be increased.

Kauffels [12] adds, that OFDM can be used in the 5 GHz frequency band since IEEE 802.11a.

Bandwidth (BW)

The frequency bands were divided into channels in order to create several transmission channels. This results in 13 channels in Europe in the frequency band of 2.412 GHz... 2.482 GHz and 18 channels in the frequency band of 5.180 GHz... 5.350 GHz and 5.180 GHz... 5.350 GHz [13]. Transmission channels can be combined to enable higher data rates. Every channel has a width called BW and is specified in MHz. The possible BWs for the IEEE 802.11 standards are shown in Table 2.2.

| Standard | Channel BWs in 2.4 GHz | Channel BWs in 5 GHz | Channel BWs in 5.9 GHz |
|-----------------------|---------------------------|------------------------------------|---------------------------|
| IEEE 802.11n [13] | 20 MHz, 40 MHz | 20 MHz, 40 MHz | - |
| IEEE 802.11ac [14] | - | 20 MHz, 40 MHz, 80 MHz, 160 MHz | - |
| IEEE 802.11ax [15] | 20 MHz, 40 MHz | 20 MHz, 40 MHz, 80 MHz, 160 MHz | - |
| IEEE 802.11p [16] | - | - | 10 MHz |
| IEEE 802.11bd [16] | - | - | 10 MHz, 20 MHz |

Table 2.2 – Available BWs for the IEEE 802.11 standards per frequency band.

IEEE 802.11ac and IEEE 802.11ax enable also the use of a discontinuous BW, which combines two 80 MHz channel to a 160 MHz BW channel [15], [14].

While wider channels increase the theoretical data rate, Avallone et al. [17] mentions that narrower channels can boost the signal's power spectral density and thus increase the transmission range.

Modulation and Coding Scheme (MCS)

In order to encode as many bits as possible on one OFDM symbol, different MCSs can be used. The MCSs for the IEEE 802.11 standards are based on Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM). [12]. The smallest MCS is Binary - PSK and encodes 1 bit per symbol. IEEE 802.11ax has the most complex MCS of 256 - QAM IEEE 802.11ac to 1024 - QAM and thus now encodes 10 bit per symbol [18]. In the V2X range, so can MCSs from binary-PSK to 256- QAM.

An imaginary, theoretical transmission channel is usually specified as a square-wave signal in the frequency domain with limits of both minimum and maximum amplitude and cut-off frequency. Kauffels [12] defines the roll-off factor as a cosine-shaped flattening of the square signal between 0 and 1. In addition, the author points out that QAM can generate high roll-off factors so that signals interfere significantly more with adjacent channels.

In this regard, the author recommends setting the parameters in an OFDM system so that first, the coding rate and then the complexity of the MCS is reduced in challenging transmission environments. The more bits a MCS encodes on a symbol, the more error-prone the correct decoding.

Forward Error Correction (FEC)

Nevertheless, bit errors can occur during transmission. In this regard, [12] mentions and explains FEC as a technique to reduce bit errors during transmission. FEC adds redundant bits to the data. The receiver uses these redundant bits to check the integrity or correct errors of the received data. The proportion of non-redundant transmission bits is defined in the Coding Rate (CR).

To achieve this, binary convolutional coding (BCC) is used mandatory since the IEEE 802.11n standard [18], [19]. Syafei et al. [19] add that it is optionally possible to use low-density parity-check (LDPC). The authors state that LDPC can achieve a better channel capacity performance. This impact is also confirmed by Afaqui, Garcia-Villegas, and Lopez-Aguilera [18], who point out that LDPC also generates higher computational cost.

IEEE 802.11ax stations must support LDPC when using the IEEE 802.11ax standard under the following conditions [15], [18] :

- The used bandwidth is greater than 20 MHz
- The chosen MCS is 1024-QAM
- More than four transmission channels are used for the transmission.

IEEE 802.11ax achieves CR of $\frac{1}{2}$, $\frac{2}{3}$, $\frac{3}{4}$, and $\frac{5}{6}$ [15]. Similarly, IEEE 802.11p uses the BCC technique, which has been superseded by LDPC in its successor IEEE 802.11ax [16], [20]. Yacheur, Ahmed, and Mosbah [20] argue that this step was important, as LDPC offers better error correction possibilities for higher communication ranges greater than 50 m.

Together with the MCS, the FEC CR form a physical layer specification, which is named after the specific standard. For IEEE 802.11ax, this results in the HE-MCS values in Table 2.3.

Guard Interval (GI)

Pulimamidi, Nulu, and Tahernezehadi [21] explain the Guard Interval as a cyclic prefix of OFDM symbols before Inter Symbol Interference and through Inter Carrier Interference. Inter Symbol Interference is caused by multipath delays, where the reflected delayed previous symbol can interfere with the currently received symbol [22]. Similarly, Inter Carrier Interference is caused by time-varying channel resulting in a longer OFDM symbol duration [23].

Pulimamidi, Nulu, and Tahernezehadi [21] explain how a guard interval can prevent these interferences. Since the guard interval is to prevent possible interference on the following symbol, it must be at least long enough to catch all channel impulse responses with the resulting delay in the guard interval. The guard interval is then

| HE-MCS index | Modulation and Coding Scheme (MCS) | Coding Rate (CR) |
|--------------|------------------------------------|------------------|
| 0 | Binary PSK | 1/2 |
| 1 | Quadrature PSK | 1/2 |
| 2 | Quadrature PSK | 3/4 |
| 3 | 16-QAM | 1/2 |
| 4 | 16-QAM | 3/4 |
| 5 | 64-QAM | 2/3 |
| 6 | 64-QAM | 3/4 |
| 7 | 64-QAM | 5/6 |
| 8 | 256-QAM | 3/4 |
| 9 | 256-QAM | 5/6 |
| 10 | 1024-QAM | 3/4 |
| 11 | 1024-QAM | 5/6 |

Table 2.3 – MCS and CR for HE-MCS values [15]

removed again at the receiver. This results in an attenuation of bandwidth which can be described by the following formula:

$$\text{GI_Bandwidth_Attenuation} = \frac{\text{OFDM_symbol_duration} \times 100}{\text{OFDM_symbol_duration} + \text{GI}}. \quad (2.1)$$

Since IEEE 802.11n, a shortened GI of 400 ns is usable, which increases the maximum data rate from 270 Mbit/s to 300 Mbit/s compared to the usual GI of 800 ns [13]. IEEE 802.11ax supports GIs of 800 ns, 1600 ns and 3200 ns to enable better protection against multipath effects in indoor and outdoor communications [24].

No condition for the use of the different GI is mentioned in [24], [25], [26] or [18]. Moreover, the sources mentioned only specify a OFDM symbol length of 12.8 μ s.

Nevertheless, the standard IEEE 802.11ax [15] specifies the following rules for using the different GIs. A 1600 ns GI can only be used with a symbol length of 6.4 μ s. The same applies to a GI of 800 ns, with the optional extension for use with a symbol length of 3.2 μ s. A GI of 3200 ns can only be used for a symbol length of 12.8 μ s.

Dual Carrier Modulation (DCM)

To introduce additional robustness DCM can be applied to the physical layer since IEEE 802.11ax [16], [27], [15]. Jacob et al. [16] describe DCM as sending data twice over two coherent carriers. At the receiver, the data copies are combined with the log-likelihood ratio. Thus DCM increases the probability of receiving the data.

[15] provides a receiver minimum input sensitivity, which indicates until which RSS a packet is received with a probability of 90 %. The receiver minimum input sensitivity for a BW of 20 MHz is displayed in Figure 2.4. It demonstrates that when

using DCM, the receiver minimum input sensitivity can be lower than without using DCM. The effect on the receiver minimum input sensitivity increases as the HE-MCS value increases.

A similar development of the receiver minimum input sensitivity can also be observed for higher BW, except that the lowest value increases with BW.

The higher probability of achieving data is achieved at the expense of the data rate. The same amount of data now takes twice as long to transmit.

[15] lists the theoretically possible data rates. These reveal that the maximum achievable data rate with DCM is only half of the attainable data rate without DCM.

Support for DCM is only optional in the IEEE 802.11ax standard and can only be used for HE-MCS-0, HE-MCS-1, HE-MCS-3 and HE-MCS-4 for 1...2 spatial transmission streams [15].

Jacob et al. [16] and Triwinarko, Dayoub, and Cherkaoui [27] mention plans, to allow using DCM in the physical layer of IEEE 802.11bd.

Extended Range

Since IEEE 802.11ax, the Extended Range Mode exists, which defines the new HE ER SU Physical layer convergence protocol data unit (PPDU) as physical layer amendment [15], [18]. Deng et al. [24] explains that the HE ER SU PPDU format

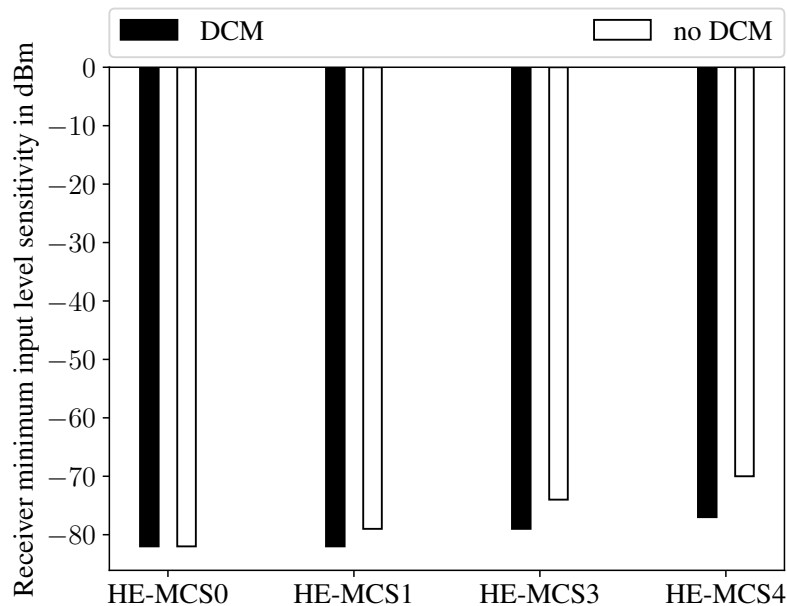


Figure 2.4 – Receiver minimum input level sensitivity for different HE-MCS values according to [15], where packet error rate (PER) is less than 10 %

is intended to extend the range of a single station to access point transmission. According to the authors, this is accomplished by the PPDU containing a repetition of the HE-SIG-A field.

In addition, the authors explain that the preamble transmission power is boosted, to guarantee reliable transmission for longer ranges. The power-boost is limited to additional 3 dB in [15], [16]

The IEEE 802.11ax [15] standard defines that the HE ER SU PPDU format may only be used when 20 Mhz transmissions with either 242-Resource Unit with HE-MCS-0 - HE-MCS-2 or 106-Resource Unit with HE-MCS-0 are used on a spatial stream. In addition, one can use DCM. Sauter [13] defines the Resource Unit as fragments of a wi-Fi channel. The number before the Resource Unit indicates the number of subcarriers, which are part of the Resource Unit.

Optionally, the HE ER SU PPDU may also be transmitted with a GI of 800 ns, where an additional application of DCM is forbidden.

Jacob et al. [16] and Triwinarko, Dayoub, and Cherkaoui [27] add, that it is planned to use the extended range mode also in the IEEE 802.11bd standard.

Multiple Input Multiple Output (MIMO)

In order to further exploit the physical layer capabilities, the single transmitting and receiving antenna systems called Single-Input-Single-Output can be extended to MIMO - systems. Sauter [13] describe the idea behind MIMO as the usage of multiple transmit antennas and multiple receiving antennas. Spatial multiplexing is used so that the transmitted signals from each antenna are reflected differently on objects and can thus be received from different directions at the receiver antennas.

The authors explain that since IEEE 802.11n, it is possible to use up to 4 MIMO streams. This number was increased again to up to 8 MIMO streams in IEEE 802.11ax [15]. Since data can be sent simultaneously via each MIMO stream, the theoretical data rate can thus increase proportionally depending on the usable streams. The mechanism is called Single-User (SU)-MIMO [15].

Sauter [13] mentions, that since IEEE 802.11ac it is possible to use Downlink Multi-User (MU)-MIMO, which allows an AP to transmit data to multiple station (STA) via different available MIMO stream simultaneously. According to the authors, MU-MIMO can increase the network throughput. IEEE 802.11ax introduced MU-MIMO in the Uplink direction [15], where multiple STA can transmit data simultaneously to the AP via different available MIMO streams. MU-MIMO DCM can also be applied in IEEE 802.11ax [15].

Another MIMO technique is Orthogonal Frequency-Division Multiple Access (OFDMA), which can be utilized since IEEE 802.11ax [15], [17], [28]. Avallone et al. [17] explains, OFDMA enables an AP to transmit data to multiple STA simultaneously

by dividing the available bandwidth into Resource Unit (RU) and assigning each RU to a STA. The authors add, that OFDMA can be used in both the uplink and downlink direction. The AP can choose the best suited RU for each STA and thus increase the Signal-to-Interference-plus-Noise Ratio [29] Behara and Venkatesh [30] adds, that OFDMA is designed to improve the per-user throughput in high-density networks, e.g. stadiums, airports or public transportation systems.

Space-Time-Block-Code (STBC)

Abbas et al. [31] further explains that MIMO spatial streams can be utilized to enhance the quality of the received signal. The Technology is called STBC. Santumon [32] explains as follows. STBC is a technique used in Wi-Fi networks to improve the reliability and robustness of wireless communications. STBC encodes multiple redundant copies of data at the transmit side, which are transmitted in different spatial streams to reduce fading and interference effects. At the receiver side, these multiple copies are combined using a maximum likelihood detector to retain a high-quality signal and decrease the packet error rate (PER).

Here, Stamoulis and Al-Dhahir [33] has investigated the potential effect of STBC on Wi-Fi. Their simulations showed that STBC increase the range and robustness for IEEE 802.11a. In addition, the authors concluded that STBC increases the Signal Noise Ratio (SNR) in nearly all cases at the same throughput or even allows higher MCS values to be used, thus allowing a higher throughput at the same SNR. This results in STBC improving the reliability and robustness of wireless communications.

Ghosh et al. [34] analyzed the error rate performance for an increased number of used antennae and found that a lower bit error rate can be achieved when increasing the number of transmit antennas with STBC.

Gast [35] and Sauter [13] mention, that STBC can extend the signal range due to the increased robustness.

IEEE 802.11ax stations can optionally use STBC the following conditions [15]:

- DCM is not applied
- The number of spatial streams is 2
- The GI is not 0.8 ns and the symbol length is not 12.8 μ s

[35] states that STBC is only supported in one-fifth of the Wi-Fi-certified devices.

Wi-Fi Data Link Layer

The next layer in the OSI model is the Data Link Layer. The Data Link Layer consists of Medium Access - and Logic Link Control functionalities.

According to Kauffels [12], the medium access control functionalities cover network entry, authentication, and media access methods. The author explains that every AP send beacon frames periodically to synchronise its stations in the BSS and that the beacon frame contains the Service Set Identifier (SSID), which identifies the BSS or ESS of the station. Sauter [13] adds that a beacon frame contains a 16 bit - long capability information element. Each bit here signals that the AP provides a particular function or has a specific feature.

Kauffels [12] explains a station's network entry procedure. A station can use the passive or the active scanning mode. The station listens for a beacon frame in the various transmission channels in passive scanning mode. Alternatively, a station can also send out a probe frame in active scanning mode. This can contain an already known SSID to test the presence of the AP. To get an AP in range, the probe frame can also contain a broadcast SSID that causes all nearby APs to respond. The response of an AP to the probe frame is the probe-response frame, which contains the same information as a beacon frame. With the information from the beacon frame, a station can start the authentication process.

For this process, Kauffels [12] names the two methods Open System Authentication and Shared Key Authentication. Sauter [13] explains that Open System Authentication is based on a device making an authentication request to the AP. If the AP answers with a positive status in the Authentication Frame, the station is included in the BSS. The actual encryption and authentication is then performed by the Wi-Fi Protected Access (WPA) functions. The author points out that Shared Key Authentication is no longer used today. Sommer and Dressler [36] adds that this authentication process differs for the Ad-Hoc mode, where every station can authenticate new stations.

After the authentication process, the station receives a time-synchronisation function with a timestamp, the physical layer parameter configuration and the SSID of the BSS or ESS. The STA can start the media access method now.

The IEEE 802.11 standard describes the two media access methods Distribution Coordination Function (DCF) and Point Coordination Function (PCF).

Sauter [13] explains that DCF is based on the media access method Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). In CSMA/CA, a device willing to transmit senses in the air transmission medium for a transmitting activity. If no other device is transmitting, the device can transmit. In transmitting activity, the terminal must wait at least until the transmission and the Interframe Space (IFS) are over. Various access priorities are implemented by different IFS lengths [36]. Since data transmission via the air transmission medium is very vulnerable to errors, the standard IEEE 802.11 requires that each received unicast packet must be confirmed with an Acknowledgement (ACK) frame [36]. The DCF IFS ensures that an ACK frame can be sent before another station uses the same channel to

OFDM? Keine Erklärung aber eigentlich auch ausreichend. würde mir eine kürze Arbeit ermöglichen

send a data frame. To avoid multiple devices transmitting at the same time after Distributed Coordination Function Interframe Space (DIFS), each ready-to-transmit device determines a random backoff time from a time interval called the contention window. The device with the shortest backoff time transmits next, and all other ready-to-transmit devices restart the media access procedure. If two devices start sending next because they randomly chose the shortest backoff time, the transmitted signal will interfere, and the packets will not be answered with an ACK frame. Sommer and Dressler [36] adds that in case of such a faulty transmission, the contention window increases exponentially until the maximum value of retries is reached and the contention window size is reset to the starting value.

To share the knowledge of a transmission time and the subsequently IFS, a packet contains a Network Allocation Vector (NAV) that specifies the time the air transmission medium is used. Collisions can occur as the NAV information can be reset by other transmissions from a different, overlapping network. To avoid this, IEEE 802.11ax maintains two NAVs, one for intra-BSS and one for inter-BSS transmissions [15]

The extension IEEE 802.11e introduced a amendment of CSMA/CA called Enhanced Distributed Channel Access (EDCA) [36] [37]. According to Sommer and Dressler [36], EDCA provides a Quality-of-Service transmission procedure, which classifies 4 access categories. Each access category has a different minimum and maximum contention window sizes and different IFS lengths, named arbitration IFS. Wu et al. [37] explains that each access category keeps its own backoff counter and frame queue. Every access category is handled as an independent virtual station which tries to access the medium. When a collision of two transmissions of different access categories occur, and both contention windows are set to zero simultaneously, the EDCA mechanism ensures that the access category with the higher priority wins.

The four access categories are listed in Table 2.4.

EDCA is integrated into the modern IEEE 802.11 standard data link layer of IEEE 802.11ac[14] and IEEE 802.11ax [15].

| Access Category | Priority (1 = Highest) |
|-----------------|------------------------|
| Voice | 1 |
| Video | 2 |
| Best Effort | 3 |
| Background | 4 |

Table 2.4 – Access Categories and their priorities for IEEE 802.11e EDCA [37]

In various network architectures, the "hidden station"-problem may occur. As you can see in Figure 2.5, Station A cannot sense a transmission of station B and vice

versa. In case of simultaneous transmission of both stations, interferences around the AP may occur.

To prevent the hidden station problem, Sauter [13] explains that a STA can access the medium via the point coordination function. The STA sends a Request-to-Send (RTS) frame to the AP and waits for a Clear-to-Send (CTS) frame. After receiving the CTS frame, the STA has reserved the medium for a specific time and can send its data frame. The successful transmission of the data frame is confirmed with an ACK frame. To avoid another STA accessing the medium during the RTS and CTS frames, the PCF IFS is shorter than the DCF IFS. This allows the AP to send the CTS frame before another STA can access the medium.

Sauter [13] states that the point coordination function is usually not configured because it introduces additional overhead of the RTS and CTS frames, which is only worth it when the data frame is large.

Larger frames can also be split into smaller frames to reduce the probability of collisions. This procedure is called fragmentation, which divides the data in up to 16 frames when a certain data length threshold is exceeded [15]. The fragmented frames are transmitted by the three following different ACK policies in Figure 2.6, which are described by Sauter [13].

Using the normal ACK policy, the sender applies the DCF mechanism before sending each frame. Additionally, the sender waits for an ACK frame from the receiver after each transmission.

Instead of operating in the DCF mode, the sender can also send the next frame after waiting the Short Interframe Space (SIFS) time, when the ACK frame has been received. This is displayed in 2.6b and saves the overhead of acquiring the medium again.

Additional transmission time can be saved by using the Block ACK policy, which is shown in 2.6c. The sender sends the first frame and waits for the ACK frame. After

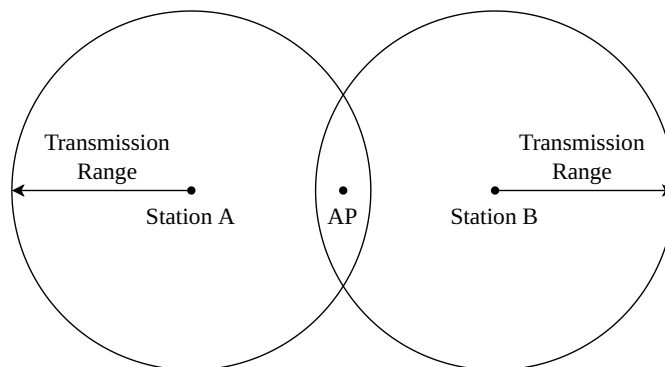


Figure 2.5 – Hidden Station Problem, where interferences at the Access Point (AP) can occur, when station (STA) A and B send simultaneously

transmitting all fragments, the sender sends the Block ACK request. The receiver sends the Block ACK frame, which contains the information of all received frames. Any missing frames are retransmitted. The Block ACK frame can be sent delayed, when some processing time is required.

Every Block ACK session is started with an add Block Acknowledgment (ADDBA) request frame, which is sent by the sender and contains the session parameters. The receiver sends an ACK and answers with an add Block Acknowledgment (ADDBA) response frame. After the sender acknowledges the response frame, the Block ACK session is established. The Block ACK session is ended with a delete Block Acknowledgment (DELBA) frame, which is sent by the sender and is acknowledged by the receiver.

The Block ACK policy can be used in IEEE 802.11n [14], IEEE 802.11ac [14] and IEEE 802.11ax [15]. In the IEEE 802.11p standard, the Block ACK policy can be added as an optional feature [14].

[29] Power Management Modes Enhanced Time TWT Enhanced Microsleep

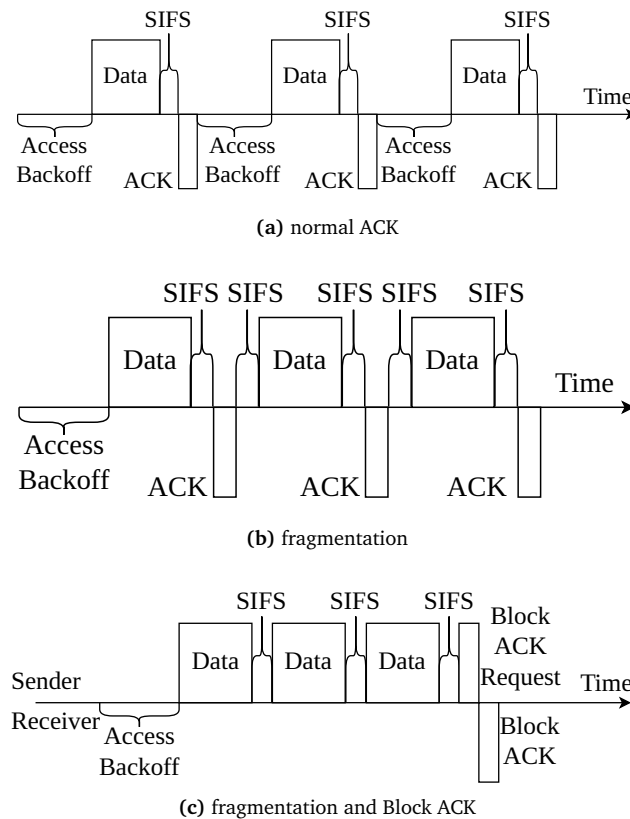


Figure 2.6 – Data transmission between a sender and receiver in regards to the time with normal Acknowledgement (ACK) 2.6a, fragmentation 2.6b and additional Block ACK 2.6c

Spatial Reuse Adaptive Power and Sensitivity Thresholds, BSS COlor
 Quiet Period
 Midamble Preamble
 more levels of fragmentation

IEEE 802.11ac - Wi-Fi 5

The 5th generation WLAN is IEEE 802.11ac (802.11ac) and operates in the 5 GHz frequency range [38].

According to Perahia and Gong [39], 802.11ac is a further evolution of IEEE 802.11n, where 802.11ac adds to the known bandwidth of IEEE 802.11n of 40 MHz the bandwidths 80 MHz, 160 MHz and the interrupted bandwidth of 80 MHz + 80 MHz.

nach Sauter [13] ist die Aufspaltung in zwei 80 Mhz Kanäle sehr nützlich, wenn das Frequenzband reservierte Regionen enthält. Dadurch kann ein 160 Mhz breiter Kanal um eine reservierte Region des Frequenzbandes gebaut werden.

The modulation technique used is OFDM. Additionally, a new MIMO Downlink functionality for multiple users, called DL MU-MIMO, with up to 8 partial streams is introduced according to the authors. Together with the new MCS from 64 QAM to 256 QAM, these three enhancements ensure that a higher data rate can be achieved. The maximum data rate is 6.9 Gbps according to the authors.

As declared by Abdelrahman, Mustafa, and Osman [40], the 5th generation of WLAN has made it possible to expect better performance as in addition to a longer communication range compared to the previous IEEE 802.11 standards. This statement could be proven at least for indoor range. Dhawankar, Le-Minh, and Aslam [38] were able to demonstrate that 802.11ac with a range of over 60 m enables a longer indoor communication range than previous IEEE 802.11 standards.

new Physical Layer Very High Throughput (VHT) Physical Layer
 80 Mhz
 Beamforming

IEEE 802.11ax - Wi-Fi 6

The 6th generation of WLAN is IEEE 802.11ax (802.11ax). Khorov et al. [29] reveals what has changed from 802.11ac to 802.11ax. For this, the authors make the following statements.

802.11ax uses the same bandwidths in the 5 GHz range and can also operate in the 2.4 GHz frequency range with a maximum bandwidth of 40 MHz. Similar to DL MU transmission, 802.11ax enables UL MU transmissions. These can also use OFDMA in addition to the already known MIMO of 802.11ac. OFDMA groups the orthogonal frequency subcarriers into RUs, which can be selected by the transmitter

for optimal transmission to the receiver. This increases the Signal-to-Interference-plus-Noise Ratio (SINR).

An extension in the PHY layer are the new MCS's of up to 1024-QAM. However, these should only be used with very good channel characteristics. For better outdoor communication 802.11ax increases the OFDM symbol duration from 3.2 μ s for 802.11ac to up to 12.8 μ s and the OFDM Guard Interval from a maximum of 0.8 μ s for 802.11ac to up to 3.2 μ s.

MIMO und OFDMA MU Streams

BSS Coloring

Backward Kompatibilität über CTS Reservierungen.

Tabelle Vergleich

| Parameter | IEEE 802.11ac | IEEE 802.11ax |
|----------------------------|---------------|-----------------------|
| Frequency bands | 5 GHz | 2.4 GHz, 5 GHz, 6 GHz |
| Symbol Length | 3.2 μ s | 12.8 μ s |
| OFDM Subcarrier Spacing | 312.5 kHz | 78.125 kHz |
| OFDM Subcarriers in 80 MHz | 256 | 1024 |
| max. MCS | 256 -QAM | 1024 -QAM |
| max. GI | 0.8 μ s | 3.2 μ s |

Table 2.5 – Comparison of IEEE 802.11ac and IEEE 802.11ax

2.4 Related Work

Since my undergraduate thesis ³ about *Wirelessly Networked Coordination of Automatic Section Control for Agricultural Machines*, I have been working on the topic of WIC. I conducted both field experiments and simulations to investigate the performance of LoRa as a technology to exchange process data in meshed Automatic Section Control, a prototypical application of connected vehicles in the agricultural domain. A summary of my results is published in a paper [41]. In my undergraduate thesis and paper, I described the current state of research in the field of WIC.

The first research paper on WIC that I found was from Ali [42]. The authors developed a system based on General Packet Radio Service (GPRS) to exchange

³<https://github.com/klautenschlaeger/mvsc>

position data between TMs and combine harvesters to guide empty TMs to a combine harvester.

Smolnik and Lücke [10] describes the research project *5G Netmobil* in which the authors investigated how existing technologies like IEEE 802.11 or 3GPP LTE can be integrated into 5G technologies to enable Agricultural Platooning Services. The research plan was to evaluate the use of User Datagram Protocol (UDP) and Basic Transport Protocol (BTP) to exchange guidance data via the underlying technologies 3GPP LTE and 5G V2X and IEEE 802.11p. The authors implemented a system using 802.11p, as according to their technical analysis, this technology already fulfils the requirements for data rate, latency and the number of participants. The authors report that the project results demonstrated that achieved latencies were five times lower than the defined maximum latency of 50 ms for Agricultural Platooning Services.

Further research on WIC is not based on cellular networks. Zhang et al. [7] used IEEE 802.15.4 to implement a prototype of an Agricultural Platooning Service, where the developed system exchanges relevant control data between a leading tractor to guide a following tractor.

Smolnik and Lücke [10] states, that the developed system of Zhang et al. [7] is part of the project *Elektronische Deichsel für landwirtschaftliche Arbeitsmaschinen (EDA)* and it was further improved within the scope of project *Elektronische Deichsel für landwirtschaftliche Arbeitsmaschinen mit Umfeldsensorik und zusätzlichen Geoinformationen (EDAUG)*.

Klingler, Blobel, and Dressler [43] investigated how IEEE 802.11p can be used for WIC. Experiments revealed that data could be exchanged over a maximum range of 1700 m, where Line-Of-Sight (LoS) was lost. But during the measurement in an agricultural work scenario from the corn harvest, there were collapses in the Received Signal Strength (RSS) due to shadowing effects of the machines. The authors point out that the size and shape of the forage harvester can cause intensified shadowing effects.

There are also more developments from the industry in the field of WIC. In this context, Thomasson et al. [44] describe the John Deere Machine Sync and Case IH V2V systems as follows:

John Deere Machine Sync enables the WIC use cases Process Data Exchange and Agricultural Platooning Service. Liu et al. [8] have extended the system to use Combine Harvesters, adding that the Machine Sync system is based on Metzler, Flohr, and Hoeh [45]’s patent. Smolnik and Lücke [10] adds that John Deere Machine Sync is only available for a subgroup of John Deere machine types and cannot be used with machines of other brands.

Case IH V2V also offers an agricultural platooning service. However, according to the authors, the system can only be used for harvesting and loading scenarios.

Also currently on the market is the Raven Autonomy™ Driver Assist Harvest Solution ⁴ system from Raven Industries. This system allows the harvester to take control of a TM from a distance of 70 m. The harvester then automatically guides the TM into the perfect position to load the harvested crop onto the TM via the spout. Once the harvesting and loading process is complete, the driver of the TM driver retakes control.

A comparable system is CartACE from AgLeader ⁵

The technology used in the mentioned systems is not known. In response to questions about how the systems can be used on farms worldwide and what prerequisites must be created for this, the manufacturers refer to the regional distribution options.

Wireless communication technologies are also used to implement wireless sensor networks in the agricultural domain.

According to Ahmed, De, and Hussain [46], wireless sensor networks in the agricultural domain can be used to monitor soil and water conditions, plant diseases, and farm automation solution or track animals or assets. The authors mention similar requirements for wireless sensor network applications compared to WIC applications. For example, asset-tracking applications require low latency and must support asset mobility. The authors' results indicate that fog computing can lessen the latency and the required bandwidth compared to cloud computing. When a higher data rate is required, the authors recommend wi-fi technologies like IEEE 802.11n or IEEE 802.11ac.

As wireless sensor networks for agricultural applications, they must be able to operate in the same agricultural environment as WIC applications. Brinkhoff and Hornbuckle [47] describe that they expect a limited cellular network coverage and complex outdoor environments with large water areas, different crop vegetation, and other obstacles or various weather conditions. The researchers developed a wireless sensor network based on IEEE 802.11b, where they exchanged data between an AP and multiple stations on a cotton and rice field. The authors report that they easily achieved a communication of 1000 m in a LoS scenario. They mention that different wheater conditions have little impact on communication reliability. A significant influence on the communication range is the height above ground or the crop vegetation, where the authors recommend using at least a height of 0.2 m.

Wi-Fi technologies are also used in various outdoor scenarios. The outdoor performance of Wi-Fi technologies in different use cases and scenarios have been investigated by various researchers. Aust, Prasad, and Niemegeers [48] surveyed past research on outdoor performance of IEEE 802.11 technologies. The authors summarize results of urban, rural, desert or water surface scenarios with different

⁴<https://ravenind.com/products/autonomy/driver-assist-harvest-solution>

⁵<https://www.agleader.com/harvest/cartace/>

environmental conditions and antenna configurations. I focus on the findings for wi-Fi with omnidirectional antennas in rural areas.

In their general findings, they cite [49] and [50], which name the inter-symbol interference due to multipath effects as main reason for packet losses in wi-fi outdoor communication. The authors conclude, that using directional antennas instead of omnidirectional antennas can lead to fewer multipath effect. Furthermore, the authors add that external wi-fi interference is only expected in urban areas and are not very likely in rural areas.

Due to the experiment results of [51], the authors state that the weather conditions only have a small impact of 1 dB . . . 2 dB on the outdoor communication. These findings are also confirmed by [47] in their experiments on a rice and cotton field.

Paul et al. [52] analyzed the open outdoor performance for different physical layer and MAC layer configurations of IEEE 802.11n. The authors conducted experiments with different omnidirectional antenna constellations and spacings ranging from 0 cm . . . 25.4 cm. They found out, that no positive impact on the communication can be achieved by changing antenna constellations or spacings.

For the MAC layer with its CSMA/CA mechanism, the Aust, Prasad, and Niemegeers [48] state, that the increased propagation delay in outdoor scenarios can cause a higher number of packet collisions. They refer to findings of [52] and recommend using Block Acknowledgement and Frame Aggregation. These mechanisms introduce a MAC frame overhead, which cost less transmission time than retransmission of a whole frame or a single acknowledgment frame.

Chapter 3

Analyzing Corn Harvest Process Data

To gain a better insight into requirements of the WIC use cases Platooning and Streaming Services, I analysed process data of a corn harvest scenario.

The goal of analysing the corn harvest data was to investigate the machines moving in the working scenarios relative to each other. The machines' speed and distance in tracked harvest platoons data may result in new use case requirements, e.g. latency or communication range of Platooning and Streaming Services. The machinery movement profile can be used to identify when shadowing effects may occur in the work scenario or when machines meet in the field.

To get GPS data of the corn harvest, I collected GPS tracks of a FH and two to three TMs harvesting corn on a field in Germany for two days in September. The workflow for collecting the corn harvest process data was as follows. I handed out the tablets to the drivers, which left the farm with the tablets in the driver's cabs to drive to the field in the morning. The tablets recorded the position and speed of the FH and the TMs every second of the day. During breaks, the tablets continued to capture the NMEA data stream of their GPS even if the positions and speed did not change.

After recording the process data, I anonymised it. First, I deleted data points of the log files until the recorded accuracy of the following data points was less than 2 m. Then, I replaced the timestamp and the date for all data points with a continuous index.

Then I anonymised the location data by adding a random offset to the GPS coordinates. As a result, this procedure moved the areas to a random location in the world with a continuous index as a timestamp, where the exact date is unknown.

To get a first glance at the recorded data, I built a dashboard with the Python framework *Dash*⁶. I initially plotted all the positions in a polyline for each machine on a map in the dashboard. An added slider allows one to set a time interval that

⁶<https://dash.plotly.com/introduction>

narrows down the data points for display in the dashboard. In addition, one could select which TMs are displayed next to the FH. For the chosen time interval, the distance and velocity difference between the selected TMs and the FH were plotted in graphs as time histories. In the dashboard, I could get an overview of the machine's behaviour before, during, and after the overloading scenario. The overview shows that a FH is nearly always in the overloading process with a TM. In doing so, the FH may occasionally stay in the same place if the cutter is clogged or there is a transition of TMs where a full TM moves away from the FH and an empty TM catches up to the FH to take over the forage.

A TM is in a platoon with a FH if the distance to the FH is less 10 m and they are moving at nearly the same speed with a maximum velocity difference of 5 km/h (1.39 m/s). The distance between TM and FH increases during a turning manoeuvre on the field. Since both machines have different curve radii in a turning manoeuvre, a different machine's speed can be observed to finish turning simultaneously. Smolnik and Lücke [10] also describes these observations and indicates that this speed difference adds a new level of complexity.

A new harvesting process begins as soon as the machines finish turning and are at the beginning of a new lane. Again, the machines drive closely and nearly at the same speed to harvest and overload forage.

Furthermore, another TM can sometimes be close to the FH. For example, an empty TM that waits to work with the FH in the next platoon drives close behind the current platoon at the same speed to be ready in the vicinity.

Based on the above observations, I developed an algorithm for detecting platooning scenarios in the recorded harvest process data.

It starts by searching for every TM that could be in a harvest and overloading scenario with the FH by filtering the data points by the distance and speed difference between TM and FH. If the distance is less than 10 m, the speed difference is less than 5 km/h (1.39 m/s) and the FH and TM drive at a speed within 5 km/h... 14 km/h (1.39 m/s... 3.89 m/s), the TM could be harvest and overloading scenario with the FH.

In some cases, this algorithm would also detect the waiting TM. To avoid this, I applied a weighted sum of distance and speed difference between TM and FH to detect the harvest and overloading scenario. The weights are $\frac{3}{5}$ and $\frac{2}{5}$ for the distance and speed difference, respectively, to ensure that the closer TM is more likely in a harvest and overloading scenario with the FH. It uses a weighted sum of distance and speed difference between FH and TM to detect the platooning scenarios. I determined the weights using the Trial-and-Error method, setting the weights and displaying the found platoons scenarios on the map. Then I adjusted the weights until the detected platoons scenarios were correct.

For verification purposes, I displayed the found platoons scenarios on the map and confirmed that the found platoon was correct and the weights were set correctly.

After the platoons scenarios were correctly detected, I included the data points before each harvest and overloading scenario till a maximum distance of 50 m between FH and TM was exceeded. These data points are also relevant to the requirements because at the beginning of an agricultural platooning service, the FH, as the system leader, must be able to guide an empty TM to the appropriate position for overloading. Furthermore, no turning manoeuvres are detected. So far, the algorithm only detected consecutive time intervals, where the TM and FH are in a harvest and overloading scenario driving down the field. By adding the data points until a distance of 50 m before every time interval, the turning manoeuvres with their turning radii are also included in the detected harvest and overloading scenarios.

The final output shows the detected harvest and overloading scenarios with the FH and TM, which have roughly the same length every time the FH and TM are in a harvest and overloading scenario. This verifies that the algorithm is operating correctly, as it should generally take roughly the same time to fill the constant volume of TM's trailer with forage.

I also implemented the following verification method to determine whether the found platoon scenarios were correct. I observed that a fully loaded TM leaves the field via one of the field exits to bring the crop to a farm building. Via a check, if it has left the field and thereby passed the exit after leaving a platoon, wrongly recognised platoons can be detected.

The data points of a detected harvest and overloading scenario are represented in Figure 3.1. The FH and TM, plotted as black and white lines respectively, drive from the left lower corner to the top middle of the map in 3.1a. In between, the FH and TM do 2 turning manoeuvres on the right side of the map in 3.1a. At the end of the scenario, the TM turns to the right and heads towards the field exit.

The plotted distance and velocity data in 3.1b illustrates the same events. In the beginning, the TM drives with a higher velocity to catch up with the FH's position. After that, the TM and FH drive with a similar velocity and a distance below 10 m down the field lane. As soon as a turning manoeuvre starts, the distance increases and the velocity difference can be seen. After every turning manoeuvre, the TM and FH drive again with a similar velocity and a distance below 10 m. In the end, when the TM is full and leaves the harvest and overloading scenario, the distance increases and the TM drives at a higher velocity.

For the detected data points of the platooning services from recorded data of the corn harvest, the proportion where the FH and TM move in a specific distance is shown in Figure 3.2. For the same data points, the proportion in which FH and TM move at a given speed is available in Figure 3.3.

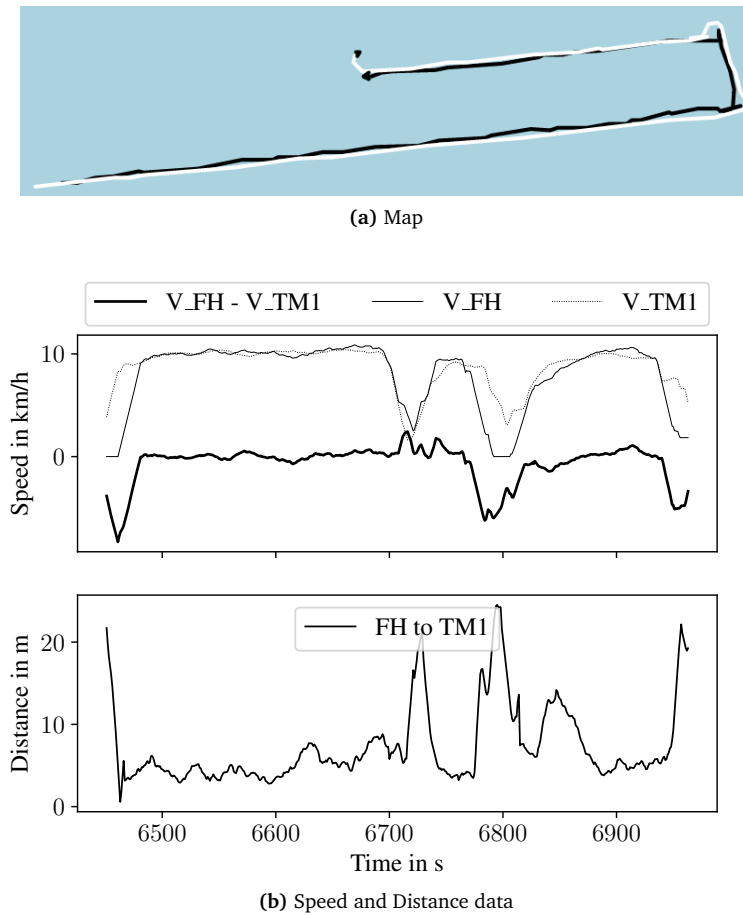


Figure 3.1 – A FH and a TM in harvest and overloading scenario, which is represented as distance and speed data plotted in regards to the time and which is visualised on a map as a black line and white line for the FH, TM respectively

These analysing results show that the TM and the FH usually move with a distance of less than 10 m. In addition, the distance can also be higher, e.g. in turning manoeuvres or before the overloading process.

Smolnik and Lücke [10] specifies the required communication range of platooning services in the corn harvest process as less than 30 m.

One notable observation in Figure 3.3 is that the FH and TMs in the corn harvesting platooning scenario often travel at a speed of approximately 10 km/h. This speed is significantly higher than the average speed of 5.6 km/h of a FH in an entire corn harvesting process from [6]. It is necessary to classify that in the year of the recorded data was little precipitation, so the corn was not dense and high, and the last speed value is an average value of the entire corn harvest process, which can

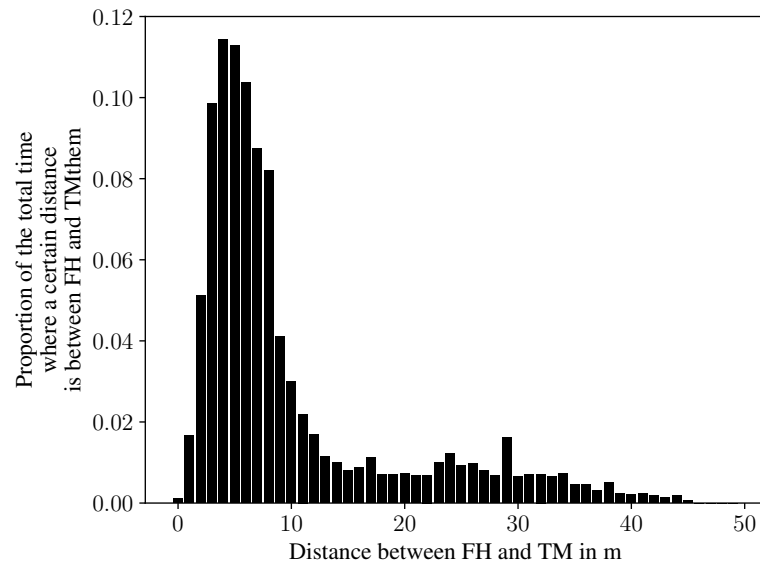


Figure 3.2 – Distribution of time proportions where a given distance was between Forage Harvester (FH) and Transport Machine (TM) in a harvest platoon scenario.

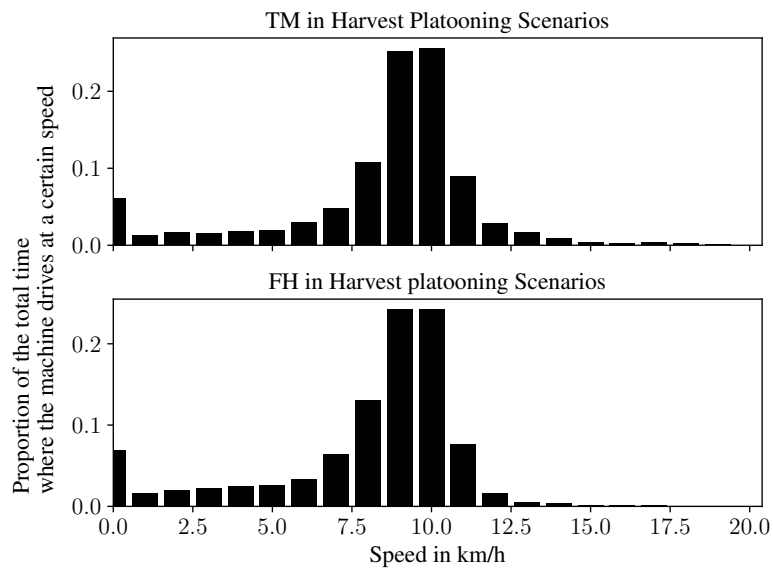


Figure 3.3 – Distribution of time proportions where Forage Harvester (FH) and Transport Machine (TM) drove with a certain speed in a harvest platoon scenario

be calculated from the data in [6]. Nevertheless, the recorded data shows that a platooning service in agriculture must also be designed for higher speeds.

In Figure 3.3 is a local maximum at a speed of 0 km/h. In a harvest platoon scenario, FH and TM can stand still briefly when the cutting device is jammed. The driver's specific actuation usually clears the forage jam of the cutting device so that the platoon can continue its work.

Smolnik and Lücke [10] defines an average speed of 4.5 km/h for the development of platooning services in the corn harvesting process. Depending on the PD, the speed can vary from 2 km/h... 6 km/h according to the authors. The authors do not give a basis for the figures. However, the report is from the agricultural machinery manufacturer Claas, which is a major producer of FH worldwide and thus can be regarded as having good knowledge of the topic.

Klingler, Blobel, and Dressler [43] investigated the suitability of IEEE 802.11p for WIC. The authors detected that shadowing effects occur in the harvest scenario. The authors explain the effect because another tractor or the spout of the FH was in Line-of-sight (LOS). I reviewed the recorded position data to get an overview of the TM's position relative to the FH in the overloading process. The relative bearing is the angle between the position of the TM and the heading of the position of the FH. Using the previous position of the FH, the relative bearing between FH and TM can be calculated with the angles α and β in Figure 3.4 as:

$$\text{Relative_Bearing} = \beta - \alpha, \quad (3.1)$$

Assuming that the FH does not move backwards, the relative bearing describes the relative angle from the FH to TM. The result is displayed in Figure 3.5. It can be observed that the TM is mainly close to the FH at an angle of $30^\circ \dots 150^\circ$ at a distance between 0 m... 10 m.

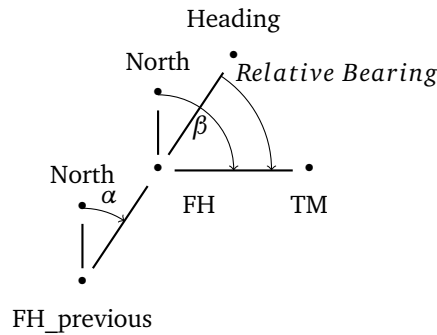


Figure 3.4 – Relative bearing between FH and TM which is calculated using the previous location of FH by using β and α for Equation 3.1

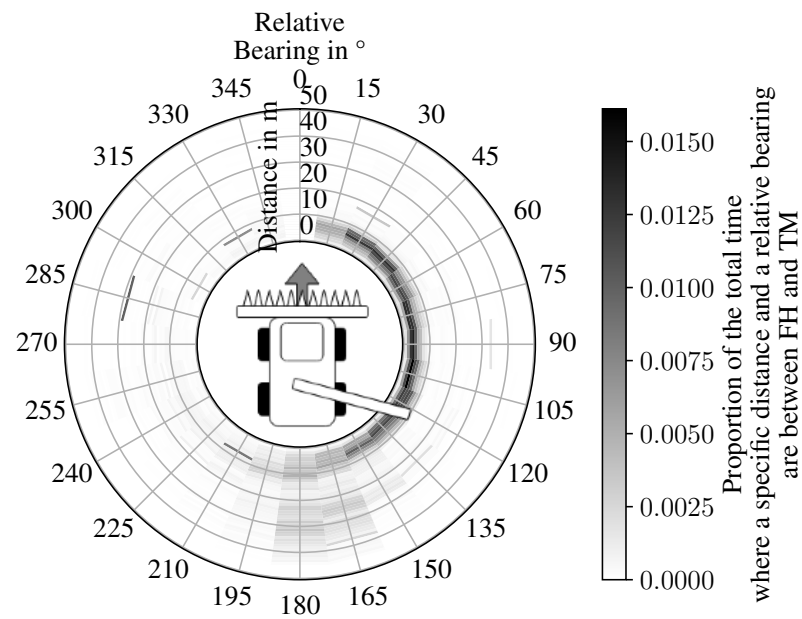


Figure 3.5 – Distribution of time proportion at specific distances and relative bearings between Forage Harvester (FH) and Transport Machine (TM)

In addition, it is noticeable that the machine can also be directly behind the FH. This driving behind each other is typical when a new part of the field is being cut in harvesting, as shown in Figure 3.6. When there is a greater distance between TM and FH, the TM is usually behind the FH at an angle of $157.5^\circ \dots 187.5^\circ$. At these moments, the TM is empty and closes up to the FH to operate in a new platooning Service together.



Figure 3.6 – Forage Harvester (FH) and Transport Machine (TM) start cutting a new field section

Another notable fact is that the TM hardly ever stayed to the left of the FH. Since the FH often made left turns, the crop was usually already harvested to the right of the FH so that the TM could drive there without running over the crop. On rare occasions, the TM was also to the left of the FH. Such a platooning scenario can be an exception or a driving manoeuvre to start cutting a new part of the field.

The results reveal only a first impression of the requirements of the harvest and loading process. More data from around the world must be analysed to make a general statement. The low rainfall this year has already resulted in a low plant population. This field condition made a higher process speed possible. The data may also vary on the size of the agricultural machinery. Using a smaller FH would result in a smaller distance between TM and FH. To make a general statement, I should use data from different years, machines or harvest and loading scenarios because they can reveal other initial field conditions. git

Chapter 4

Field Measurements

Figure 3.4 shows, that the TM can be positioned at various distances and angles in relation to the FH. For one corn harvest scenario, Klingler, Blobel, and Dressler [43] found out, that the RSS can drop due to shadowing effects caused by the size and shape of the FH and the TM.

In a field experiment, I want to analyze which positions of the TM and FH cause the shadowing effects, which subsequently reduce the RSS and how physical layer parameters like MCS and STBC can be used to ensure a low PER.

For the experiment, I will use a Combine Harvester (CH) instead of a FH as it has a similar shape and size as a FH and is available. The TM will be a Tractor pulling a trailer of the type HW80. Both machines will be equipped with a Global Positioning System (GPS) receiver and Wi-Fi devices which record the position, RSS and the PER of the exchanged packets. The CH will be positioned in an agricultural field. The tractor will start 50 m behind the CH, advance to the CH and pass the CH slowly with a speed of 1 km/h... 5 km/h (0.28 m/s... 1.39 m/s) as shown in Figure ???. While driving along the specified path, the tractor will mimic various overloading positions, where shadowing effects can occur. After the tractor has passed the CH, it will drive back to its starting position, and the experiment will be repeated with different overloading distances between the CH and the tractor.

During the experiments, GPS receivers at the agricultural machines will record the position and speed of the machines every 1 s.

The Wi-Fi setup consists of a Milesight Industrial Router UR75⁷, which implements the standards IEEE 802.11 b/g/n in the 2.4 GHz band and IEEE 802.11 a/n/ac in the 5 GHz band and IEEE 802.11 a/n/ac in the 5 GHz band. The router is equipped with two omnidirectional antennas for 2.4 GHz and 5 GHz usage. Brinkhoff and Hornbuckle [47] and Paul et al. [52] already found out that placing the antenna

⁷<https://iot-shop.de/en/shop/mil-ur75-500gl-g-p-w-milesight-ur75-500gl-g-p-w-industrial-cellular-5g-router-with-gps-wifi-and-poe-5677>

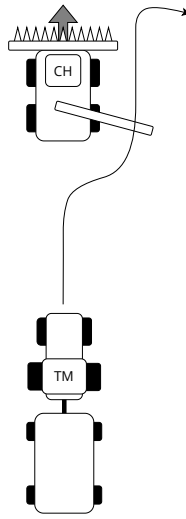


Figure 4.1 – Path around the static Combine Harvester (CH), which the Transport Machine (TM) will drive during the experiment to mimic various overloading positions

higher above ground improves the robustness and communication range of Wi-Fi networks in an outdoor environment. As the regulation in the German Law StVZO §32 Abs. 2 limits the height of every agricultural vehicle or combination of vehicles to less than 4.0 m, the maximum antenna height is 4 m above the ground. Therefore, I will mount the router on the tractor's roof at a height 4 m above the ground.

I set up two Wi-Fi devices on the CH, which are two UP Squared Board⁸ with an Intel AX210 Wi-Fi module⁹.

Every Intel AX210 Wi-Fi module supports the IEEE 802.11ax standard for 2.4 GHz, 5 GHz and 6 GHz band and is equipped with two antennas, which support omnidirectional transmissions in the 2.4 GHz, 5 GHz and 6 GHz band and have a gain of 5 dB. The boards are mounted on the roof of the CH next to one another at a height 4 m above the ground too.

The router on the tractor sets up a Wi-Fi AP. One of the boards on the CH connects to the AP of the router as a Wi-Fi STA and hosts an iperf3¹⁰ server. A notebook is connected via LAN to the router and runs an iperf3 client, which connects to the iperf3 server on the CH. The iperf3 client sends 100 Byte UDP packets every 100 ms to the iperf3 server on the CH. The server records the received packets.

Many different Wi-Fi transmissions arise through the iperf3 UDP packets, the Wi-Fi manager of the Milesight Industrial Router, and the Intel AX210 Wi-Fi card. These transmissions can be RTS/CTS, ACK, Data, Beacon or Probe request frame,

⁸https://eu.mouser.com/datasheet/2/826/UP_Square_DatasheetV0_4-3084829.pdf

⁹https://docs.alfa.com.tw/datasheets/alfa-network_ait-ax210-ex_latest.pdf

¹⁰<https://iperf.fr/>

displayed in Figure 4.2. Through testing, I found out that the Wi-Fi manager of the Wi-Fi devices can apply VHT MCS 0...9 and STBC as physical layer configurations.

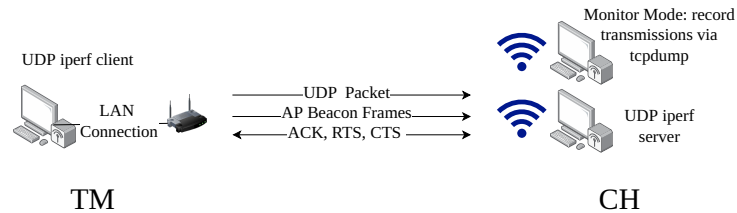


Figure 4.2 – Wi-Fi transmissions between the Wi-Fi AP on the Transport Machine (TM) and the Wi-Fi STA on the Combine Harvester (CH), which are recorded by a third Wi-Fi device in monitor mode on the CH

The other UP Squared Board on the CH uses the Wi-Fi card in the monitor mode and records every transmission in the 5.6 GHz band using tcpdump¹¹. Since the UP Squared board is placed next to the other board on the roof of the CH, it can record the same signals the other board receives in the UDP transmission. The tcpdump records are in pcap - format, which can be analyzed using Wireshark¹². Using Wireshark, I can identify possible retransmissions to calculate a PER. At the same time, the data contains the RSS of each antenna and the physical layer parameters for every transmission, allowing each transmission's robustness to be calculated as a function of the RSS and the physical layer configuration.

In order to get insights on the robustness of different physical layer BWs and used frequencies, the frequency channels in Table 4.1 are configured in the Every specified channel is used separately. To be able to calculate the means and standard deviations of the result for every configuration, the experiment is repeated 5 times for each channel, which means that the tractor drives 5 times the same path, which is displayed in Figure ??.

| BW | Channel number 2.4 GHz | Channel number 2.4 GHz |
|--------|------------------------|------------------------|
| 20 MHz | 1 | 100 |
| 40 MHz | 3 | 102 |
| 80 MHz | - | 106 |

Table 4.1 – Frequency Channels numbers for 2.4GHz and 5 GHz for the different Bandwidth (BW)s of the IEEE 802.11 standard [14], which can be used for outdoor communication [53], [54] and are configured in the Milesight Industrial Router UR75 for the field experiments.

¹¹<https://www.tcpdump.org/>

¹²<https://www.wireshark.org/>

Trail Run

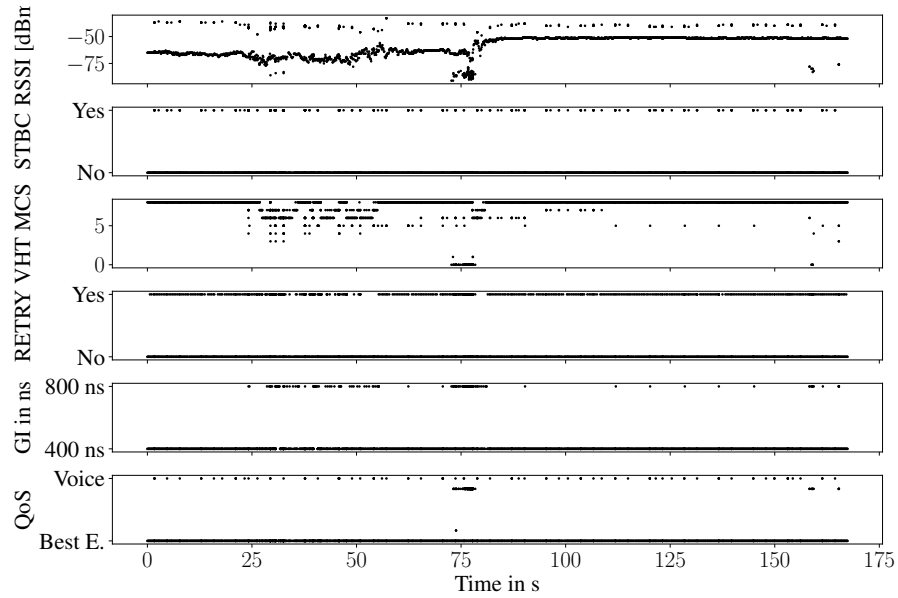


Figure 4.3 – All QoS data transmissions between the Wi-Fi Access Point (AP) on the Transport Machine (TM) and the Wi-Fi STA on the Combine Harvester (CH) in a trail run

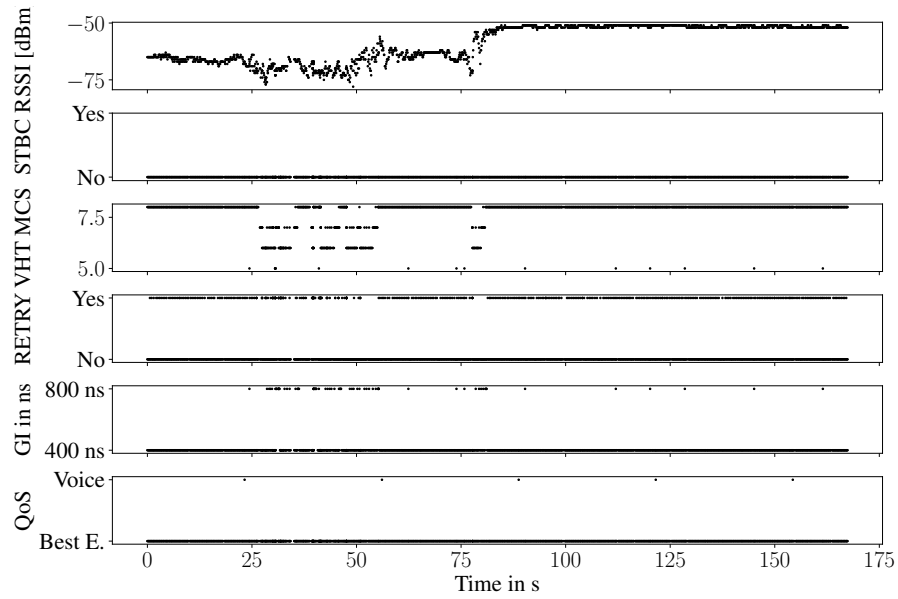


Figure 4.4 – All QoS data transmissions between the Wi-Fi Access Point (AP) on the Transport Machine (TM) and the Wi-Fi STA on the Combine Harvester (CH) in a trail run, which were initiated by the iperf3 client on the Transport Machine (TM)

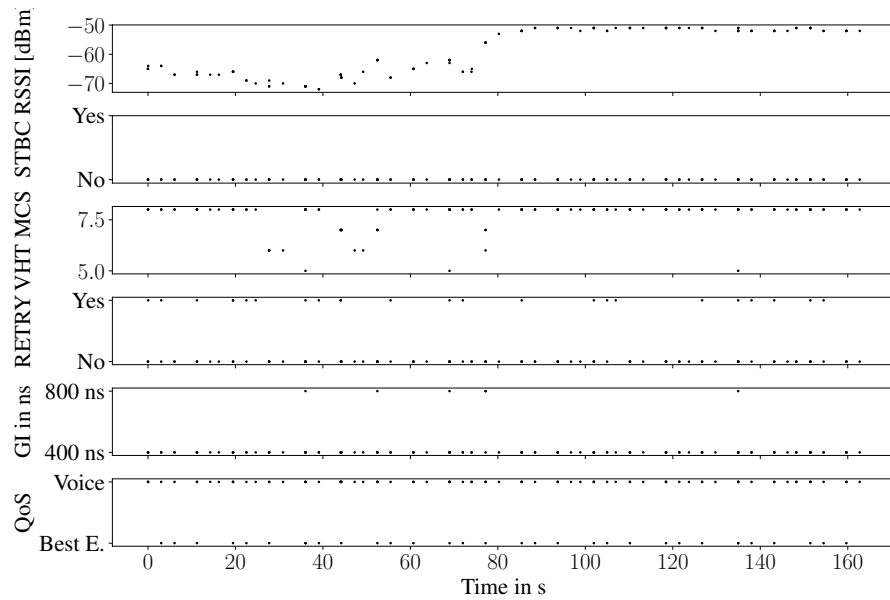


Figure 4.5 – QoS data transmissions between the Wi-Fi Access Point (AP) on the Transport Machine (TM) and the Wi-Fi STA on the Combine Harvester (CH) in a trail run, which were initiated by AP

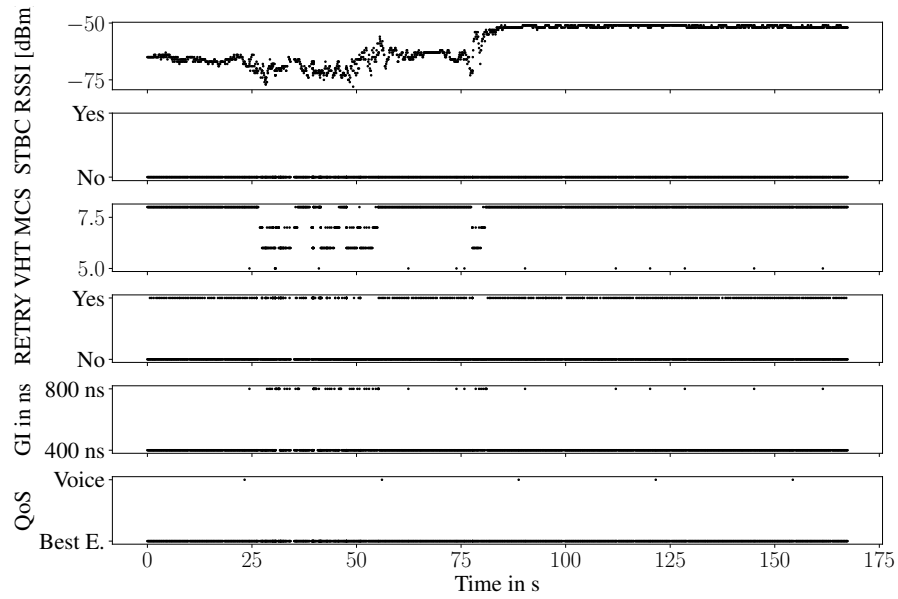


Figure 4.6 – All QoS data transmissions between the Wi-Fi Access Point (AP) on the Transport Machine (TM) and the Wi-Fi STA on the Combine Harvester (CH) in a trail run, which were initiated by the Wi-Fi STA on the CH

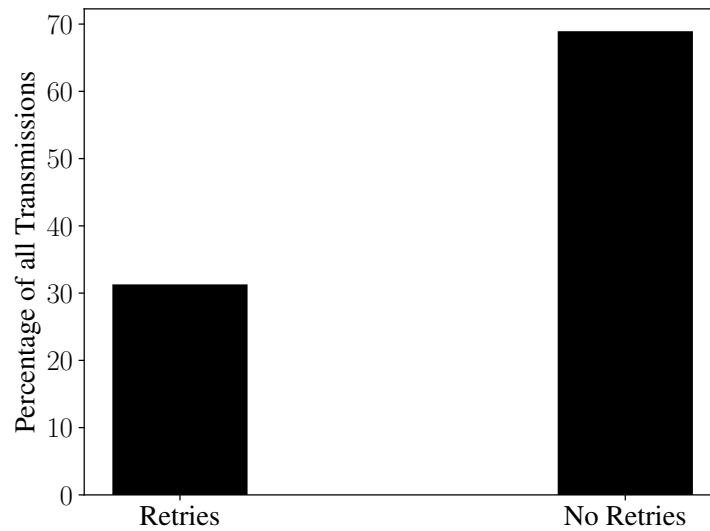


Figure 4.7 – Percentage of retransmissions for every transmission in the trail run

Chapter 5

Simulation

Robustheit: Matlab? Goodput: ns3 Range: Matlab? Somehow? overview other papers? Enough?

In the next chapter, I would like to examine the influence of the different parameters on the goodput, robustness and latency. Since, as described, the existing technology cannot be specifically controlled in order to investigate the influence of the parameters, a simulation is carried out. Further advantages are the flexibility and the possibility to simulate different communication protocols and network protocols [55].

Omar et al. [28] adds, that simulation is the main evaluation method for IEEE 802.11 networks which the IEEE 802.11ax task group considers.

The authors distinguish between link-level simulations and system-level simulations for the simulation of HE wireless networks. The authors explain both methods as follows.

Link-level simulations, according to the authors, investigate the performance of the HE physical layer for different physical layer parameters as PER in terms of SNR. As an example, the authors cite different multiple researcher, which simulated PER in regard to SNR and chosen MCS. Link-level simulations are usually visualized in so-called waterfall plots, which represent the PER in regard to SNR for different physical layer parameters.

For system-level simulation, it requires abstractions of the physical and MAC layers to simulate a system close to real on this basis.

For the simulation of Wifi, there are already various tools available, such as Matlab, ns-2 and ns-3, OMNeT++, Qualnet [56] or OPNet [55].

Kumar et al. [55] compares different available simulators for the simulation of wireless networks and concludes that, in general, ns-2, ns-3 and OMNeT++ are the most popular simulators for academic research of wireless networks. Keller [56] adds, that ns-3 keeps an more accurate Implementation of the IEEE 802.11 standard

than OMNeT++. So far, I only know, that OMNeT++ supports some IEEE 802.11ac modes via the library INET Release 4.0.0¹³. Therefore, OMNeT++ seems unsuitable for Wifi 6 simulations.

ns-3 Network Simulator

Ns-3 is well documented in the ns-3 manual in the *./doc* - folder of [57], where I found the following information about the simulator. Ns-3 is a discrete-event network simulator project, which was founded in 2006. The ns-3 project is open source with a licence based on n GNU GPLv2 compatibility. It aims to provide an open, extensible network simulator for research and educational use. Ns-3 scripts can be written in C++ or Python.

The concept of ns3 is based on the abstraction of simulated systems. For this purpose, the term node was introduced for basic computing devices. The Node class offers the possibility to install protocol stacks and applications or to add peripheral cards and mobility models to the node. Applications are the abstraction of the user-level applications, which represent an activity to be simulated. For this purpose, the applications use resources and functionalities provided by the system software of a node.

Every node gets network access via the Net Device class. The Net Device class represents the physical interface of a node, which can be Network Interface card or peripheral card. The Net Device simulates the software driver and the hardware of the network interface.

Every Net Device is connected to a channel. The channel class represents the physical medium, which is used to transmit data. The channel behaviour is based on the channel model, which may include interference, propagation delay and loss.

The current version ns-3.37 supports IEEE 802.11ax as a standard in infrastructure and ad-hoc mode¹⁴. However, support for the 802.11ax standard is not yet complete. It is already possible to configure DCM and STBC, but there is a comment in line 496 of the file *he-ppdu.cc* that these are not yet taken into account in the current ns-3 version 3.37¹⁵.

When examining the implementation of 802.11ax in ns-3, one notices that the implementation of 802.11ax in ns-3 already implements a HE ER SU PPDU preamble, but this is never used and one cannot activate the extended range mode. cannot be activated. The implementation of 802.11ax in ns-3 is therefore not yet complete and there are still some open points that need to be implemented in the future.

Black, Gamboa, and Rouil [58] have developed a 3D visualisation of ns-3, which visualises the simulations in 3D to make the ns-3 simulation scenarios tangible.

¹³<https://inet.omnetpp.org/2018-06-28-INET-4.0.0-released.html>

¹⁴<https://www.nsnam.org/docs/models/html/wifi-design.html>

¹⁵<https://www.nsnam.org/docs/models/html/wifi-user.html>

The authors' graphical extension consists of two open source programmes. The NetSimulyzer ns-3 module ¹⁶ can be integrated into the ns-3 simulation and builds a JSON file using the specified functions and configurations. This file contains all the data required for visualisation in the application NetSimulyzer ¹⁷.

Nevertheless, ns-3 is chosen as a simulation tool for the simulation of 802.11ax by [59], [25] and [30].

5.1 Data Rate

As ns-3 is a open source simulation software and was used by other researchers in the past too, I used ns-3 to evaluate effect of physical layer configuration on the achievable goodput between two nodes using IEEE 802.11ax Wi-Fi Netdevices to exchange UDP packets in Adhoc Mode.

The setup consists of two nodes placed in static positions with a distance of 20 m. I chose the short communication range setup with no simulated interference to enable wi-Fi transmission without any packets lost.

Every node is equipped with a Wi-Fi NetDevice with the following parameters: GI of 3200 ns, a bandwidth of 20 MHz and 2 spatial streams.

A Constant Rate Wifi Manager is used to set a constant data rate according to the fixed HE-MCS for data, non-uniform and control data transmissions. The used frequency band is 2.4 GHz or 5 GHz as higher frequencies are less resistant to shadowing and fading and a higher data rate is not needed for the WIC use cases. The Wi-Fi Netdevices operate in the frequency channels specified in Table 4.1, which can be used for outdoor Wi-Fi communication in Germany [53], [54].

As the Wi-Fi standard implements ACKs for every packet, every lost packet is repeated until it is received or the number of retries is exceeded. Platooning Services are time critical and therefore the number of retries should be as low as possible. This is why additional retransmission mechanisms like TCP are not needed. Therefore, the chosen transport layer protocol is UDP.

One nodes operate a UDP server and the other one a UDP client. The client sends 1000 Byte UDP packets to the server every 0.1 μ s. This packet interval ensures that the packet queue of the client is never empty after starting the simulation. The server receives the packets and sends an ACK back to the client.

The simulation runs five times for 5 s for every physical layer configuration. The goodput for every simulation run is calculated by dividing the number of received bytes at the UDP Server by the simulation time. The goodput is then averaged over all simulation runs per physical layer configuration and the confidence interval with a confidence level of 95 % is calculated.

¹⁶<https://github.com/usnistgov/NetSimulyzer-ns3-module>

¹⁷<https://github.com/usnistgov/NetSimulyzer>

The theoretical data rate for the different physical layer configurations is retrieved from the function `ns3::WifiMode::GetDataRate()`.

In order to verify the simulation software, I used different methods. First, I verified, that the theoretical data rate for the IEEE 802.11 ax physical layer configurations in the simulation is equal to the theoretical data rate specified in the IEEE 802.11ax standard [15].

Additionally, I used the `MonitorSnifferRxCallback` and the `MonitorSnifferTxCallback` of the `ns-3 WifiPhy` class to check the ongoing transmissions. Both Callback functions can be added to `WifiPhy` objects of `WiFi NetDevice` and are called every time a packet is received or transmitted at the Wi-Fi Netdevice respectively. The function parameters are Information about the packet, channel frequency and station ID and an instance of the `WifiTxVector` class. The `WifiTxVector` instance in the current ns-3 version 3.37 describes all parameters of the transmission in accordance to the `TXVECTOR` field of the IEEE 802.11 standard [15]. Additionally, the function parameters of the `MonitorSnifferRxCallback` contain the signal strength and the noise power of the received packet.

Using the provided information from the `MonitorSnifferRxCallback` and the `MonitorSnifferTxCallback` I was able to comprehend the ongoing transmissions and verify the simulation results.

Guard Interval (GI)

In the first simulation I varied the GI of the Wi-Fi Netdevices for different HE-MCS values. The results are shown in Figure 5.1. The achieved goodput is plotted against the theoretical data rate for the different GI values. The theoretical data rate is always higher than the achieved goodput of the UDP applications, because the channel is used for ACK and ad-hoc Beacon transmissions as well. Due to these additional transmissions the goodput is lower than the theoretical data rate.

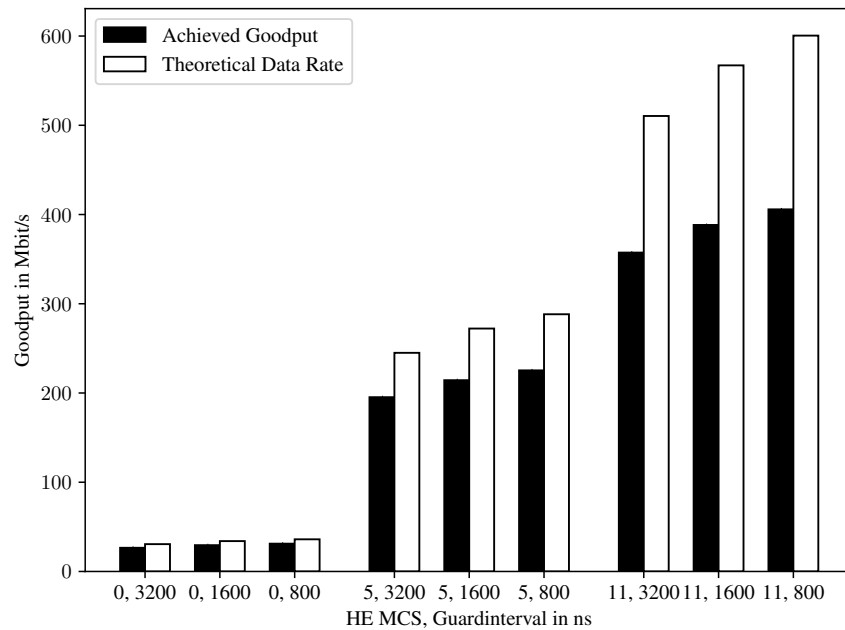


Figure 5.1 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with 2 Multiple Input Multiple Output (MIMO) streams and a bandwidth of 80 MHz in regards to the number of Multiple Input Multiple Output (MIMO) streams and the chosen HE-Modulation and Coding Scheme (MCS) value

As the GI length increases the achieved goodput deceases. This effect can be characterized by the aforementioned formula. The bandwidth attenuation for the possible GI lengths is displayed in Table 5.1. The effect of the bandwidth attenuation for the different GI lengths can be observed in the mean achieved goodput in Table 5.1, where the decrease of the mean goodput reflects the bandwidth attenuation of the decreasing GI length.

A similar effect can be observed whit higher HE-MCS values.

| GI | Mean achieved good- put | BW attenuation |
|---------|----------------------------|----------------|
| 800 ns | 31.15 Gbit/s | 94 % |
| 1600 ns | 29.47 Gbit/s | 89 % |
| 3200 ns | 26.52 Gbit/s | 80 % |

Table 5.1 – Bandwidth (BW) attenuation and mean goodput for HE-MCS0 in regards to Guard Interval (GI) length

Patil et al. [60] and Karmakar et al. [61] conducted similar simulations for the 400 ns and 800 ns GI lengths in IEEE 802.11n and IEEE 802.11ac, respectively.

Both papers, state that shorter GI lengths lead to higher goodput values under the condition, that there is a short delay spread and a low channel loss due to interference.

Multiple Input Multiple Output (MIMO)

Extended Range Mode

In the next simulation I analyzed the effect of the Extended Range Mode on the goodput of the IEEE 802.11ax physical layer. As mentioned in ns-3 Version 3.37, the Extended Range Mode is implemented as an HE Capability with the new extended WifiPreamble. But the new Preamble in the HE Extended Range (ER) SU PPDU format is not used in ns-3 version 3.37.

As I was using the ConstantRateWifiManager, all parameter for the data transmission are set in the function ConstantRateWifiManager::DoGetDataTxVector(). The function creates a WifiTxVector instance with the parameters of the transmission. There I overwrote the preamble type to the already implemented ns3 WifiPreamble::WIFI_PREAMBLE_HE_ER_SU, when the Extended Range Mode is enabled and conditions for the Extended Range Mode in the IEEE 802.11ax standard [15] are

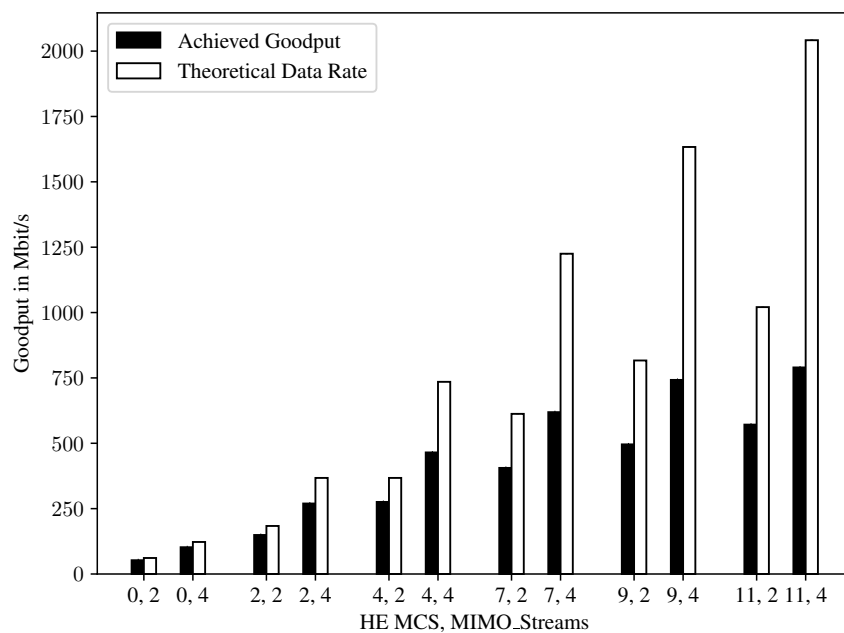


Figure 5.2 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with a Guard Interval (GI) of 3200 ns and a bandwidth of 80 MHz in regards to the number of Multiple Input Multiple Output (MIMO) streams and the chosen HE-MCS value

fulfilled. Ns-3 version 3.37 implements `ns3::GlobalValue`, which allow users to set global values for the simulation, which can be accessed in every class without changing Constructor or function parameters. This leaves the original functionality of the ns3 code intact.

I used the `ns3::GlobalValue` to create an instance named `HE_ER_Mode`, which is set to true at the start and read in the `ns3::ConstantRateWifiManager::DoGetDataTxVector()` function to overwrite the preamble type.

Via the `MonitorSnifferRxCallback` and the `MonitorSnifferTxCallback` I was able to verify, that the `ns3 WifiPreamble::WIFI_PREAMBLE_HE_ER_SU` was used for data transmission, when the following conditions were met: a) the Extended Range Mode is enabled, b) the number of spatial streams is 1, c) the HE-MCS value is less than 3 and d) the BW is 20 MHz.

The results of the simulation are shown in Figure 5.3, where the lost achieved goodput is plotted against the theoretical data rate for the different HE-MCS values. The only difference between HE SU and HE ER SU transmissions is the preamble, which repeats the HE-SIG-A field in the HE ER SU PPDU format. This results in a longer transmission time, which reflects in the lower achieved goodput for the Extended Range Mode.

describe lost goodput calculation

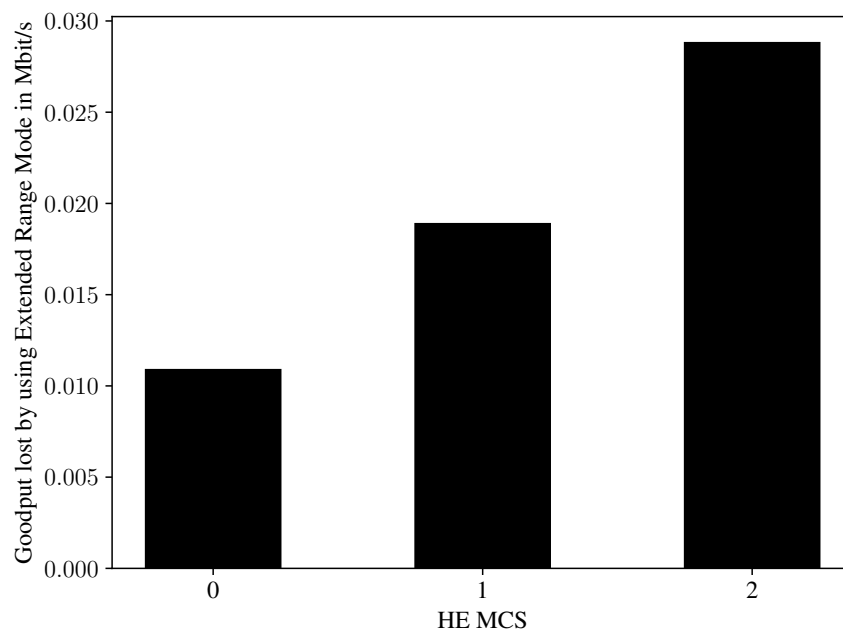


Figure 5.3 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with a Guard Interval (GI) of 3200 ns and a bandwidth of 20 MHz in regards to the number of Multiple Input Multiple Output (MIMO) streams and the chosen HE-MCS value

The effect increases with smaller packet sizes, because the longer transmission time of preamble is more significant for smaller packets. For higher HE-MCS values more achievable goodput is lost, because longer transmission time for the preamble could have been used more OFDM symbol transmissions, where more data is coded onto a symbol.

nothing to cite?

Dual Carrier Modulation (DCM)

Using the DCM in the IEEE 802.11ax physical layer has also an effect on the achievable goodput. As aforementioned, the DCM is not supported by ns-3 version 3.37. Therefore, I implemented the DCM for this simulation in the ns-3 version 3.37 by transmitting a payload of twice the size, which represents the original payload and a copy of the original payload for the HE-MCS values 0, 1, 3 and 4, where MCS is allowed. Using DCM, the receiver would apply maximum likelihood decoding to decode the original payload with a higher probability.

The results of the simulation are shown in Figure 5.4, where the lost achieved goodput is plotted against the theoretical data rate for the different HE-MCS values. The theoretical data rate while using DCM is half of the theoretical data rate without DCM, which complies with the IEEE 802.11ax standard [15].

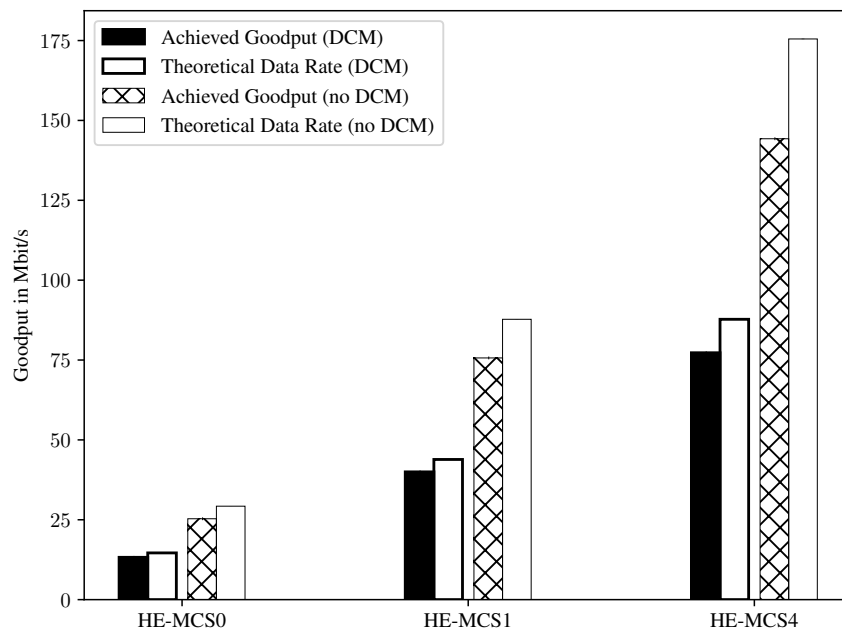


Figure 5.4 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with for IEEE 802.11ax physical layer parameters of a Guard Interval (GI) of 3200 ns, a Bandwidth (BW) of 40 MHz and 2 spatial streams in regards to the number of the chosen HE-Modulation and Coding Scheme (MCS) value and whether Dual Carrier Modulation (DCM) is enabled

The achieved goodput is always lower than the theoretical data rate, because data transmission time is lost to the header overhead and media access time. WiFi access is based on CSMA CA, which means that the stations have to wait for a random time before they can transmit on a free channel. Additionally, the channel can be occupied by ACK or adhoc beacon frames, which also have to be transmitted.

Using DCM increases the ratio of achievable goodput to theoretical data rate, because only one header and one ACK frame is transmitted per 2000 Byte payload and the node has to go to the medium access procedure only once per 2000 Byte payload.

Space-Time-Block-Code (STBC)

Another physical layer parameter, which reduces the theoretical data rate for more robustness is the STBC. As mentioned, ns-3 version 3.37 does not support the STBC for the IEEE 802.11ax standard. Therefore, I reduced the number of MIMO streams from two to one, when the STBC is enabled. STBC would transmit a redundant copy of the data on the second antenna, which would be combined using the space-time block code (STBC) to increase the robustness and reliability of the transmission. The results of the simulation are shown in Figure 5.5, where the lost achieved goodput is plotted against the theoretical data rate for the different HE-MCS values. The theoretical data rate while using STBC is half of the theoretical data rate without STBC, which complies with the IEEE 802.11ax standard [15].

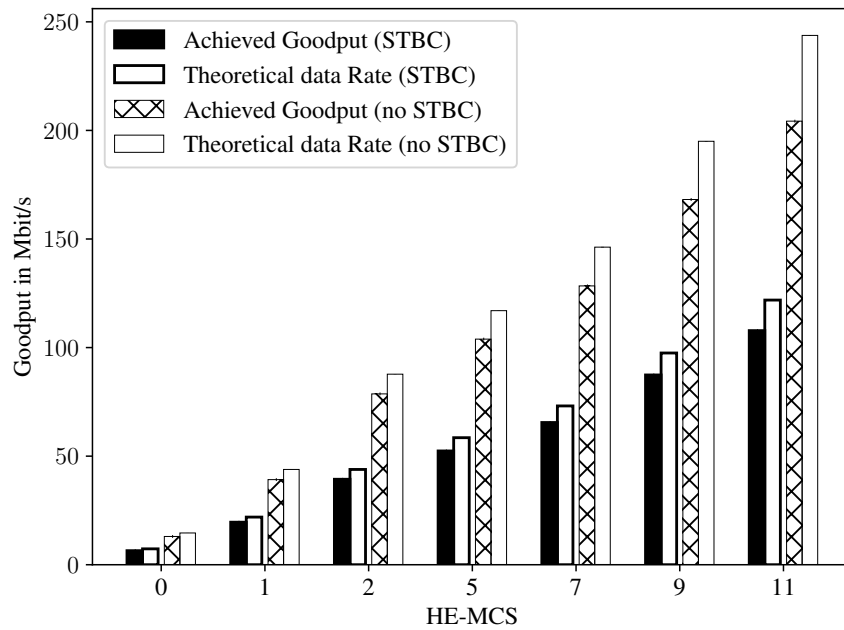


Figure 5.5 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with for IEEE 802.11ax physical layer parameters of a Guard Interval (GI) of 3200 ns, a Bandwidth (BW) of 40 MHz and 2 spatial streams in regards to the number of the chosen HE-Modulation and Coding Scheme (MCS) value and whether Space-Time-Block-Code (STBC) is enabled

Through the new IEEE 802.11ax standard [15], the Wi-Fi standard has been extended to support more MIMO streams or higher MCS values and use LDPC compulsory for the aforementioned configurations. The effect of more MIMO streams is already known from **Lot of stuff**. LDPC no new effect for data rate, but more robustness which results in a lower PER. Robustness?

Error bars goodput lost

5.2 Robustness

The field measurements showed. [10] 3 m corn plants Therefore, the following section focuses on the influence of the different physical layer parameters on the robustness of the IEEE 802.11ax standard Wi-Fi transmissions.

A known simulation tool for wireless communication networks is GNU Radio ¹⁸. GNU Radio is an open-source software development toolkit, which has additional blocks for IEEE 802.11 network simulation, called gr-ieee802-11 ¹⁹. However, the gr-ieee802-11 only supports the IEEE 802.11a, IEEE 802.11b, IEEE 802.11g and IEEE

¹⁸<https://www.gnuradio.org/>

¹⁹<https://github.com/bastibl/gr-ieee802-11>

802.11p. This means, that the gr-ieee802-11 does not support the ER mode, DCM or STBC. Therefore, I decided that the GNU Radio is not suitable for my simulation.

S, Kuri, and Akhtar [62] cites ns-3²⁰, that ns-3 does not implement any frequency-selective fading effects, such as multipath propagation and shadowing. Therefore, the authors decided to use the MATLAB WLAN Toolbox, which is standards-compliant and credible. I also decided to use Matlab because besides [62], [63] and [64] have also considered the MATLAB WLAN Toolbox to be suitable for IEEE 802.11ax simulations.

The MATLAB WLAN Toolbox²¹ is a add-on to simulate, analyse, and test of wireless LAN communications systems. The WLAN Toolbox supports a wide range of IEEE 802.11 standards. Since Release R2019b²², the WLAN Toolbox supports the Signal Recovery, Packet Extension and Physical Layer abstractions to simulation IEEE 802.11ax networks.

My robustness analysis is based on the WLAN Toolbox example wlan/HESUEExample²³ to simulate the PER of point-to-point IEEE 802.11ax networks for a specified SNR values.

First, I set the IEEE 802.11ax physical layer parameters using the wlanHEConfig object, where I define the default settings in Table 5.2.

Next, I chose a channel model to simulate the channel. The WLAN Toolbox supports a wide range of channel models, such as wlanTGaxChannel, wlanTGnChannel, wlanTGacChannel, and wlanTGnChannel. The wlanTGaxChannel model supports 6 different channel models for IEEE 802.11ax networks, named TGax-A, TGax-B, TGax-C, TGax-D, TGax-E, and TGax-F, where the TGax-F channel model is suitable

²⁰<https://www.nsnam.org/docs/models/html/wifi-design.html>

²¹https://de.mathworks.com/products/wlan.html?s_tid=AO_PR_info

²²<https://de.mathworks.com/help/wlan/release-notes.html>

²³<https://de.mathworks.com/help/wlan/ug/802-11ax-packet-error-rate-simulation-for-single-user-format.html>

| Parameter | Chosen Default Settings |
|-------------------------|-------------------------|
| GI | 3200 ns |
| BW | 20 MHz |
| Number Spatial Streams | 2 |
| Number Transmit Antenna | 2 |
| DCM | disabled |
| STBC | disabled |
| HE-MCS | 0 |
| ER | disabled |
| LDPC | enabled |

Table 5.2 – Default physical layer settings for the IEEE 802.11ax robustness simulations

for pseudo-outdoor scenarios [65]. The TGax channel models were used for Matlab Wlan Toolbox simulations by [62], [63] and [64].

[65] and [28] list, that IEEE 802.11ax task group has also implemented the channel models UMa and UMi for outdoor urban scenarios. However, the WLAN Toolbox does not support these channel models and they are intended for urban scenarios, which

As I want to simulate outdoor scenarios, I chose the TGax-F channel model, which is suitable for pseudo-outdoor scenarios [65]. The wlanTGaxChannel model supports configuring the BW, the number of transmit and receive antennas, which I set equal to the configuration of the wlanHEConfig object. [53] and [54] allow outdoor transmission in the frequency range of 5.725 GHz to 5.825 GHz. Therefore, I set the carrier frequency to 5.6 GHz. The TGax-F channel sampling rate is set to 20 MHz, which is the nominal sampling rate for the configured BW of 20 MHz. Additional parameters are left at their default values as they are not relevant for outdoor scenarios. According to the MATLAB WLAN Toolbox documentation ²⁴, the TGax-F channel model has a maximum delay of 1050 ns and root mean square delay spread of 150 ns.

The simulations is based on the procedure 5.1. To get a PER for every SNR value ranging from 0 dB . . . 45 dB, the procedure 5.1 is executed 5 times for 500 packets each. All packet errors are counted and the PER is calculated by dividing the number of packet errors by 500 packets. A mean PER and the confidence interval with a confidence level of 95 % is calculated of the PER values of the 5 iterations.

²⁴<https://de.mathworks.com/help/wlan/ref/wlantgaxchannel-system-object.html>

Require: Global variable *numPacketErrors*

- 1: Create random packet data *txData* of length 1000 Byte
 - 2: Create transmission waveform *txWaveform* from packet data *txData*
 - 3: *rxWaveform* \leftarrow *txWaveform* passed through TGax channel model
 - 4: Add noise to *rxWaveform* based on SNR value
 - 5: Run packet detection on *rxWaveform*
 - 6: **if** no packet detected **then**
 - 7: *numPacketErrors* \leftarrow *numPacketErrors* + 1
 - 8: **end if**
 - 9: Detect packet delay *delay*
 - 10: **if** *delay* > 50 samples **then**
 - 11: *numPacketErrors* \leftarrow *numPacketErrors* + 1
 - 12: **end if**
 - 13: Steps to recover packet data *rxData* from *rxWaveform*
 - 14: **if** *txData* \neq *rxData* **then**
 - 15: *numPacketErrors* \leftarrow *numPacketErrors* + 1
 - 16: **end if**
-

Algorithm 5.1 – Procedure to detect packet errors

The procedure 5.1 starts with the creation of a random packet of the specified length of 1000 Byte. The packet is used to create a Wlan waveform based on the physical layer parameters specified in the wlanHEConfig object using the wlanWaveformGenerator function.

The waveform is extended by 50 trailing zeros to ensure, that packet delays can be detected by finding trailing samples unequal to null. When the possible maximum detectable channel delay can be calculated by

$$\text{detectable channel delay} = \frac{\text{Length of trailing zeros}}{\text{Sampling rate}}, \quad (5.1)$$

then 50 trailing zeros match a maximum channel delay of 2.5 μs . As the maximum channel delay of the TGax-F channel model is 1.05 μs , 50 trailing zeros are sufficient to detect the maximum channel delay. I verified Equation 5.1 by comparing the length of the maximum detected packet delay with the maximum channel delay of the TGax-F channel model. The results showed, that maximum detected packet delay is 11 samples, which can be transferred using Equation 5.1 to rounded maximum TGax-F channel delay of 1.1 μs .

After creating the waveform an appending the trailing zeros, the waveform is passed through the TgaxF channel model to simulate the channel. The output of the channel model is the received waveform, where I added noise to the transmitted waveform based on the specified SNR value and active OFDM subcarriers.

The generated waveform is then passed through the configured wlanTGaxChannel to simulate the channel. The output of the channel model is the received waveform, where I added additive white gaussian noise to the transmitted waveform based on the specified SNR value.

In the next step, the received waveform is passed through the packet detection algorithm, which is based on the WLAN Toolbox example wlan/HESUExample²⁵ and shown in an abstracted form in ???. The procedure calls various functions to decode the preamble, header and payload of the received waveform. A packet error is detected, when, no packet can be detected, the packet delay is greater than 50 samples or the recovered packet data is not equal to the transmitted packet data.

Modulation and Coding Scheme (MCS) and Coding Rate (CR)

In a first simulation run, I analysed the influence of a chosen set of HE-MCS values on the PER in regards to the SNR. The results in Figure 5.6 show that the PER decreases with higher SNR for all HE-MCS values. The PER decreases at lower SNR values for lower HE-MCS values. Increasing the HE-MCS value by 2 increases the SNR, where a PER of less than 10 % is achieved, by 5 dB ... 6 dB.

²⁵<https://de.mathworks.com/help/wlan/ug/802-11ax-packet-error-rate-simulation-for-single-user-format.html>

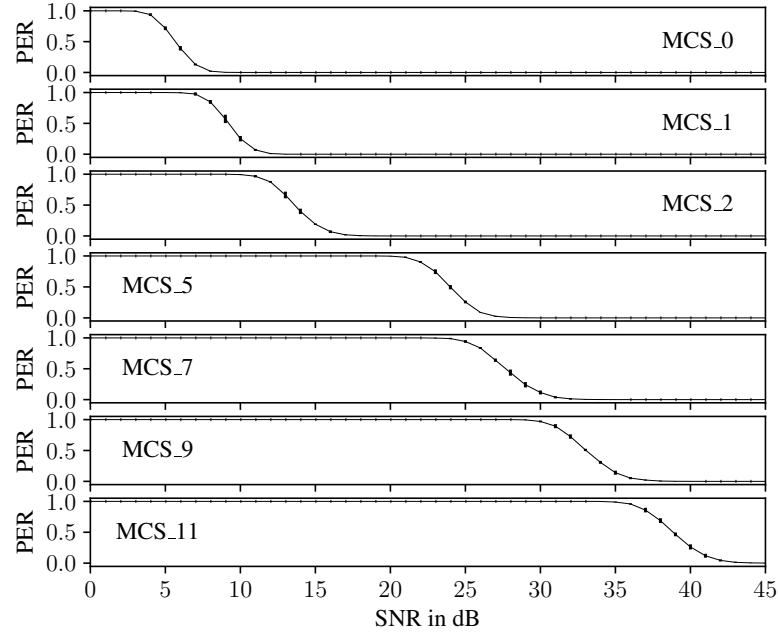


Figure 5.6 – Simulated PER in regards to SNR for chosen HE-MCS values for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a bandwidth of 20 MHz and 2 spatial streams.

Paul et al. [52] conducted outdoor experiments to analyse the error rate and SNR of different IEEE 802.11n MCS for the communication distances of 300 m, 800 m and 1800 m. Their results show that SNR decreases, when the transmissions range is longer. Additionally, they experienced a higher error rate for higher.

The effect, that the PER decreases, when the a lower MCS or CR is used, is the basis for the design of wifi rate managers. A rate manager is a software component responsible to select physical layer parameters, such as MCS or CR, based on the current network conditions to achieve the best possible throughput. Known rate managers of the linux kernel are the minstrel or the minstrel HT rate manager.

Forward Error Correction (FEC)

Another parameter that influences the PER is the choice of the forward error correction (FEC) procedure. In order to analyse the influence of the FEC procedure on the PER, I simulated the PER in regards to the SNR for HE-MCS 0...9 and whether LDPC or BCC is enabled. For higher HE-MCS values BCC can be used as LDPC is compulsory, so no comparison of the FEC procedures is possible.

The results are displayed in Figure 5.7. The PER decreases with higher SNR for both FEC procedures for all HE-MCS values as expected. Using LDPC instead of BCC, a PER of less than 10 % can be achieved at 2 dB higher SNR for all HE-MCS values. The effect increases to 3 dB with higher HE-MCS values than HE-MCS 5.

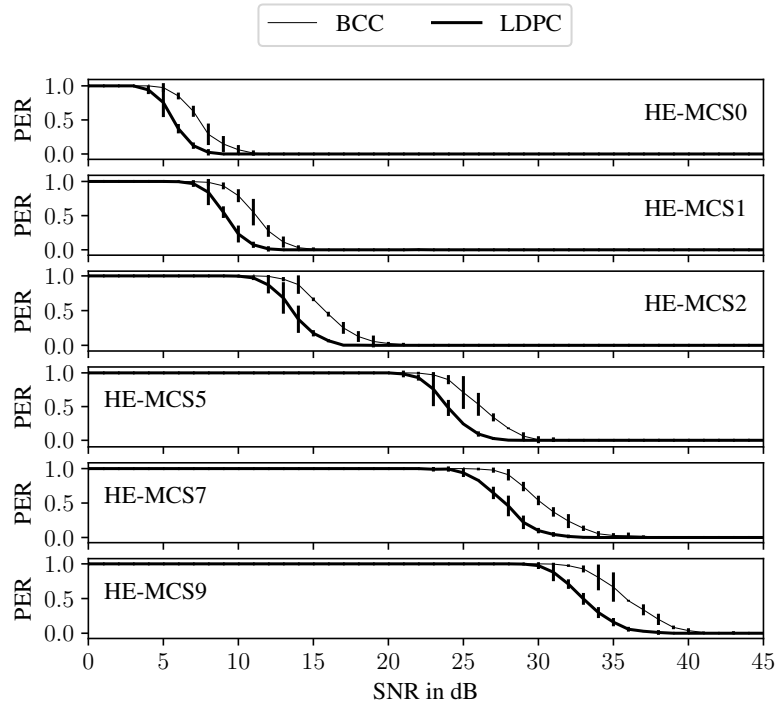


Figure 5.7 – Simulated PER in regards to SNR for chosen HE-MCS values and whether LDPC or BCC is enabled for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a bandwidth of 20 MHz and 2 spatial streams

Syafei et al. [19] simulated the effect of the FEC procedure on the PER for IEEE 802.11n. They had similar results and state, that using LDPC instead of BCC, a PER of 0.1 % can be achieved at a 3.2 dB ... 6 dB higher SNR.

According to Tran et al. [66], this effect is also present for IEEE 802.11ac. A PER of 0.1 % can be achieved at a 1.1 dB higher SNR for using LDPC instead of BCC for 64 - QAM. The effect increases to 1.5 dB for 256 - QAM.

Guard Interval (GI)

Robustness against intercarrier interference and intersymbol interference can be achieved by using a longer GI [21]. In order to analyse the impact of the GI on the PER, I simulated the PER in regards to the SNR for different HE-MCS values. The results for a GI of 3200 ns and 800 ns are plotted in Figure 5.8. The PER decreases with higher SNR for all HE-MCS values as expected. Using a GI of 3200 ns instead

of 800 ns no significant difference of PER in regards to the SNR can be observed for HE-MCS values lower than 5. Increasing the HE-MCS value, the robustness of the MCS sinks and the effect of the intercarrier interference and intersymbol interference increases. As the maximum channel delay for the Tgax-F channel model is 1050 ns, the channel delay can be longer than the GI of 800 ns. This can result in intersymbol interference, which results in a higher PER for higher HE-MCS values. For HE-MCS5, a PER of less than 10 % can be achieved at 1 dB lower SNR for a GI of 3200 ns instead of 800 ns. The effect increases with higher HE-MCS values.

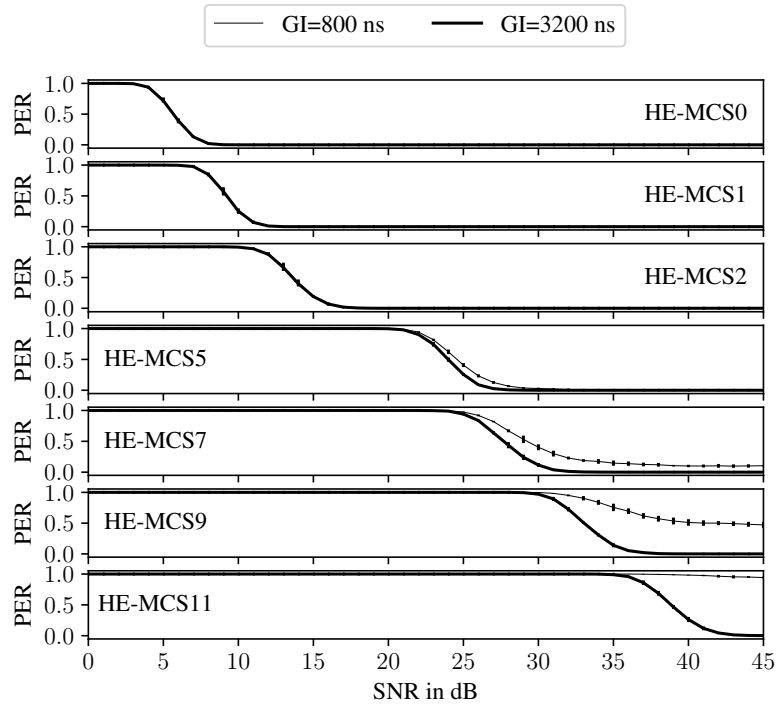


Figure 5.8 – Simulated PER in regards to SNR for chosen HE-MCS values and whether a GI of 800 ns or 3200 ns is enabled for IEEE 802.11ax physical layer parameters of a bandwidth of 20 MHz and 2 spatial streams

Patil et al. [60] conducted similar simulations for IEEE 802.11n. They agree, that a longer GI can increase the robustness against longer delay spreads as they are in the TGn-E and TGn-F channel models, which are predecessors of the TGax-F channel model [65].

Dual Carrier Modulation (DCM)

Next, I simulated the PER in regards to the SNR and whether DCM is enabled for the specified HE-MCS values. Dabei habe ich für die Simulation die möglichen HE-MCS 0,1,3 und 4 aus dem IEEE 802.11ax Standard verwendet.

The results indicate, that using DCM can achieve the same PER at lower SNR values compared to not using DCM. A PER of less than 10 % can be achieved at a 2 dB lower SNR when using DCM. The effect increases to 4 dB for higher HE-MCS4. The results are plotted in Figure 5.9.

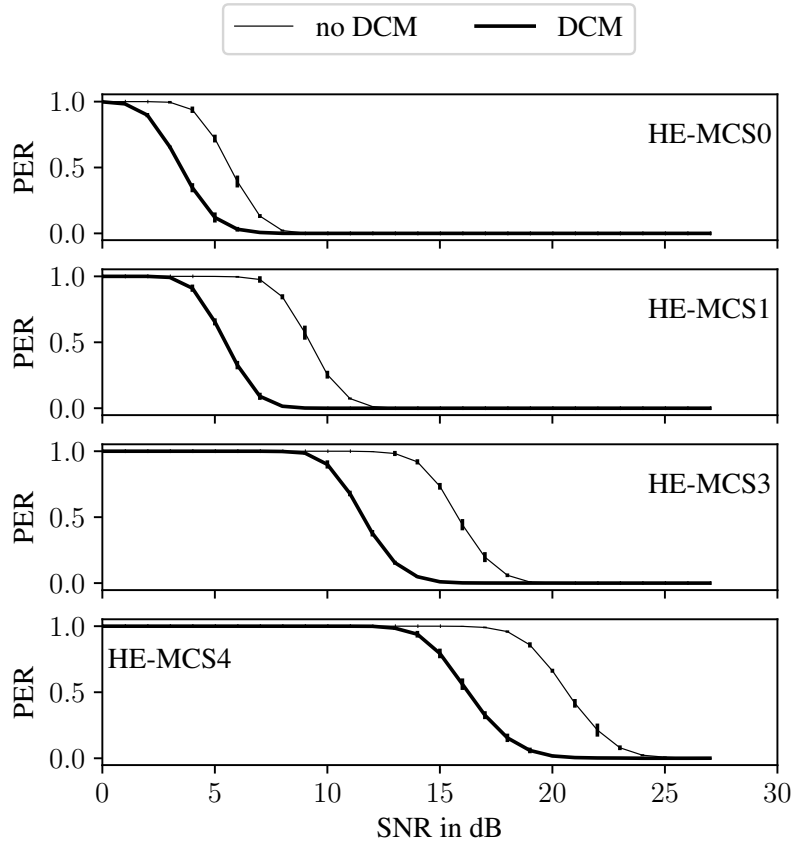


Figure 5.9 – Simulated PER in regards to SNR for chosen HE-MCS values and whether DCM is enabled for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a BW of 20 MHz and 2 spatial streams

Ryu, Lee, and Kang [67] and Park, Sung, and Ko [68] conducted a similar simulation, where they analyse the bit error rate in regards to the normalized SNR and whether DCM was enabled for rayleigh fading channels. Both authors wrapped two Quadrature PSK modulated symbols into one 16-QAM symbol. As Quadrature PSK modulates 2 bit per symbol, the information of two Quadrature PSK modulated symbols can be transmitted in one 16-QAM symbol, which encodes 4 bit. The authors transmit the 16-QAM symbols and a redundant copy of the 16-QAM symbols via orthogonal subcarriers. At the receiver the authors combine the copies and retrieve the transmitted information using the Maximum likelihood criterion. The results

of the author show that a better bite error rate can be achieved while applying DCM than sending the information via two Quadrature PSK or 16-QAM modulated symbols without DCM. [69] DCM 2db gain

Extended Range (ER)

For a HE-MCS 0 and 1 the ER range mode can be applied additional to DCM, when one spatial stream is used [15]. In order to analyse the impact of the ER mode, I set the physical layer parameters to a GI of 3200 ns, a BW of 20 MHz and one spatial streams. For He-MCS 0, 1 and 3 I run simulations, where I enabled the ER mode and compared the PER to the PER of the same HE-MCS values without ER mode.

The results in Figure 5.10 indicate , that the PER is influenced by the ER mode. The difference in SNR with ER mode to without ER mode, where a PER of 10 % is achieved, is 1 dB... 2 dB.

Additionally, I simulated the impact of applying the ER mode and DCM for the allowed HE-MCS values 0 and 1. Applying DCM additionally makes the transmission more robust. As it is displayed in ??, a PER of less than 10 % can be achieved at a

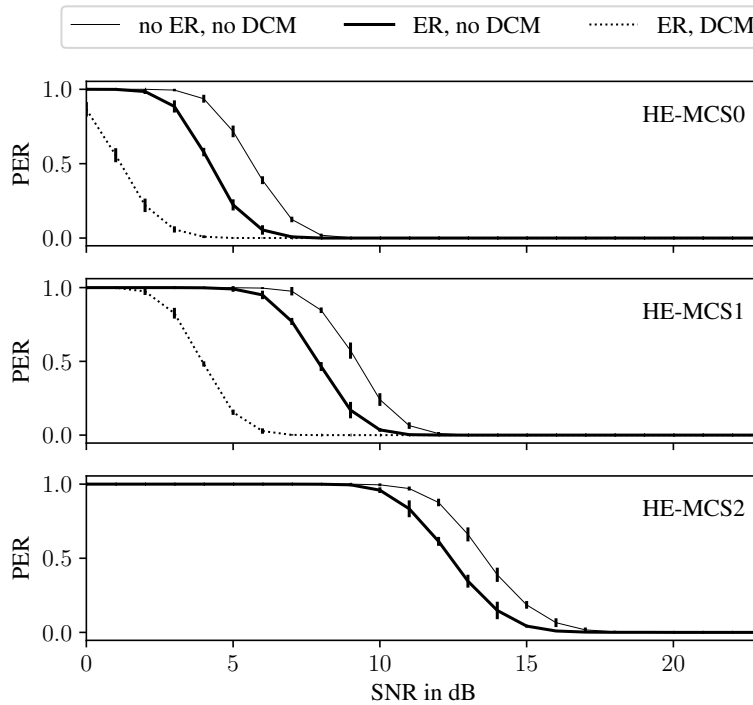


Figure 5.10 – Simulated PER in regards to SNR for chosen HE-MCS values and whether Extended Range or DCM is enabled for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a BW of 20 MHz and 2 spatial streams

4 dB ... 5 dB lower SNR when using DCM and ER mode together instead of using ER mode alone.

Jacob et al. [16] conducted a simulation, where they analysed the effect of DCM and ER on the PER for IEEE 802.11bd in vehicular environments to the transmission range. The authors found out, that the using DCM and ER can increase the transmission range for LoS by 65 % for a PER greater than 0.1. After additional analysis with higher vehicle densities, the authors remark, that using DCM and the ER mode cause channel congestion in CSMA/CA based networks with low bandwidths. The authors conclude, that the ER mode and DCM should be used for long range transmissions, where the physical layer parameters can extend the transmission range significantly.

A similar simulation was conducted by Triwinarko, Dayoub, and Cherkaoui [27]. The researchers state, that using DCM and the ER mode results in better PER performance at lower SNR values in LoS and non LoS scenarios.

Space-Time-Block-Code (STBC)

As aforementioned, additional robustness can be achieved by applying STBC. In order to analyse the impact of STBC on the PER in regards to the SNR, I run the simulation for the HE-MCS values 0 ... 11 with and without STBC.

The results in Figure 5.11 indicate, that the PER is influenced by the STBC mode. A PER of less than 10 % is possible at a 2 dB ... 10 dB lower SNR when using STBC additionally. The impact of STBC on the PER grows from 2 dB for HE-MCS0 to 10 dB for HE-MCS11.

Stamoulis and Al-Dhahir [33] analysed the impact of STBC on the bit error rate for IEEE 802.11a in regards to the SNR. Their simulation was based on a HiperLAN/2 channel with 2 antennas. They used HiperLAN/2, because it has a similar physical layer as IEEE 802.11a. The authors found out, that applying STBC results in a lower bit error rate for a given SNR value. The authors conclude, that STBC can be used to Santumon [32] and Tarokh, Jafarkhani, and Calderbank [70] conducted simulations, where they analysed the effect of STBC on the bit error rate for wireless communication systems. In general, the authors found out, that STBC can be used to increase the bit error rate for a given SNR value for different MCS values. Additionally, the authors remark, that the impact of STBC on the bit error rate grows with the number of antennas. However, the number of antennas is limited to 2 for IEEE 802.11ax [15].

The robustness analysis results indicate, which PER decreases can be achieved by applying the different physical layer parameters. The intensity of the impact varies depending on the environment and the actual communication channel.

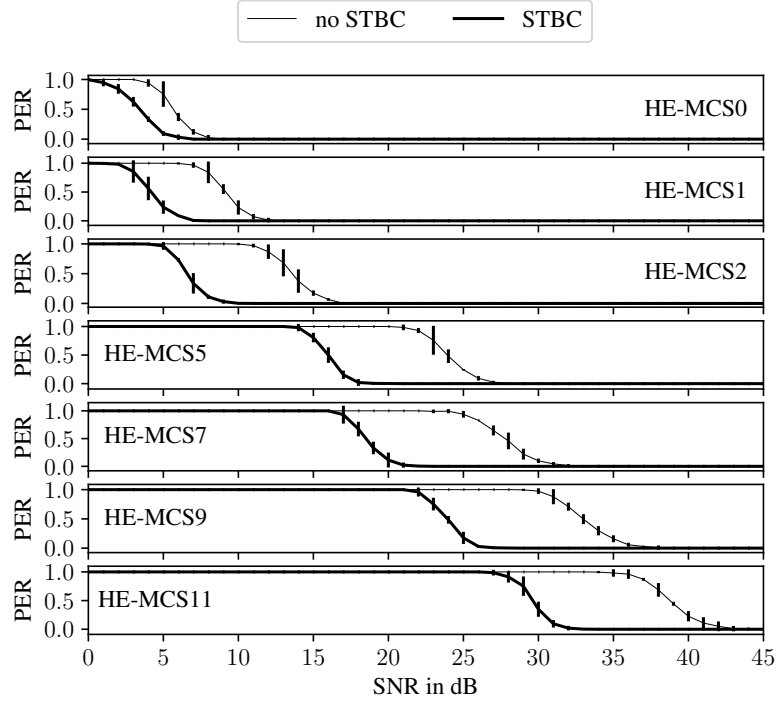


Figure 5.11 – Simulated PER in regards to SNR for chosen HE-MCS values and whether STBC is enabled for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a BW of 20 MHz and 2 spatial streams

I conducted the same simulations for the frequency band of 2.4 GHz. Using the same physical layer parameters in the 2.4 GHz band achieve a similar PER in regards to the SNR and chosen physical layer parameters as in the 5 GHz band.

But how does the effect of the frequency bands on the PER in regards to the SNR differ? Taking the Friis transmission model [71] into account, the RSS for omnidirectional antennas can be calculated in regard to the distance d , receiving antenna gain G_R , transmitting antenna gain G_T and transmission power P_T as follows:

$$RSS = P_T * G_T * G_R * \frac{\lambda^2}{(4 * \pi * d)^2}. \quad (5.2)$$

When λ is replaced and P_T , G_T , and G_R are set to 1 the following equation can be derived:

$$RSS = \frac{c^2}{(f * 4 * \pi * d)^2}, \quad (5.3)$$

where c is the speed of light and f is the frequency of the transmission. Converting the equation to d it results in the following equation:

$$d = \frac{c}{(4 * \pi * f * \sqrt{RSSI})}. \quad (5.4)$$

The equation shows, that a lower frequency results in a higher RSS for a given distance. This means, that the 2.4 GHz band can achieve a higher SNR for a given distance and noise floor compared to the 5 GHz band. The simulation results can now be used to derive the following conclusion, that a lower PER for the 2.4 GHz band can be accomplished for a given set of physical layer parameters, distance and noise floor.

What should be chosen?

5.3 Platooning Services

After I analyzed the impact on data rate and robustness of physical layer parameter, I will simulate a platooning scenario in ns-3 to find the influence of the found physical layer configuration on the network performance. The network performance metric consists of the transmission latency, which describes the time needed to transmit the data on application layer, and the update rate of the platooning service, which defines how long ago a new position update was received by the TM in the Platooning Service.

Ns-3 is suitable for this simulation, because it supports simulation on the application layer level. Via the extension Netsimulyzer a graphical user interface to visualize the simulation results is available.

Any packets in ns-3 can be tagged with a packet Tag²⁶, which are designed to add additional information to the packet. Every added packet Tag belongs to the packet and does not change the packet size or characteristics. Throughout the simulation, I used packets tags to add information, which were needed to be transferred.

The simulation scenario is based on the corn harvest and loading scenario, which is described in section 2.2, where multiple FHs harvest the corn and load it onto one of the TMs.

Thereby, every FH starts in the lower left corner of the field and harvests the corn along the path, which is displayed in Figure 5.12. As soon as a FH reaches a field border, it makes a U-turn and continues in the opposite direction. Every FH harvests the corn until it reaches the end of the field in the lower right corner. The initial position of the TMs is a row below the FHs, which is displayed in Figure 5.13.

²⁶https://www.nsnam.org/docs/release/3.36/doxygen/classns3_1_1_tag.html

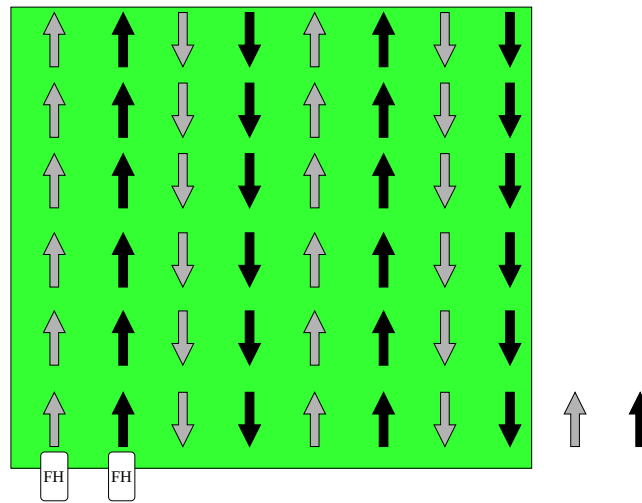


Figure 5.12 – Path of the Forage Harvester (FH) for harvesting corn on the field

Every machine is represented by a ns-3 Node. Each Node has a mobility model, which describes the movement of the machine. In order to exchange data between the machines, every machine is equipped with ns-3 WifiNetDevice, which is a IEEE 802.11ax Wi-Fi device. Every Wi-Fi Device runs in Ad-Hoc mode to enable direct communication between the machines. The Wi-Fi data rate is managed by a Constant Rate Wifi Manager, which has a Non-Uniform transmission mode and a data mode for uniform transmissions. The transmission modes are configured according to the parameters in Table 5.3.

The parameters are chosen from the results of the physical layer analysis of section 5.1 and section 5.2. Non-uniform transmissions are used to broadcast the Agricultural Platooning Service advertisements. The non-uniform transmission parameters enable the longest possible transmission range, which results in the lowest data rate. Since no high data rate is required to advertise the Service, the parameters were chosen to maximize the transmission range. Uniform transmission parameters are used to exchange Agricultural Platooning Service data between the FH and the TM.

The simulation is based on the ns-3 ConstantSpeedPropagationDelayModel, which use the speed of light as a signal propagation speed. Additionally, I configured the ns-3 FriisPropagationLossModel, which is a free space propagation loss model.

Robustness?DataRate?
Fieldexperiments

explain?

| General Parameters | |
|-------------------------------------|---------------|
| Wi-Fi Standard | IEEE 802.11ax |
| GI | 3200 ns |
| Frequency Spectrum | 5.6 GHz |
| BW | 20 MHz |
| max. Transmission Power | 25 dB |
| Antenna Gain | 5 dB |
| Maximum retries | 3 |
| Uniform Transmission Parameters | |
| MCS | 5 |
| Number MIMO Streams | 2 |
| Non-Uniform Transmission Parameters | |
| Broadcast MCS | 0 |
| ER mode enabled | True |
| DCM enabled | True |

Table 5.3 – Simulation parameters for Wi-Fi Devices

Every machine node runs a ns-3 Application, which is responsible for the Agricultural Platooning Service. The application is identified by a unique identifier runs an UDP socket to exchange data with other Agricultural Platooning Service applications. Every UDP socket can be addressed by a IP address and a port number. The IP address is the IP address of the machine node.

In the beginning, every FH broadcasts a search request to find a empty TM to load the corn onto. As shown in Figure 5.13, multiple TMs receive the search request and answer with their current fill level of the TM's trailer. The FH chooses the TM with the lowest fill level and sends a connection request to the TM. As soon as the TM receives the connection request, it answers with a connection response. When the FH receives the connection response, a Agricultural Platooning Service is started.

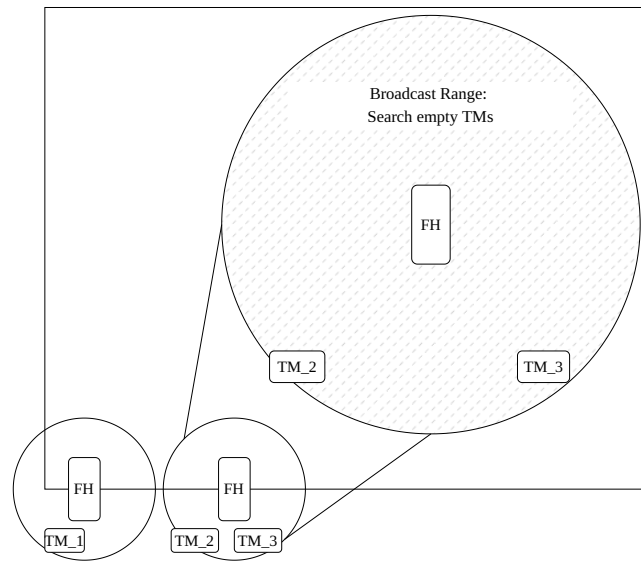


Figure 5.13 – Start position of the Forage Harvester (FH)s and Transport Machine (TM)s, where a FH broadcasts a search request to find a TM to load the corn onto

Next, the FH starts to harvest the corn. All steps of the harvest process and Agricultural Platooning Service are summarized in 5.3.

The FH harvest process is defined by the harvest states in ??, where every harvest state represents a different PD and FH speed. When the PD is low, the FH can harvest faster and vice versa.

Starting in the harvest state H1, the FH determines the next harvest state every 50 ms by the Markov chain in Figure 5.14. This Markov chain ensures that the

Require: Defined *search_TM_interval*, *search_TM_packet_length*

- 1: Create packet *search_TM* of length *search_TM_packet_length* bytes
 - 2: Broadcast *search_TM* to all TMs
 - 3: **if** no TM answers **then**
 - 4: Repeat Broadcasting *search_TM* every *search_TM_interval* seconds
 - 5: **else**
 - 6: Send connection request
 - 7: **if** No TM response **then**
 - 8: Repeat Broadcasting *search_TM* every *search_TM_interval* seconds
 - 9: **else**
 - 10: Connection established
 - 11: Start Agricultural Platooning Service
 - 12: **end if**
 - 13: **end if**
-

Algorithm 5.2 – Procedure of the Forage Harvester (FH) to search for a Transport Machine (TM) to load the corn onto

harvest state can't transverse from H0 to H2 directly, which would represent a low PD immediately followed by a high PD. As I have not enough harvest process data, which contain the PD and the FH speed, I chose the transition probabilities randomly.

by common sense?

| Harvest State | PD | FH speed |
|---------------|---------|----------|
| H0 | 30 t/ha | 10 km/h |
| H1 | 40 t/ha | 8 km/h |
| H2 | 50 t/ha | 6 km/h |

Table 5.4 – Corn harvest states, which define a range of Plant Density (PD)s and Forage Harvester (FH) speeds, where the data is based on the key figures [6]

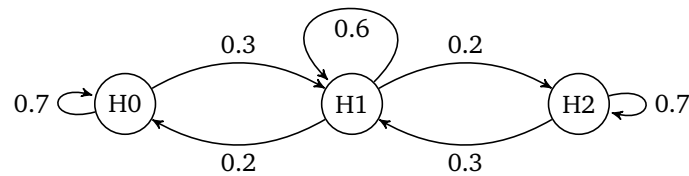


Figure 5.14 – Markov Chain for the states Plant Density (PD) 0, 1 and 2, which represent the current PD and harvest speed from Table 5.4.

After determining the next harvest state, the FH sets the PD and the FH speed according to the defined values in ??. The position of the FH is advanced by the FH

Require: Defined *platoon_data_interval*, *platoon_data_packet_length*

- 1: Calculate harvested volume
- 2: Advance FH position
- 3: Add harvested volume to TM fill level
- 4: **if** TM fill level is full **then**
- 5: Disconnect from current TM
- 6: Start Agricultural Platooning Service with waiting TM
- 7: **else**
- 8: Create packet *TM_data* of length *platoon_data_packet_length* bytes, which contains the TM fill level and the new guidance position
- 9: Send *TM_data* to TM
- 10: **if** TM fill level is half full **then**
- 11: Start Algorithm 5.2 to search for new TM
- 12: **end if**
- 13: **end if**

Algorithm 5.3 – Procedure of the Forage Harvester (FH) to send the Transport Machine (TM) fill level and the TM guidance position every *platoon_data_interval*

speed multiplied with 50 ms along the harvest path in Figure 5.12. The harvested volume during this time step of 50 ms is calculated with the following equations:

$$\text{Harvested Area} = \frac{\text{Harvest width} \times \text{Harvest speed} \times \text{Time step}}{10000}, \quad (5.5)$$

$$\text{Harvested Volume} = \text{Harvested Area} \times \text{PD} \times \text{Corn volume per tonne}. \quad (5.6)$$

The harvested area is represented in ha and the harvested volume is represented in m³. The needed parameters for the calculation are from [6] and are listed in Table 5.5. The calculated harvested volume is added to the TM's fill level, which is tracked by the FH's application. Keeping track of the fill level represents the knowledge of the FH about the TM's fill level, which the FH would normally get through the Sprout guidance system.

Next, the FH determines whether the TM is full or not. If the TM is full, the FH stops harvesting and sends a disconnect request to the TM. The TM answers with a disconnect response and leaves the field to unload the corn.

If the TM is not full, the FH sends the new TM fill level and the new guidance position to the TM. The TM updates the fill level and drives to the new position to load the corn, as it is shown in Figure 5.16. The guidance position is always left of the FH, because this part of the field was already harvested. The distance between the FH and the TM is 5 m as the FH and the TM moved mostly with a distance of around 5 m in the recorded process data in chapter 3.

If the TM fill level is half full, the FH starts the 5.2 to search for a new TM to load the corn onto. This is visualized in Figure 5.16. As soon as the FH finds a new TM, the FH connects to the new TM and starts sending the TM guidance positions, which place the TM 20 m behind the FH. The FH continues harvesting until the TM is full. Meanwhile, the new TM is waiting behind the FH and can take over the loading position next to the FH as soon as the TM, where the FH is currently loading onto, is full.

| Parameters | |
|----------------------------------|-----------------|
| <i>search_TM_interval</i> | 1 s |
| <i>search_TM_packet_length</i> | 500 Byte |
| Position Service Update Interval | 50 ms |
| Platoon Service Data | 1000 Byte |
| Platoon Overloading Distance | 6 m |
| Field Size | 2000 m x 1000 m |

Table 5.5 – Simulation parameters for the Application Agricultural Platooning Service

ha? Conversion? Introduce Abbreviations?

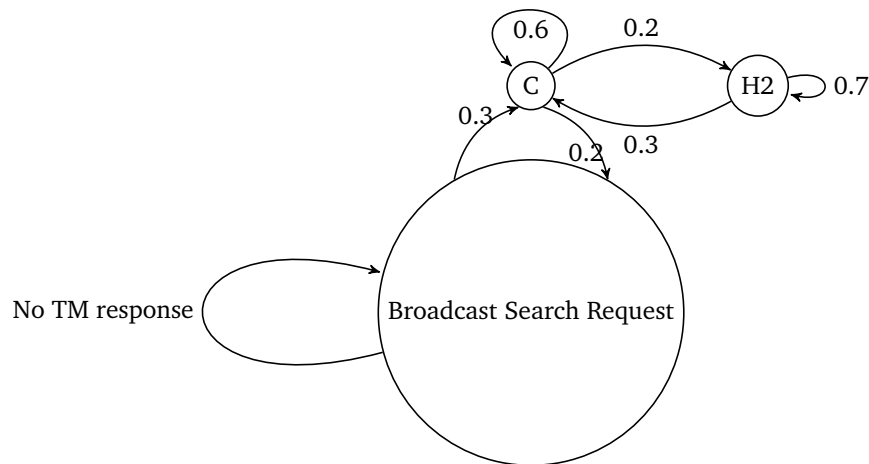


Figure 5.15 – Markov Chain for the states Plant Density (PD) 0, 1 and 2, which represent the current PD and harvest speed from Table 5.4.

Zhang et al. [7] defined a data frame of 32 Byte, which includes an identifier, timestamp, Longitude, Latitude, Heading, Speed and Direction. Diese Menge an Daten umfasst eine Grundmenge, welche für die Umsetzung eines Platooning Services ausreichen kann, wie die Autoren zeigen. Schlingmann and Benishek [2] spezifizieren die Datenmenge nicht weiter und weisen darauf hin, dass die benötigte Datenrate für Platooning Services gering ist.

Ich habe für die Simulation von Platooning Services die Datenmenge auf 1 kByte gesetzt. Diese Datengröße ist eine Abstrahierung des Speicherplatzes, welcher möglicherweise für zusätzliche Daten oder Implementierungen von Authentifizierung - und Sicherheitsmechanismen benötigt wird. Im Corn Harvest scenario können zusätzliche Daten z.B. der Füllstand der Transportmaschine sein.

Service Discovery

Rebroadcast by Count? additional Traffic

MANET Service discovery

Visualisierung Netsimulyzer

Farbcodes

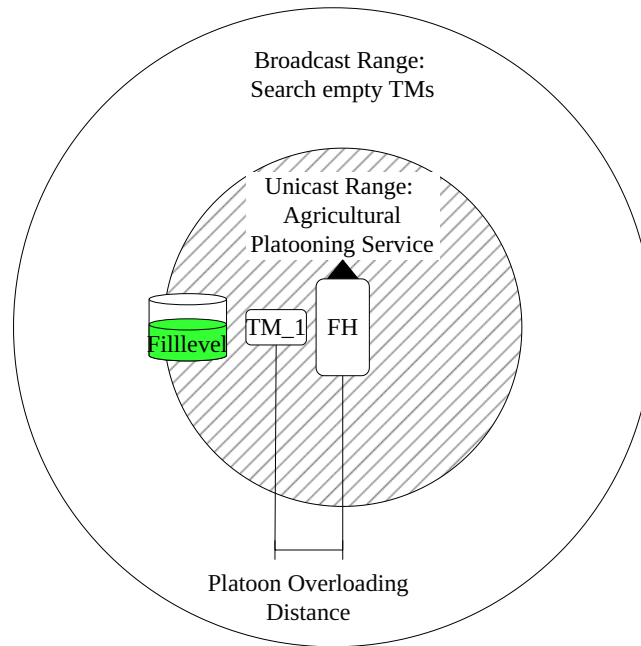


Figure 5.16 – Transport Machine (TM) position left of the Forage Harvester (FH) for overloading, where the TM is half full and the FH starts the 5.2 to search for a next empty TM, which can later take over the loading position.

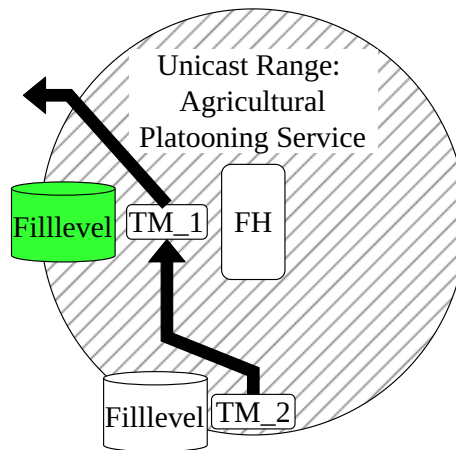


Figure 5.17 – Change of Transport Machine (TM)s in the Application Agricultural Platooning Service, where *TM_1* is full and leaves the field while the empty *TM_2* takes over the overloading position.

Chapter 6

Evaluation

- measurement setup / results / evaluation / discussion
- whatever you have done, you must comment it, compare it to other systems, evaluate it
- usually, adequate graphs help to show the benefits of your approach
- each result/graph must not only be described, but also discussed (What's the reason for this peak? Why have you observed this effect? What does this tell about your architecture/system/implementation?)
- recommended length: approximately one third of the thesis.

Chapter 7

Conclusion

- summarize again what your paper did, but now emphasize more the results, and comparisons
- write conclusions that can be drawn from the results found and the discussion presented in the paper
- future work (be very brief, explain what, but not much how, do not speculate about results or impact)
- recommended length: one page.

Untersuchen, welche Routing protocols

List of Abbreviations

| | |
|-----------------|--|
| 802.11ac | IEEE 802.11ac |
| 802.11ax | IEEE 802.11ax |
| ACK | Acknowledgement |
| AEF | Agricultural Industry Electronics Foundation |
| AP | Access Point |
| BCC | binary convolutional coding |
| BSS | Basic Service Set |
| BW | Bandwidth |
| CH | Combine Harvester |
| CR | Coding Rate |
| CSMA/CA | Carrier Sense Multiple Access/Collision Avoidance |
| CTS | Clear-to-Send |
| DCF | Distribution Coordination Function |
| DCM | Dual Carrier Modulation |
| DIFS | Distributed Coordination Function Interframe Space |
| EDCA | Enhanced Distributed Channel Access |
| ER | Extended Range |
| ESS | Extended Service Set |
| FEC | Forward Error Correction |
| FH | Forage Harvester |
| FMIS | Farm Management Information System |
| GI | Guard Interval |
| GPS | Global Positioning System |
| HE | High-Efficiency |
| HT | High-Throughput |
| IBSS | Independent Basic Service Set |
| IFS | Interframe Space |
| LDPC | low-density parity-check |
| LOS | Line-of-sight |
| LoS | Line-Of-Sight |

| | |
|--------------|---|
| M2M | Machine-To-Machine |
| MCS | Modulation and Coding Scheme |
| MIMO | Multiple Input Multiple Output |
| MU | Multi-User |
| NAV | Network Allocation Vector |
| OFDM | Orthogonal Frequency-Division Multiplexing |
| OFDMA | Orthogonal Frequency-Division Multiple Access |
| PCF | Point Coordination Function |
| PD | Plant Density |
| PER | packet error rate |
| PPDU | Physical layer convergence protocol data unit |
| PSK | Phase Shift Keying |
| QAM | Quadrature Amplitude Modulation |
| RSS | Received Signal Strength |
| RTS | Request-to-Send |
| RU | Resource Unit |
| SIFS | Short Interframe Space |
| SINR | Signal-to-Interference-plus-Noise Ratio |
| SNR | Signal Noise Ratio |
| SSID | Service Set Identifier |
| STA | station |
| STBC | Space-Time-Block-Code |
| SU | Single-User |
| TM | Transport Machine |
| UDP | User Datagram Protocol |
| V2X | Vehicle-to-everything |
| VHT | Very-High-Throughput |
| WIC | Wireless-Infield Communication |
| WPA | Wi-Fi Protected Access |

List of Figures

| | | |
|-----|---|----|
| 2.1 | Forage Harvester (FH) and Transport Machine (TM) in a corn harvesting and loading process | 5 |
| 2.2 | Lateral and longitudinal offset between the two agricultural machines Forage Harvester (FH) and Transport Machine (TM) in a corn harvest scenario | 6 |
| 2.3 | Decrease in the agricultural labor force in Germany based on the data from [9] | 7 |
| 2.4 | Receiver minimum input level sensitivity for different HE-MCS values according to [15], where PER is less than 10 % | 13 |
| 2.5 | Hidden Station Problem, where interferences at the Access Point (AP) can occur, when station (STA) A and B send simultaneously | 18 |
| 2.6 | Data transmission between a sender and receiver in regards to the time with normal Acknowledgement (ACK) 2.6a, fragmentation 2.6b and additional Block ACK 2.6c | 19 |
| 3.1 | A FH and a TM in harvest and overloading scenario, which is represented as distance and speed data plotted in regards to the time and which is visualised on a map as a black line and white line for the FH, TM respectively | 28 |
| 3.2 | Distribution of time proportions where a given distance was between Forage Harvester (FH) and Transport Machine (TM) in a harvest platoon scenario. | 29 |
| 3.3 | Distribution of time proportions where Forage Harvester (FH) and Transport Machine (TM) drove with a certain speed in a harvest platoon scenario | 29 |
| 3.4 | Relative bearing between FH and TM which is calculated using the previous location of FH by using β and α for Equation 3.1 | 30 |
| 3.5 | Distribution of time proportion at specific distances and relative bearings between Forage Harvester (FH) and Transport Machine (TM) . . | 31 |

| | |
|---|----|
| 3.6 Forage Harvester (FH) and Transport Machine (TM) start cutting a new field section | 31 |
| 4.1 Path around the static Combine Harvester (CH), which the Transport Machine (TM) will drive during the experiment to mimic various overloading positions | 34 |
| 4.2 Wi-Fi transmissions between the Wi-Fi AP on the Transport Machine (TM) and the Wi-Fi STA on the Combine Harvester (CH), which are recorded by a third Wi-Fi device in monitor mode on the CH | 35 |
| 4.3 All QoS data transmissions between the Wi-Fi Access Point (AP) on the Transport Machine (TM) and the Wi-Fi STA on the Combine Harvester (CH) in a trail run | 36 |
| 4.4 All QoS data transmissions between the Wi-Fi Access Point (AP) on the Transport Machine (TM) and the Wi-Fi STA on the Combine Harvester (CH) in a trail run, which were initiated by the iperf3 client on the Transport Machine (TM) | 37 |
| 4.5 QoS data transmissions between the Wi-Fi Access Point (AP) on the Transport Machine (TM) and the Wi-Fi STA on the Combine Harvester (CH) in a trail run, which were initiated by AP | 37 |
| 4.6 All QoS data transmissions between the Wi-Fi Access Point (AP) on the Transport Machine (TM) and the Wi-Fi STA on the Combine Harvester (CH) in a trail run, which were initiated by the Wi-Fi STA on the CH | 38 |
| 4.7 Percentage of retransmissions for every transmission in the trail run | 38 |
| 5.1 Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with 2 Multiple Input Multiple Output (MIMO) streams and a bandwidth of 80 MHz in regards to the number of Multiple Input Multiple Output (MIMO) streams and the chosen HE-Modulation and Coding Scheme (MCS) value | 43 |
| 5.2 Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with a Guard Interval (GI) of 3200 ns and a bandwidth of 80 MHz in regards to the number of Multiple Input Multiple Output (MIMO) streams and the chosen HE-MCS value | 44 |
| 5.3 Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with a Guard Interval (GI) of 3200 ns and a bandwidth of 20 MHz in regards to the number of Multiple Input Multiple Output (MIMO) streams and the chosen HE-MCS value | 45 |

| | | |
|------|--|----|
| 5.4 | Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with for IEEE 802.11ax physical layer parameters of a Guard Interval (GI) of 3200 ns, a Bandwidth (BW) of 40 MHz and 2 spatial streams in regards to the number of the chosen HE-Modulation and Coding Scheme (MCS) value and whether Dual Carrier Modulation (DCM) is enabled | 46 |
| 5.5 | Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with for IEEE 802.11ax physical layer parameters of a Guard Interval (GI) of 3200 ns, a Bandwidth (BW) of 40 MHz and 2 spatial streams in regards to the number of the chosen HE-Modulation and Coding Scheme (MCS) value and whether Space-Time-Block-Code (STBC) is enabled | 48 |
| 5.6 | Simulated PER in regards to SNR for chosen HE-MCS values for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a bandwidth of 20 MHz and 2 spatial streams. | 52 |
| 5.7 | Simulated PER in regards to SNR for chosen HE-MCS values and whether LDPC or BCC is enabled for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a bandwidth of 20 MHz and 2 spatial streams | 53 |
| 5.8 | Simulated PER in regards to SNR for chosen HE-MCS values and whether a GI of 800 ns or 3200 ns is enabled for IEEE 802.11ax physical layer parameters of a bandwidth of 20 MHz and 2 spatial streams | 54 |
| 5.9 | Simulated PER in regards to SNR for chosen HE-MCS values and whether DCM is enabled for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a BW of 20 MHz and 2 spatial streams | 55 |
| 5.10 | Simulated PER in regards to SNR for chosen HE-MCS values and whether Extended Range or DCM is enabled for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a BW of 20 MHz and 2 spatial streams | 56 |
| 5.11 | Simulated PER in regards to SNR for chosen HE-MCS values and whether STBC is enabled for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a BW of 20 MHz and 2 spatial streams | 58 |
| 5.12 | Path of the Forage Harvester (FH) for harvesting corn on the field . . | 60 |
| 5.13 | Start position of the Forage Harvester (FH)s and Transport Machine (TM)s, where a FH broadcasts a search request to find a TM to load the corn onto | 62 |
| 5.14 | Markov Chain for the states Plant Density (PD) 0, 1 and 2, which represent the current PD and harvest speed from Table 5.4. | 63 |
| 5.15 | Markov Chain for the states Plant Density (PD) 0, 1 and 2, which represent the current PD and harvest speed from Table 5.4. | 65 |

-
- 5.16 Transport Machine (TM) position left of the Forage Harvester (FH) for overloading, where the TM is half full and the FH starts the 5.2 to search for a next empty TM, which can later take over the loading position. 66
- 5.17 Change of Transport Machine (TM)s in the Application Agricultural Platooning Service, where TM_1 is full and leaves the field while the empty TM_2 takes over the overloading position. 66

List of Tables

| | | |
|-----|---|----|
| 2.1 | Key figures of corn harvest of a Forage Harvester (FH) with a working width of 6.2 m in a 80 ha-field in regards to Plant Density (PD) [6] . . | 6 |
| 2.2 | Available BWs for the IEEE 802.11 standards per frequency band. . . | 10 |
| 2.3 | MCS and CR for HE-MCS values [15] | 12 |
| 2.4 | Access Categories and their priorities for IEEE 802.11e EDCA [37] . . | 17 |
| 2.5 | Comparison of IEEE 802.11ac and IEEE 802.11ax | 21 |
| 4.1 | Frequency Channels numbers for 2.4 GHz and 5 GHz for the different Bandwidth (BW)s of the IEEE 802.11 standard [14], which can be used for outdoor communication [53], [54] and are configured in the Milesight Industrial Router UR75 for the field experiments. | 35 |
| 5.1 | Bandwidth (BW) attenuation and mean goodput for HE-MCS0 in regards to Guard Interval (GI) length | 43 |
| 5.2 | Default physical layer settings for the IEEE 802.11ax robustness simulations | 49 |
| 5.3 | Simulation parameters for Wi-Fi Devices | 61 |
| 5.4 | Corn harvest states, which define a range of Plant Density (PD)s and Forage Harvester (FH) speeds, where the data is based on the key figures [6] | 63 |
| 5.5 | Simulation parameters for the Application Agricultural Platooning Service | 64 |

Bibliography

- [1] N. Iglesias, P. Bulacio, and E. Tapia, “Enabling powerful GUIs in ISOBUS networks by transparent data compression,” *Computer Standards & Interfaces*, vol. 36, no. 5, pp. 801–807, Sep. 2014. DOI: <https://doi.org/10.1016/j.csi.2014.01.007>.
- [2] N. Schlingmann and M. Benishek, “AEF - Providing electronic communication to the Ag sector for Wireless In - Field Communication,” in *2019 ASABE Annual International Meeting*, Issue: 1901864, Boston, Portugal, Jul. 2019. DOI: [10.13031/aim.201901864](https://doi.org/10.13031/aim.201901864).
- [3] N. Schlingmann, H. Schallermayer, J. Witte, and C. Gossard, “Challenges of digital revolution – How the AEF plans to manage interoperability,” in *VDI-Berichte: LAND.TECHNIK AgEng 2017*, vol. 2300, Jan. 2017, pp. 477–484. DOI: [10.51202/9783181023006-477](https://doi.org/10.51202/9783181023006-477).
- [4] “ICT Facts and Figures 2016,” ITU, ITU-D ICT Statistics 2016, 2016.
- [5] H. Seifert, K. Grimm, and M. Schurig, *Der Feldhäcksler und was dazu gehört*. Wolfratshausen bei München: Neureuter, 1962.
- [6] *Faustzahlen für die Landwirtschaft*, ger, 15. Aufl. Darmstadt: Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL), 2018.
- [7] X. Zhang, M. Geimer, L. Grandl, and B. Kammerbauer, “Method for an electronic controlled platooning system of agricultural vehicles,” in *2009 IEEE International Conference on Vehicular Electronics and Safety (ICVES)*, Nov. 2009, pp. 156–161. DOI: [10.1109/ICVES.2009.5400187](https://doi.org/10.1109/ICVES.2009.5400187).
- [8] Z. Liu, S. Dhamankar, J. T. Evans, C. M. Allen, C. Jiang, G. M. Shaver, A. Etienne, T. J. Vyn, C. M. Puryk, and B. M. McDonald, “Automation of Agricultural Grain Unloading-on-the-go,” in *IFAC-PapersOnLine*, 10th IFAC Symposium on Advances in Automotive Control AAC 2022, vol. 55, no. 24, pp. 248–253, Jan. 2022. DOI: [10.1016/j.ifacol.2022.10.292](https://doi.org/10.1016/j.ifacol.2022.10.292).
- [9] “Arbeitskräfte in der Landwirtschaft / BMEL (723),” Statistisches Bundesamt: Fachserie 3, BMEL (723) Reihe 2.1.8, 2020, <https://www.bmel-statistik.de/landwirtschaft/landwirtschaftliche-arbeitskraefte>.

- [10] I. Smolnik and A. Lücke, "5G NetMobil - 5G Lösungen für die vernetzte Mobilität der Zukunft : Schlussbericht : Teilvorhaben: "Entwicklung eines Parallelen Platooning Systems für den Bereich der Landtechnik unter Verwendung von 5G Technologien"\$dSchlussbericht," [Dissen a.T.W.], Tech. Rep., 2020. DOI: 10.2314/KXP:1757666915.
- [11] H. Murcia, "A quadrotor as remote sensor for on-line profile measurement during harvesting process," Ph.D. dissertation, May 2014. DOI: 10.13140/RG.2.1.1842.3522.
- [12] F.-J. Kauffels, Wireless LANs: drahtlose Netze planen und verwirklichen, der Standard IEEE 802.11 im Detail, WLAN-Design und Sicherheitsrichtlinien (Netzwerke), ger, 1. Aufl. Bonn: mitp-Verl, 2002.
- [13] M. Sauter, "Wireless LAN IEEE 802.11," de, in *Grundkurs Mobile Kommunikationssysteme: 5G New Radio und Kernnetz, LTE-Advanced Pro, GSM, Wireless LAN und Bluetooth*, M. Sauter, Ed., Wiesbaden: Springer Fachmedien, 2022, pp. 265–338. DOI: 10.1007/978-3-658-36963-7_4.
- [14] "IEEE Standard for Information Technology–Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks–Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Std 802.11-2020 (Revision of IEEE Std 802.11-2016)*, pp. 1–4379, Feb. 2021, Conference Name: IEEE Std 802.11-2020 (Revision of IEEE Std 802.11-2016). DOI: 10.1109/IEEESTD.2021.9363693.
- [15] "IEEE Standard for Information Technology–Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks–Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 1: Enhancements for High-Efficiency WLAN," *IEEE Std 802.11ax-2021 (Amendment to IEEE Std 802.11-2020)*, pp. 1–767, May 2021, Conference Name: IEEE Std 802.11ax-2021 (Amendment to IEEE Std 802.11-2020). DOI: 10.1109/IEEESTD.2021.9442429.
- [16] R. Jacob, W. Anwar, N. Schwarzenberg, N. Franchi, and G. Fettweis, "System-level Performance Comparison of IEEE 802.11p and 802.11bd Draft in Highway Scenarios," en, in *2020 27th International Conference on Telecommunications (ICT)*, Bali, Indonesia: IEEE, Oct. 2020, pp. 1–6. DOI: 10.1109/ICT49546.2020.9239538.
- [17] S. Avallone, P. Imputato, G. Redieteb, C. Ghosh, and S. Roy, "Will OFDMA Improve the Performance of 802.11 Wifi Networks?" *IEEE Wireless Commu-*

- nications, vol. 28, no. 3, pp. 100–107, Jun. 2021, Conference Name: IEEE Wireless Communications. DOI: 10.1109/MWC.001.2000332.
- [18] M. S. Afaqui, E. Garcia-Villegas, and E. Lopez-Aguilera, “IEEE 802.11ax: Challenges and Requirements for Future High Efficiency WiFi,” *IEEE Wireless Communications*, vol. 24, no. 3, pp. 130–137, Jun. 2017, Conference Name: IEEE Wireless Communications. DOI: 10.1109/MWC.2016.1600089WC.
- [19] W. A. Syafei, R. Yohena, H. Shimajiri, T. Yoshida, M. Kurosaki, Y. Nagao, B. Sai, and H. Ochi, “Performance Evaluation and ASIC Design of LDPC Decoder for IEEE802.11n,” in *2009 6th IEEE Consumer Communications and Networking Conference*, ISSN: 2331-9860, Jan. 2009, pp. 1–5. DOI: 10.1109/CCNC.2009.4784735.
- [20] B. Y. Yacheur, T. Ahmed, and M. Mosbah, “Analysis and Comparison of IEEE 802.11p and IEEE 802.11bd,” en, in *Communication Technologies for Vehicles*, F. Krief, H. Aniss, L. Mendiboure, S. Chaumette, and M. Berbineau, Eds., vol. 12574, Series Title: Lecture Notes in Computer Science, Cham: Springer International Publishing, 2020, pp. 55–65. DOI: 10.1007/978-3-030-66030-7_5.
- [21] N. Pulimamidi, J. Nulu, and M. M. Tahernezehadi, “Development of a new OFDM transceiver without guard interval,” in *2007 IEEE International Conference on Electro/Information Technology*, ISSN: 2154-0373, May 2007, pp. 300–305. DOI: 10.1109/EIT.2007.4374539.
- [22] N. S. Ravindranath, I. Singh, A. Prasad, and V. S. Rao, “Performance Evaluation of IEEE 802.11ac and 802.11n using NS3,” en, *Indian Journal of Science and Technology*, vol. 9, no. 26, Jul. 2016. DOI: 10.17485/ijst/2016/v9i26/93565.
- [23] Van Duc Nguyen and H.-P. Kuchenbecker, “Intercarrier and intersymbol interference analysis of OFDM systems on time-invariant channels,” en, in *The 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 4, Pavilhao Atlantico, Lisboa, Portugal: IEEE, 2002, pp. 1482–1487. DOI: 10.1109/PIMRC.2002.1045425.
- [24] D.-J. Deng, Y.-P. Lin, X. Yang, J. Zhu, Y.-B. Li, J. Luo, and K.-C. Chen, “IEEE 802.11ax: Highly Efficient WLANs for Intelligent Information Infrastructure,” *IEEE Communications Magazine*, vol. 55, no. 12, pp. 52–59, Dec. 2017, Conference Name: IEEE Communications Magazine. DOI: 10.1109/MCOM.2017.1700285.

- [25] A. F. Rochim, B. Harijadi, Y. P. Purbanugraha, S. Fuad, and K. A. Nugroho, "Performance comparison of wireless protocol IEEE 802.11ax vs 802.11ac," in *2020 International Conference on Smart Technology and Applications (ICoSTA)*, IEEE, Feb. 2020, pp. 1–5. DOI: 10.1109/ICoSTA48221.2020.1570609404.
- [26] E. Mozaffariahrar, F. Theoleyre, and M. Menth, "A Survey of Wi-Fi 6: Technologies, Advances, and Challenges," en, *Future Internet*, vol. 14, no. 10, p. 293, Oct. 2022, Number: 10 Publisher: Multidisciplinary Digital Publishing Institute. DOI: 10.3390/fi14100293.
- [27] A. Triwinarko, I. Dayoub, and S. Cherkaoui, "PHY layer enhancements for next generation V2X communication," en, *Vehicular Communications*, vol. 32, p. 100385, Dec. 2021. DOI: 10.1016/j.vehcom.2021.100385.
- [28] H. A. Omar, K. Abboud, N. Cheng, K. R. Malekshan, A. T. Gamage, and W. Zhuang, "A Survey on High Efficiency Wireless Local Area Networks: Next Generation WiFi," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 4, pp. 2315–2344, 2016, Conference Name: IEEE Communications Surveys & Tutorials. DOI: 10.1109/COMST.2016.2554098.
- [29] E. Khorov, A. Kiryanov, A. Lyakhov, and G. Bianchi, "A Tutorial on IEEE 802.11ax High Efficiency WLANs," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 1, pp. 197–216, Sep. 2019, Publisher: IEEE. DOI: 10.1109/COMST.2018.2871099.
- [30] A. Behara and T. Venkatesh, "Performance Study of High-Efficiency IEEE 802.11ax WLAN Standard Using NS-3 Simulator," in *2022 IEEE 27th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, ISSN: 2378-4873, Nov. 2022, pp. 226–231. DOI: 10.1109/CAMAD55695.2022.9966905.
- [31] W. Abbas, N. Abbas, U. Majeed, and S. Khan, "EFFICIENT STBC FOR THE DATA RATE OF MIMO-OFDMA," en, 2016.
- [32] S. Santumon, "Space-Time Block Coding (STBC) for Wireless Networks," en, *International Journal of Distributed and Parallel systems*, vol. 3, no. 4, pp. 183–195, Jul. 2012. DOI: 10.5121/ijdps.2012.3419.
- [33] A. Stamoulis and N. Al-Dhahir, "Impact of space-time block codes on 802.11 network throughput," en, *IEEE Transactions on Wireless Communications*, vol. 2, no. 5, pp. 1029–1039, Sep. 2003. DOI: 10.1109/TWC.2003.816798.
- [34] P. K. Ghosh, Manju, K. Gupta, and B. Dey, "Error analysis of multiple rate space-time-block-code (STBC) for MIMO networks," in *Proceedings of The 2014 International Conference on Control, Instrumentation, Energy and Communication (CIEC)*, Jan. 2014, pp. 691–695. DOI: 10.1109/CIEC.2014.6959179.













- [35] M. S. Gast, 802.11n: A Survival Guide, en.
- [36] C. Sommer and F. Dressler, Vehicular Networking. Cambridge: Cambridge University Press, 2014. DOI: 10.1017/CB09781107110649.
- [37] H. Wu, X. Wang, Q. Zhang, and X. Shen, "IEEE 802.11e Enhanced Distributed Channel Access (EDCA) Throughput Analysis," in *2006 IEEE International Conference on Communications*, ISSN: 1938-1883, vol. 1, Jun. 2006, pp. 223–228. DOI: 10.1109/ICC.2006.254731.
- [38] P. Dhawankar, H. Le-Minh, and N. Aslam, "Throughput and Range Performance Investigation for IEEE 802.11a, 802.11n and 802.11ac Technologies in an On-Campus Heterogeneous Network Environment," in *2018 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP)*, Budapest, Hungary: IEEE, Jul. 2018, pp. 1–6. DOI: 10.1109/CSNDSP.2018.8471865.
- [39] E. Perahia and M. X. Gong, "Gigabit Wireless LANs: An Overview of IEEE 802.11ac and 802.11ad," *ACM SIGMOBILE Mobile Computing and Communications Review.*, vol. 15, no. 3, pp. 23–33, Nov. 2011, Place: New York, NY, USA Publisher: Association for Computing Machinery. DOI: 10.1145/2073290.2073294.
- [40] R. B. M. Abdelrahman, A. B. A. Mustafa, and A. A. Osman, "A Comparison between IEEE 802.11 a, b, g, n and ac Standards," *IOSR Journal of Computer Engineering (IOSR-JEC)*, vol. 17, no. 5, pp. 26–29, 2015.
- [41] K. Lautenschlaeger and C. Sommer, "Beyond Sensing: Suitability of LoRa for Meshed Automatic Section Control of Agricultural Vehicles," in *2022 17th Wireless On-Demand Network Systems and Services Conference (WONS)*, Mar. 2022, pp. 1–4. DOI: 10.23919/WONS54113.2022.9764458.
- [42] O. Ali, "Multi-agent coordination and control system for multi-vehicle agricultural operations," *Proceedings of the ...*, May 2010.
- [43] F. Klingler, J. Blobel, and F. Dressler, "Agriculture meets IEEE 802.11p: A Feasibility Study," in *2018 15th International Symposium on Wireless Communication Systems (ISWCS)*, Lisbon, Portugal: IEEE, Aug. 2018. DOI: 10.1109/ISWCS.2018.8491239.
- [44] J. A. Thomasson, C. P. Baillie, D. L. Antille, C. L. McCarthy, and C. R. Lobsey, "A review of the state of the art in agricultural automation. Part II: On-farm agricultural communications and connectivity," en, in *2018 Detroit, Michigan July 29 - August 1, 2018*, American Society of Agricultural and Biological Engineers (ASABE), 2018. DOI: 10.13031/aim.201801590.

- [45] P. Metzler, W. Flohr, and M. Hoeh, "System for determining the relative position of a second farm vehicle in relation to a first farm vehicle," DE102004039460 (B3) ■
Apr. 2006.
- [46] N. Ahmed, D. De, and I. Hussain, "Internet of Things (IoT) for Smart Precision Agriculture and Farming in Rural Areas," *IEEE Internet of Things Journal*, vol. 5, no. 6, pp. 4890–4899, Dec. 2018, Conference Name: IEEE Internet of Things Journal. DOI: 10.1109/JIOT.2018.2879579.
- [47] J. Brinkhoff and J. Hornbuckle, "Characterization of WiFi signal range for agricultural WSNs," in *2017 23rd Asia-Pacific Conference on Communications (APCC)*, Dec. 2017, pp. 1–6. DOI: 10.23919/APCC.2017.8304043.
- [48] S. Aust, R. V. Prasad, and I. G. M. M. Niemegeers, "Outdoor Long-Range WLANs: A Lesson for IEEE 802.11ah," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 3, pp. 1761–1775, 2015, Conference Name: IEEE Communications Surveys & Tutorials. DOI: 10.1109/COMST.2015.2429311.
- [49] A. Sheth, S. Nedeveschi, R. Patra, S. Surana, E. Brewer, and L. Subramanian, "Packet Loss Characterization in WiFi-Based Long Distance Networks," in *IEEE INFOCOM 2007 - 26th IEEE International Conference on Computer Communications*, ISSN: 0743-166X, May 2007, pp. 312–320. DOI: 10.1109/INFCOM.2007.44.
- [50] D. Aguayo, J. Bicket, S. Biswas, G. Judd, and R. Morris, "Link-level measurements from an 802.11b mesh network," vol. 34, Oct. 2004, pp. 121–132. DOI: 10.1145/1030194.1015482.
- [51] K. Chebrolu, B. Raman, and S. Sen, "Long-distance 802.11b links: performance measurements and experience," in *Proceedings of the 12th annual international conference on Mobile computing and networking*, ser. MobiCom '06, New York, NY, USA: Association for Computing Machinery, Sep. 2006, pp. 74–85. DOI: 10.1145/1161089.1161099.
- [52] U. Paul, R. Crepaldi, J. Lee, S.-J. Lee, and R. Etkin, "Characterizing WiFi link performance in open outdoor networks," in *2011 8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, ISSN: 2155-5494, Jun. 2011, pp. 251–259. DOI: 10.1109/SAHCN.2011.5984905.
- [53] "Allgemeinzuteilung von Frequenzen für die Nutzung in lokalen Netzwerken; Wireless Local Area Networks (WLAN-Funkanwendungen)," Bundesnetzagentur, Vfg. 136 / 2022, <https://www.bundesnetzagentur.de -> Fachthemen -> Telekommunikation -> Funk und Frequenzen -> Allgemeinzuteilungen -> WLAN>.

- [54] "Allgemeinzuteilung von Frequenzen in den Bereichen 5150 MHz - 5250 MHz, 5250 - 5350 MHz und 5470 MHz - 5725 MHz für drahtloser Zugangssysteme einschließlich lokaler Funknetze (WAS/Funk-LANs)," Bundesnetzagentur, Vfg. 136 / 2022, Nov. 2022, <https://www.bundesnetzagentur.de> -> Fachthemen -> Telekommunikation -> Funk und Frequenzen -> Allgemeinzuteilungen -> WLAN.
- [55] A. Kumar, S. K. Kaushik, R. Sharma, and P. Raj, "Simulators for Wireless Networks: A Comparative Study," in *2012 International Conference on Computing Sciences*, Sep. 2012, pp. 338–342. DOI: 10.1109/ICCS.2012.65.
- [56] S. Keller, "Simulation of WiFi Networks on Hardware," en, 2021, Medium: PDF Publisher: Chair of Network Architectures and Services, Department of Computer Science, Technical University of Munich. DOI: 10.2313/NET-2022-01-1_01.
- [57] nsnam, ns-3, en.
- [58] E. Black, S. Gamboa, and R. Rouil, "NetSimulyzer: a 3D network simulation analyzer for ns-3," en, in *Proceedings of the Workshop on ns-3*, Virtual Event USA: ACM, Jun. 2021, pp. 65–72. DOI: 10.1145/3460797.3460806.
- [59] I. Dolińska, M. Jakubowski, and A. Masiukiewicz, "New IEEE 802.11 HEW Standard Throughput per User Analysis," in *2019 International Conference on Information and Digital Technologies (IDT)*, ISSN: 2575-677X, Jun. 2019, pp. 118–123. DOI: 10.1109/DT.2019.8813700.
- [60] P. Patil, M. Patil, S. Itraj, and U. Bombale, "IEEE 802.11n: Joint modulation-coding and guard interval adaptation scheme for throughput enhancement," en, *International Journal of Communication Systems*, vol. 33, no. 8, e4347, 2020, _eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/dac.4347>. DOI: 10.1002/dac.4347.
- [61] R. Karmakar, S. De, A. Ghosh, T. Adhikari, and P. Jain, "S2-GI: Intelligent Selection of Guard Interval in High Throughput WLANs," in *2020 11th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*, Jul. 2020, pp. 1–7. DOI: 10.1109/ICCCNT49239.2020.9225322.
- [62] S. C. S, J. Kuri, and N. Akhtar, "Performance Analysis of Channel-Dependent Rate Adaptation for OFDMA transmission in IEEE 802.11ax WLANs," in *2022 14th International Conference on COMMunication Systems & NETWORKS (COMSNETS)*, ISSN: 2155-2509, Jan. 2022, pp. 877–882. DOI: 10.1109/COMSNETS53615.2022.9668513.
- [63] L. Cao, L. Zhang, S. Jin, and S. Roy, "Efficient PHY Layer Abstraction under Imperfect Channel Estimation," arXiv:2205.10897 [eess], Oct. 2022. DOI: 10.48550/arXiv.2205.10897.

- [64] S. Jin, S. Roy, and T. R. Henderson, "Efficient PHY Layer Abstraction for Fast Simulations in Complex System Environments," *IEEE Transactions on Communications*, vol. 69, no. 8, pp. 5649–5660, Aug. 2021, Conference Name: IEEE Transactions on Communications. DOI: 10.1109/TCOMM.2021.3079285.
- [65] "IEEE 802.11ax Channel Model Document," IEEE, TGAX channel model document, Sep. 2014, IEEE 802.11-14/0882r4.
- [66] T. H. Tran, Y. Nagao, H. Ochi, and M. Kurosaki, "ASIC design of 7.7 Gbps multi-mode LDPC decoder for IEEE 802.11ac," in *2014 14th International Symposium on Communications and Information Technologies (ISCIT)*, Sep. 2014, pp. 259–263. DOI: 10.1109/ISCIT.2014.7011912.
- [67] H.-S. Ryu, J.-S. Lee, and C. G. Kang, "BER analysis of dual-carrier modulation (DCM) over Rayleigh fading channel," in *International Congress on Ultra Modern Telecommunications and Control Systems*, ISSN: 2157-023X, Oct. 2010, pp. 717–721. DOI: 10.1109/ICUMT.2010.5676558.
- [68] K.-h. Park, H.-k. Sung, and Y.-c. Ko, "BER Analysis of Dual Carrier Modulation Based on ML Decoding," in *2006 Asia-Pacific Conference on Communications*, ISSN: 2163-0771, Aug. 2006, pp. 1–4. DOI: 10.1109/APCC.2006.255858.
- [69] E. Khorov, A. Kiryanov, and A. Lyakhov, "IEEE 802.11ax: How to Build High Efficiency WLANs," in *2015 International Conference on Engineering and Telecommunication (EnT)*, Nov. 2015, pp. 14–19. DOI: 10.1109/EnT.2015.23.
- [70] V. Tarokh, H. Jafarkhani, and A. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, Jul. 1999, Conference Name: IEEE Transactions on Information Theory. DOI: 10.1109/18.771146.
- [71] J. A. Shaw, "Radiometry and the Friis transmission equation," *American Journal of Physics*, vol. 81, no. 1, pp. 33–37, Jan. 2013, Publisher: American Association of Physics Teachers. DOI: 10.1119/1.4755780.

Todo list

| | | |
|---|---|-----|
|  | This template is for use with pdf \LaTeX and biber. It has been tested with TeX Live 2020 (as of 25 Oct 2020). | iii |
|  | The table of contents should fit on one page. When in doubt, adjust the tocdepth counter. | vi |
|  | Add Field experiments to the thesis plan. | 2 |
|  | OFDM? Keine Erklärung aber eigentlich auch ausreichend. würde mir eine kürze Arbeit ermöglichen | 16 |
|  | describe lost goodput calculation | 45 |
|  | nothing to cite? | 46 |
|  | Error bars goodput lost | 48 |
|  | What should be chosen? | 59 |
|  | Robustness?DataRate? Fieldexperiments | 60 |
|  | explain? | 60 |
|  | by common sense? | 63 |
|  | ha? Conversion? Introduce Abbreviations? | 64 |