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

Diploma Thesis in Information Systems Engineering

8 March 2023

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

Diploma Thesis in Information Systems Engineering

vorgelegt von

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Networked Systems Modeling

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Abgabe der Arbeit:	**8. März 2023**

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(Karl Christian Lautenschläger)
Dresden, 8 March 2023

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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

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- problem: gap in knowledge, too expensive, too slow, a deficiency, superseded technology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.

For the increasing automation and digitalization of agriculture, wireless infield communication of agricultural machinery is needed. A communication network enables the automation of work processes in agriculture through the exchange of data.

Given that there are many different agricultural technology companies worldwide and mix of their machines is often used together in an agricultural company, a demand for interoperability between agricultural machines of different brands emerged. In 2008, the Agricultural Industry Electronics Foundation 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 the Wireless-Infield Communication. In the associated project group Wireless-Infield Communication, solutions for Machine-To-Machine communication between cooperating, agricultural machines are to be developed and standardized.

[1] https://www.aef-online.org/about-us/about-the-aef.html Accessed: 24.07.2022

In order to implement Wireless-Infield Communication, the Wireless-Infield Communication project group has been searching for a technology that can realize the required data rates, latencies and high transmission range. The plans for doing so are written down by members of the Wireless-Infield Communication 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, there is a major concern that the required data cannot be exchanged because there is no network connectivity in many fields. Nevertheless, the authors want to leave the future Wireless-Infield Communication system open to cellular standards.

The current focus of the authors is on IEEE 802.11 technologies, which must first be evaluated for use in the agricultural environment.

In my final thesis I want to investigate the Wireless-Infield Communication use cases for which IEEE 802.11ax or IEEE 802.11ac can be used.

In order to implement these described WIC use cases, the WIC project group has been searching for a technology that can realize the required data rates, latencies and high transmission range. The plans for doing so are written down by members of the WIC project group in [26]. The authors consider the fundamental use of cellular networks as very problem- atic because, according to [27], only 30 % of the land surface has network coverage. For this reason, there is a major concern that the required data cannot be exchanged because there is no network connectivity in many fields. Nevertheless, the authors want to leave the future WIC system open to cellular standards. The current focus of the authors is on IEEE 802.11 technologies, which must first be evaluated for use in the agricultural environment.

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.

-1/3 ist kurz, weil der Bezug und die Relation zur Landwirtschaft groß ist... Aber wen interessiert das? -1/3 related Work erwähnt man dann Unterstützung von Professor Klingler wie und wo? erwähnt man sich selber ? '

2.1 Wireless-Infield Communication

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

- Define use cases for Wireless-Infield Communication in agriculture
- Evaluate the suitability of communication technologies
- Find suitable communication protocols

[2]https://www.aef-online.org/about-us/teams.html

- Standardize the Wireless-Infield Communication common software library
- Develop functional and security requirements and concepts
- Test first prototypes in regards of cross-brand comformance
- Write a application guideline

First steps are already 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 Wireless-Infield Communication 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. Since not all agricultural machines may be connected to the Farm Management Information System, the Wireless-Infield Communication project group is looking at how to use Machine-To-Machine communications to bridge the missing communications infrastructure until the data reaches a machine that can connect to the Farm Management Information System.
- **Road Safety** describes a use case which is already a project between the European Telecommunication Standard Institute and the Agricultural Industry Electronics Foundation. 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 Wifi for Wireless-Infield-Communication and Wi-Fi 6 and Wi-Fi 5 are no long range technologies, I will focus on investigating the suitability of these two Wi-Fi standards for the Wireless-Infield Communication 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.

Rename? Preference of use cases? Which one to focus on? modern Wifi?

2.2 Harvest and Loading Processes as a Use Cases for Wireless-Infield Communication (WIC)

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: Hey, Straw, Corn, Grass and Clover.

In the harvesting and loading process, a Transport Machine typically drives alongside or behind the Forage Harvester so that the Forage Harvester can load the harvested goods onto the trailer of the Transport Machine using the spout. Drivers operate both machines and try to keep the speed and distance so that the spout only

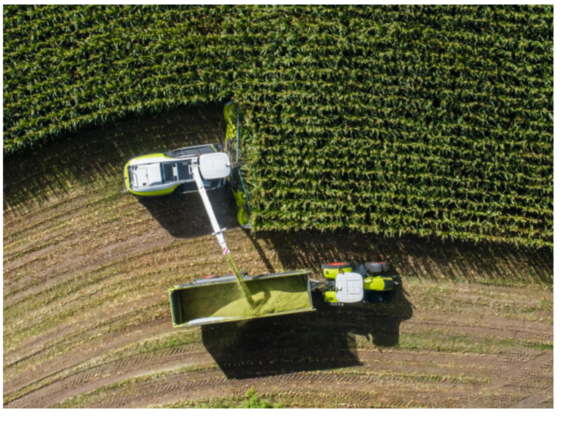

Figure 2.1 – Forage Harvester (FH) and Transport Machine (TM) in a corn harvesting and loading process

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 and show the large amount of forage harvested by a Forage Harvester every hour.

Plant Density (PD)	20 t/ha	30 t/ha	50 t/ha
Required Transport Machines	5	7	10
Harvested volume in m^3/h	285.7-333.3	428.6-500.0	595.7-695.0
Filled Transport Machine loads in 1/h	5.7 - 6.7	8.6 - 10.0	11.9 - 13.9
Harvested mass in t/h	100	150	208.5

Table 2.1 – Key figures from [6] 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)

The harvesting and loading processes are examples of the use of agricultural Platooning Services as described by Zhang et al. [7]. This Platooning Service creates a leader and follower system where an uncrewed agricultural machine follows a leading operated agricultural machine. The operated Forage Harvester, as a leader, sets the path and speed and transmits the data via Wireless-Infield Communication to the Transport Machine. Based on the path and speed data of the Forage Harvester, Transport Machine follows unmanned with a longitudinal and lateral offset, as Figure 2.2 displays.

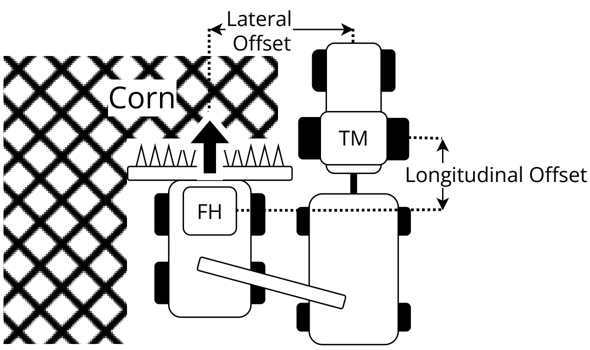

Figure 2.2 – Lateral and longitudinal offset between the two agricultural machines Forage Harvester (FH) and Transport Machine (TM) in a corn harvest scenario

The application of platooning services offers many advantages. The Transport Machine is positioned optimally to the Forage Harvester so that the forage can be loaded ideally from the Forage Harvester onto the Transport Machine.

Because, as displayed in Figure 2.3, fewer and fewer workers are working in agriculture, platooning services for harvest and loading processes can save and free up labour for other activities [8]. As stated in Table 2.1, already ten drivers for the Transport Machines are needed in the corn harvest process with a high . Using an agricultural Platooning Service, each Transport Machine can drive unmanned in the field, leading to fewer workers needed in the corn harvest process.

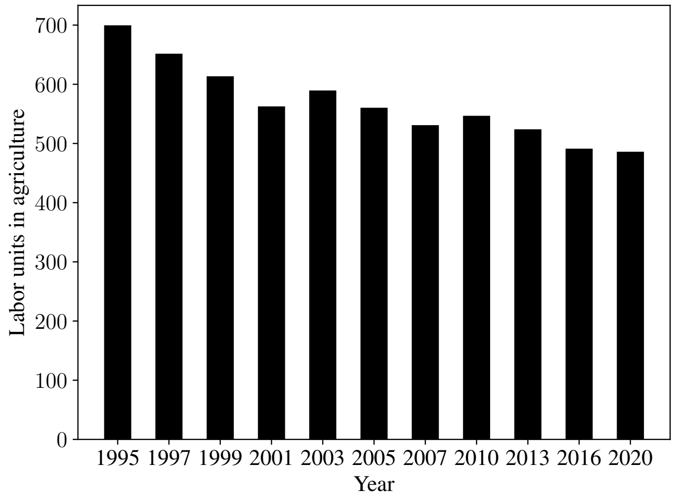

Figure 2.3 – Decrease in the agricultural labor force in Germany based on the data from [9]

Smolnik and Lücke [10] adds that platooning services at the platoon level can reduce Forage Harvester drivers' workload so that they can focus on optimally adjusting the machines. In addition, Transport Machines can be guided to the Forage Harvesters 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 Wireless-Infield Communication use case, where a video of the Transport Machine's filllevel is available at the Forage Harvester and could be transmitted to the Transport Machine in order to inform the Transport Machine driver about the machines filllevel. During these harvest and loading processes, the spout of the Forage Harvester must be controlled to set the loading position of the forage into the trailer of the Transport Machine.

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 Forage Harvester to the Transport Machine would be a practical application of the video streaming use case in the harvesting process. If the Transport Machine 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

Paper Christoph Sommer, Doktorarbeit, Diplomarbeit, Mario Franke, Tobias Hardes

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 wirless 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. Jacob et al. [14] fügt dazu noch hinzu, dass es zusätzlich noch die zwei Erweiterungen IEEE 802.11p and dessen Nachfolger IEEE 802.11bd gibt. Diese operieren in einem reservierten Frequency spectrum for Vehicle-to-everything nach den Autoren im 5.9 GHz frequency spectrum

HT, VHT, HE - phy

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.

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

Since an Access Point has limited range and can only cover a certain area, the Extended Service Set was introduced. It contains a distribution system, which links several Basic Service Set 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 Basic Service Set can be placed physically on top of each other. One can also have physically separate Basic Service Sets so that these Basic Service Sets 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 Extended Service Set, where a station can do no-transition and thereby stay within a Basic Service Set, Basic Service Set-transitioning and move from one Basic Service Set to another Basic Service Set within the same Extended Service Set and Extended Service Set-transition, where the Station moves from a Extended Service Set to another one but no stable connection can be guaranteed.

Sauter [13] adds, that usually Ethernet is used to link Access Points in within an Extended Service Set. But according to the author this can be replaced by a wireless connection, which is called wireless bridge. ESS not needed?

Sauter 2022 Ad-Hoc Infos

Wi-Fi Physical Layer

The further development of IEEE 802.11 is accompanied by a constant change of the physical layer. Sauter [13] mentions, that all new enhancements of the physical layer of IEEE 802.11 are backward compatible to previous definitions of the it.

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 can be used in the 2.4 GHz frequency band. the author explains Orthogonal Frequency-Division Multiplexing as following. Orthogonal Frequency-Division Multiplexing divides the transmission channel in 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 Orthogonal Frequency-Division Multiplexing symbols over the individual Orthogonal Frequency-Division Multiplexing subcarriers. The distance between the "highs" of the subcarriers is specified as subcarrier spacing and corresponds to the reciprocal symbol length. This has now increased from 3.2 µs for IEEE 802.11n to 12.8 µs for IEEE 802.11ax. This corresponds to a subcarrier spacing of 312.5 kHz and 78.125 kHz respectively.

For the IEEE 802.11p and IEEE 802.11bd standards, a symbol length of 6.4 µs applies, corresponding to a subcarrier spacing of 156.25 kHz [14].

For the modulation and demodulation of the transmitting bits the FFT and IFFT are used respectively. With the reduction of the subcarrier spacing, more subcarriers are created in the transmission channel, so that the FFT size must be increased.

Kauffels [12] adds, that Orthogonal Frequency-Division Multiplexing can be used in the 5 GHz frequency band since IEEE 802.11a.

bandwidth (BW)

Modulation and Coding Scheme (MCS)

In order to encode as many bits as possible on one Orthogonal Frequency-Division Multiplexing symbol, different Modulation and Coding Schemes can be used. These Modulation and Coding Schemes for the IEEE 802.11 standards are based on Phase Shift Keying or Quadrature Amplitude Modulation. [12]. The smallest Modulation and Coding Scheme is binary Phase Shift Keying and encodes 1 bit per symbol. IEEE 802.11ax has the most complex Modulation and Coding Scheme of 256-Quadrature Amplitude Modulation IEEE 802.11ac to 1024-Quadrature Amplitude Modulation and thus now encodes 10 bit per symbol [15]. In the Vehicle-to-everything range, so can Modulation and Coding Schemes from binary-Phase Shift Keying to 256-Quadrature Amplitude Modulation.

In order to encode as many bits as possible on one Orthogonal Frequency-Division Multiplexing symbol, different Modulation and Coding Schemes can be used. The Modulation and Coding Schemes for the IEEE 802.11 standards are based on Phase Shift Keying or Quadrature Amplitude Modulation. [12]. The smallest Modulation and Coding Scheme is Binary - Phase Shift Keying and encodes 1 bit per symbol. IEEE 802.11ax has the most complex Modulation and Coding Scheme of 256 - Quadrature Amplitude Modulation IEEE 802.11ac to 1024 - Quadrature Amplitude Modulation and thus now encodes 10 bit per symbol [15]. In the Vehicle-to-everything range, so can Modulation and Coding Schemes from binary-Phase Shift Keying to 256-Quadrature Amplitude Modulation.

An imaginary, theoretical transmission channel is usually specified as a square-wave signal in the frequency domain with the 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 Quadrature Amplitude Modulation can generate high roll-off factors, so that signals interfere significantly more with adjacent channels.

In this regards the author recommends setting the parameters in an Orthogonal Frequency-Division Multiplexing system in such a way that first the coding rate and then the complexity of the Modulation and Coding Scheme is reduced in difficult transmission environments. The more bits a Modulation and Coding Scheme encodes on a symbol, the more error-prone the correct decoding of the symbol.

Forward Error Correction (FEC)

Nevertheless bit errors can occur during the transmission. In this regard, [12] mentions and explains Forward Error Correction as a technique to reduce bit errors during transmission. Forward Error Correction 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 Coding Rate

explain cr ?? Cite??

To achieve this, binary convolutional coding is used mandatory since the IEEE 802.11n standard [15] [16]. Syafei et al. [16] add that it is optionally possible to use low-density parity-check. The authors state that low-density parity-check can achieve a better channel capacity performance. This is also confirmed by Afaqui, Garcia-Villegas, and Lopez-Aguilera [15], who point out that low-density parity-check also generates higher computational cost.

IEEE 802.11ax stations must support low-density parity-check when using on the IEEE 802.11ax standard under the following conditions [15] [17]:

- The used bandwidth is greater than 20 MHz
- The chosen Modulation and Coding Scheme is 1024-Quadrature Amplitude Modulation
- More then four transmission channels are used for the transmission.

IEEE 802.11ax achieves Coding Rate of 1/2, 2/3, 3/4, and 5/6 [17]. Similarly, IEEE 802.11p uses the binary convolutional coding technique, which has been superseded by low-density parity-check in its successor IEEE 802.11ax [14] [18]. Yacheur, Ahmed, and Mosbah [18] argue that this step was important, as low-density parity-check offers better error correction possibilities for higher communication ranges greater than 50 m.

Together with the Modulation and Coding Scheme, the Forward Error Correction Coding Rate form a physical layer specification. This is named after the standard and includes the possible expressions for Modulation and Coding Scheme values and Coding Rate of the standard. For IEEE 802.11ax, this results in the HE-MCS index values in Table 2.2

Symbol length, GI, subcarrier spacing reciprocal

Guard Interval (GI)

Wellenausbreitung, Überlagerungseffekte, Reflexsion, Reflexsion nicht bei Metall

Knauffel OFDM PHY

Pulimamidi, Nulu, and Tahernezhadi [19] explain the Guard Interval as a cyclic prefix of OFDM symbols before Inter Symbol Interference and through Inter Carrier Intereference. Inter Symbol Interference is caused by multipath delays , where the reflected delayed previous symbol can interfere with the current received symbol[20]. Similarly, Inter Carrier Interference is caused by time-varying channel a longer OFDM

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

Table 2.2 – HE-Modulation and Coding Scheme index table nach [17]

symbol duration, that just as an interference with the following OFDM symbol can arise [21].

About the Guard Interval Pulimamidi, Nulu, and Tahernezhadi [19] further list the following. Since the guard interval is to prevent the possible interference on the following symbol, it must be at least long enough so that all channel impulse responses with the resulting delay are caught in the guard interval. The guard interval is then removed again at the receiver. This results in an attentuation of bandwidth which can be described by the following formula:

longer GI WIfi 6 Outdoor Communication

$$\text{GI\_Bandwidth\_Attentuation} = \frac{\text{OFDM\_symbol\_duration} \times 100}{\text{OFDM\_symbol\_duration} + \text{GI}}. \tag{2.1}$$

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

better source

In **alleAX** wird keine Bedingung für die Nutzung von den OFDM Guard Interval genannt. Außerdem steht in den genannten Quellen nur die Orthogonal Frequency-Division Multiplexing symbol length von 12.8 µs aufgeführt.

Dual Carrier Modulation (DCM)

In order to introduce additional robustness Dual Carrier Modulation can be applied to the physical layer since IEEE 802.11ax [14], [44], [17]. Jacob et al. [14] describe Dual Carrier Modulation as a way to send data twice over two coherent carriers. At the receiver, the data copies are combined with the log-likelihood ratio. This increases the probability of receiving the data.

[17] 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 bandwidth of 20 MHz is displayed in Figure 2.4. It demonstrates that when using Dual Carrier Modulation, the receiver minimum input sensitivity can be lower than without using Dual Carrier Modulation. The effect on the receiver minimum input sensitivity increases as the HE-MCS value increases.

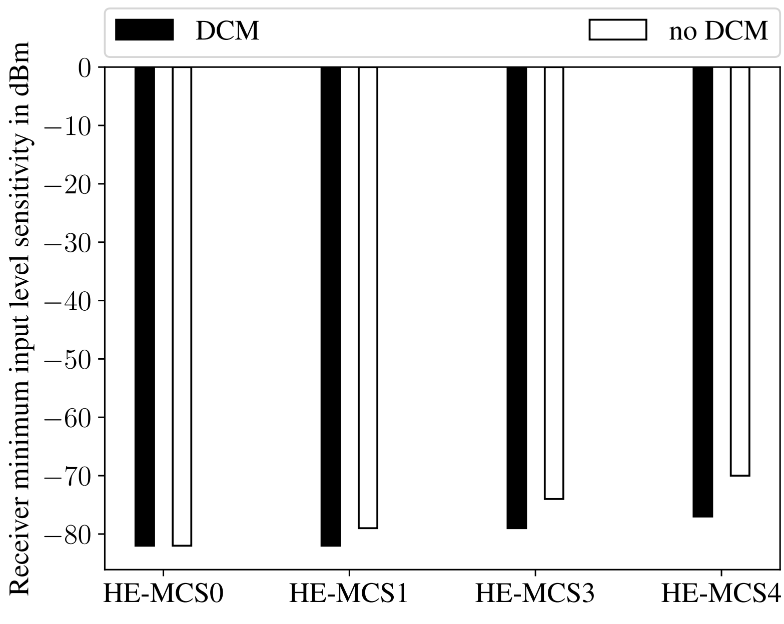

Figure 2.4 – Receiver minimum input level sensitivity for different HE-MCS values according to [17], where packet error rate is less than 10 %

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

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

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

Support for Dual Carrier Modulation is only optional in the IEEE 802.11ax standard and can only be used for HE-Modulation and Coding Scheme-0, HE-Modulation and Coding Scheme-1, HE-Modulation and Coding Scheme-3 and HE-Modulation and Coding Scheme-4 for 1 . . . 2 spatial transmission streams [17].

Jacob et al. [14] and Triwinarko, Dayoub, and Cherkaoui [44] mention plans, to allow using Dual Carrier Modulation in the physical layer of IEEE 802.11bd.

BER Ryu

Extended Range

Since IEEE 802.11ax the Extended Range Mode exists, which defines the new HE ER SU Physical layer convergence protocol data unit as physical layer amendment [17] [15]. Deng et al. [22] explains that the HE ER SU Physical layer convergence protocol data unit format is intended to extend the range of a single station to access point transmission. This is accomplished, according to the authors, by the PPDU containing a repetition of the HE-SIG-A field.

In addition, the authors explain that preamble is power-boosted, which is limited to 3 dB in [17] [14], to guarantee reliable transmission for longer ranges.

The IEEE 802.11ax [17] standard defines that the HE ER SU Physical layer convergence protocol data unit format may only be used when 20 Mhz transmissions with either 242 RU with HE-MCS-0 - HE-MCS-2 or 106 RU with HE-MCS-0 are used on a spatial stream. In addition, one can use Dual Carrier Modulation.

Optionally, the HE ER SU Physical layer convergence protocol data unit may also be transmitted with a Guard Interval of 800 ns, where an additional application of Dual Carrier Modulation is forbidden.

Jacob et al. [14] and **triwinarko** add, that it is planned to use the extended range mode also in the IEEE 802.11bd standard.

bd angenommen? Wie komme ich an den 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 Multiple Input Multiple Output - systems. Sauter [13] describe the idea behind Multiple Input Multiple Output as the usage of multiple transmit antennas and multiple receiving antenna. 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 four MIMO streams. This number was increased again to up to eight MIMO streams in IEEE 802.11ax [17]. Since data can be sent simultaneously via each MIMO stream, the theoretical data rate can thus increase proportionally depending on the usable streams.

MU-Multiple Input Multiple Output DCM only appicable, when RU contains only data for one user. [17] 607 not applicable with DCM NUM_STS = Number of Spatial Streams $n_{ss} = NUM\_STS/(1 + STBC)$

Space-Time-Block-Code (STBC)

Abbas et al. [23] sagt zudem, dass Multiple Input Multiple Output spatial streams dazu genutzt werden kann, um die Qualität des empfangenen Signals zu verstärken. Das geschieht durch Space-Time-Block-Code. Dabei werden den Autoren nach redundant copies of data transmitted via different antenna to the receiver. At the receiver the received data copies are combined and a maximum likelihood detector is applied in order to retain a high quality signal [24]. Space-Time-Block-Code is a technique used in Wi-Fi networks to improve the reliability and robustness of wireless communications. Space-Time-Block-Code encodes multiple redundant copies of data at the transmit side, which are transmitted in different spatial streams to reduce the effects of fading and interference. At the receiver side, these multiple copies are combined to improve the signal quality and decrease the packet error rate.

Thes results in Space-Time-Block-Code improving the reliability and robustness of wireless communications. Here, Stamoulis and Al-Dhahir [25] has investigated the potential effect of Space-Time-Block-Code on Wi-Fi. Their simulations showed thatSpace-Time-Block-Code can increase the range and robustness for IEEE 802.11a. In addition, the authors concluded that Space-Time-Block-Code increases the Signal Noise Ratio in nearly all cases at the same throughput or even allows higher Modulation and Coding Scheme values to be used, thus allowing a higher throughput at the same Signal Noise Ratio.

Ghosh et al. [26] analyzed the error rate performance for increasing number of used antenna and found out, that a lower bit error rate can be achieved when increasing the number of transmit antennas with Space-Time-Block-Code.

Gast [27] and Sauter [13] mention, that Space-Time-Block-Code can extend the signal range due to the increased robustness.

IEEE 802.11ax stations can optionally use Space-Time-Block-Code the following conditions [17]:

- DCM is not applied
- The number of spatial streams is 2
- The Guard Interval is not 0.8 ns and the symbol length is not 12.8 µs

[27] states, that Space-Time-Block-Code is only supported in one fifth of the Wi-Fi CERTIFIED devices. Group addressed frames

HE Capabilities nur so gut, wie das schlechteste Glied

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 - ,network authentication - and media access methods. The author explains, that every Access Point send beacon frames periodically to synchronise its stations in the Basic Service Set and that the beacon frame contains the Service Set Identifier, which identifies the Basic Service Set or Extended Service Set of the station. Sauter [13] adds that a beacon frame contains a 16 bit - long capability information element. Each bit here signals that the Access Point provides a particular function or has a specific feature.

Kauffels [12] explains the procedure for network entry of a station. A station can use the passive or the active scanning mode. In passive scanning mode, the station listens for a beacon frame in the various transmission channels. Alternatively, in active scanning mode, a station can also send out a probe frame. This can contain an already known Service Set Identifier to test the presence of the Access Point. To get an Access Point in range, the probe-frame can also contain a broadcast SSID that causes all nearby Access Points to respond. The response of an Access Point 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 Access Point. If the Access Point answers with a positive status in the Authentication Frame, the station is included in the Basic Service Set. The actual encryption and authentication is then performed by the Wi-Fi Protected Access functions. The author points out that Shared Key Authentication is no longer used today.

the IEEE 802.11 standard describes the two media access methods Distribution Coordination Function and Point Coordination Function.

Sauter [13] explains that Distribution Coordination Function is based on the media access method Carrier Sense Multiple Access/Collision Avoidance. In Carrier Sense Multiple Access/Collision Avoidance a device that is willing to transmit senses in the air transmission medium for a transmitting activity. If no other device is transmitting, the device can transmit. In the case of transmit activity, the terminal must wait at least until the transmission and Distributed Coordination Function Interframe Space are over. Since data transmission via the air transmission medium is very vulnerable to errors, the standard IEEE 802.11 requires that each received packet must be confirmed with an Acknowledgement frame. The Distributed Coordination Function Interframe Space ensures that an Acknowledgement frame can be sent before another station uses the same channel to send a data frame. To avoid multiple devices transmitting at the same time after Distributed Coordination Function Interframe Space, each ready-to-transmit device determines a random backoff time. The device with the shortest backoff time transmits next and all other ready-to-transmit devices restart the media access procedure. In case two devices start sending next because they both randomly chose the shortest backoff time, the transmitted signal will interfere and the packets will not be answered with an Acknowledgement frame. In case of such a faulty transmission, the backoff time of the ready-to-transmit devices can increase exponentially afterwards.

To share the knowledge of a transmission time and the subsequently interframe space, a packet contains a Network Allocation Vector that specifies the time the air transmission medium is used.

In various network architectures the "hidden station"-problem may occur. As you can see in Figure 2.5, Station A is not able to sense a transmission of station B and vise versa. In case of simultaneous transmission of both stations, interference around the Access Point may occur.

Um das hidden station problem zu umgehen kann eine Station nach Sauter [13] Point coordinator ohne Wettbewerb mit optionaler Priorisierung

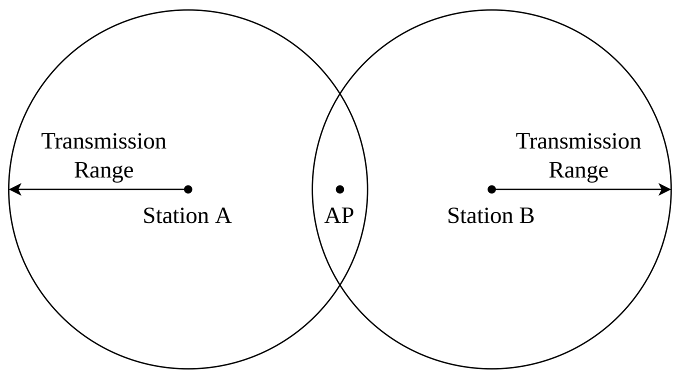

Figure 2.5 – Hidden Station Problem

PIFS interval kürzer, beacon frame CF Parameter set-element

nicht genauer eingehen, weil nicht relevant für die Arbeit? Darf ich das schreiben?

CSMA /CA Point Coordination Function

Sauter [13] DCF oberbegriff für CSMA /CA

Short Interframe Space SIFS ACK Frame

Hidden Station Problem CTS and RTS

IEEE 802.11e DCF erweiterung für Video Streaming

CSMA CA Backoff zeit Network allocation Vector NAV Zeitspanne Datensendungsdauer

MAC Header

Netzeintritt: passives und Aktives Scanning Service Set Identifier Timing Synchronisationsfunktion TSF Timer-Wert

Sauter [13] every package management or usage data send ackknowledgement

Hidden Station Szenario Reservieren RTS CTS meist nicht konfiguriert / ausgeschalten, bei großen Paketen sinnvoll

Authentifizierung - Open System -Authentification - Shared key Authentification (nach neu nicht mehr verwendet

IEEE 802.11ac - Wi-Fi 5

The 5th generation WLAN is IEEE 802.11ac and operates in the 5 GHz frequency range [28].

According to Perahia and Gong [29], IEEE 802.11ac is a further evolution of IEEE 802.11n, where IEEE 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 Orthogonal Frequency-Division Multiplexing. Additionally, a new Multiple Input Multiple Output 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 Modulation and Coding Scheme from 64 Quadrature Amplitude Modulation to 256 Quadrature Amplitude Modulation, these three enhancements ensure that a higher data rate can be achieved. The maximum data rate is 6.9 GHz according to the authors.

As declared by Abdelrahman, Mustafa, and Osman [30], 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 [28] were able to demonstrate that IEEE 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. Khorov et al. [31] reveals what has changed from IEEE 802.11ac to IEEE 802.11ax. For this, the authors make the following statements.

IEEE 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, IEEE 802.11ax enables UL MU transmissions. These can also use Orthogonal Frequency-Division Multiple Access in addition to the already known Multiple Input Multiple Output of IEEE 802.11ac. Orthogonal Frequency-Division Multiple Access groups the orthogonal frequency subcarriers into Resource Units, which can be selected by the transmitter for optimal transmission to the receiver. This increases the Signal-to-Interference-plus-Noise Ratio.

An extension in the PHY layer are the new Modulation and Coding Scheme's of up to 1024-Quadrature Amplitude Modulation. However, these should only be used with very good channel characteristics. For better outdoor communication IEEE 802.11ax increases the Orthogonal Frequency-Division Multiplexing symbol duration from 3.2 µs for IEEE 802.11ac to up to 12.8 µs and the Orthogonal Frequency-Division Multiplexing Guard Interval from a maximum of 0.8 µs for IEEE 802.11ac to up to 3.2 µs.

MIMO und OFDMA MU Streams

BSS Coloring

Backward Kompatibilität über CTS Reservierungen.

Tabelle Vergleich

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 wireless infield communication (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

[3] https://github.com/klautenschlaeger/mvsc Accessed: 5.2.2023

Parameter	IEEE 802.11ac	IEEE 802.11ax
Frequency bands	5 GHz	2.4 GHz, 5 GHz, 6 GHz
Symbol Length	3.2 µs	12.8 µs
Orthogonal Frequency-Division Multiplexing Subcarrier Spacing	312.5 kHz	78.125 kHz
Orthogonal Frequency-Division Multiplexing Subcarriers in 80 MHz	256	1024
max. Modulation and Coding Scheme	256 -Quadrature Amplitude Modulation	1024 -Quadrature Amplitude Modulation
max. Guard Interval	0.8 µs	3.2 µs

Table 2.3 – Comparison of IEEE 802.11ac and IEEE 802.11ax

in a paper [32]. 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 [33]. The authors developed a system based on General Packet Radio Service (GPRS) to exchange position data between Transport Machines and combine harvesters to guide empty Transport Machines 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 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 Wireless-Infield Communication is not based on cellular networks. [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)".

Abkürzung so? wird nur einmal verwendet

Klingler, Blobel, and Dressler [34] investigated how IEEE 802.11p can be used for Wireless-Infield Communication. Experiments revealed that data could be exchanged over a maximum range of 1700 m, where Line-Of-Sight was lost. But during the measurement in an agricultural work scenario from the corn harvest, there were collapses in the Received Signal Strength 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.

As of July 2, 2021, the frequency spectrum of IEEE 802.11p in the United States of America, ranging from 5.850 GHz . . . 5.925 GHz, has been split. The upper 30 MHz are reserved for Intelligent transportation systems now. The lower 45 MHz have been released for unlicensed operations [35].

Since the use of IEEE 802.11p has now been newly regulated by the FCC, the Wireless-Infield Communication project group is looking for an alternative technology that enables Wireless-Infield Communication.

IVAN MARION 802.11 not public available :-(

There are also more developments in the industry field of Wireless-Infield Communication. In this context, Thomasson et al. [36] describe the John Deere Machine Sync and Case IH V2V systems as follows:

John Deere Machine Sync enables the Wireless-Infield Communication 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 [37]'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 Transport Machine from a distance of 70 m. The harvester then automatically

[4] https://ravenind.com/products/autonomy/driver-assist-harvest-solution Accessed: 5.2.2023

guides the Transport Machine into the perfect position to load the harvested crop onto the Transport Machine via the spout. Once the harvesting and loading process is complete, the driver of the Transport Machine driver retakes control.

A comparable system is CartACE from AgLeader [5]

Website not beautiful but functional?

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.

OcuSync Lightbridge DJI Mavic

Wifi 6 Outdoorcommunication cows

Paul outdoor performance

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

According to **Ahmed2020**, 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 Wireless-Infield Communication applications. For example, asset tracking applications require a low latency and must support asset mobility. The results of the authors 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 to 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 Wireless-Infield Communication applications. **Brinkhoff2020** describe as requirements, that they expect a limited cellular network coverage and complex outdoor environments with large water areas, different crop vegetations and other obstacles or various weather conditions. The reseachers developed a wirless sensor network based on IEEE 802.11b, where they exchanged data between an Access Point and multiple stations on a cotton and rice field. The authors report, that they easily a achieved communication of 1000 m in a Line-Of-Sight scenario. They mention, that different wheater conditions have little impact on the communication reliability. A big influence on the communication range is the height above ground or the crop vegetation, where the authors recommend to use at least a height of 0.2 m.

[5] https://www.agleader.com/harvest/cartace/ Accessed: 5.2.2023

Chapter 3

Analyzing Corn Harvest Process Data

To gain a better insight into requirements of the Wireless-Infield Communication use cases Platooning and Streaming Services, I analysed process data of a corn harvest scenario as the example for I collected GPS tracks of a Forage Harvester and two to three Transport Machines harvesting corn on a field in Germany on two days in September. For this, I placed tablets in the driver's cabs of a Forage Harvester and three Transport Machines, which recorded the position and speed in an NMEA data stream of the tablet's GPS every second.

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 Forage Harvester and the Transport Machines all 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 anonymized 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.

To gain a better insight into requirements of the Wireless-Infield Communication use cases Platooning and Streaming Services, I analysed process data of a corn harvest scenario as the example for I collected GPS tracks of a Forage Harvester and two to three Transport Machines harvesting corn on a field in Germany on two days in September. For this, I placed tablets in the driver's cabs of a Forage Harvester and three Transport Machines in the morning, which recorded the position and speed in an NMEA data stream of the tablet's GPS every time second.

After I collected the tablets in the evening, I anonymised the recorded process data. Starting, 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.

After that, 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.

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.

For this purpose, 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 narrows down the data points for display in the dashboard. In addition, one could select which Transport Machines are displayed next to the Forage Harvester. For the chosen time interval, the distance and velocity difference between the selected Transport Machines and the Forage Harvester 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 Forage Harvester is nearly always in the overloading process with a Transport Machine. In doing so, the Forage Harvester may occasionally stay in the same place if the cutter is clogged or there is a transition of Transport Machines where a full Transport Machine moves away from the Forage Harvester and an empty Transport Machine catches up to the Forage Harvester to take over the forage.

A Transport Machine is in a platoon with a Forage Harvester if it is close to the Forage Harvester and they are moving at nearly the same speed. The distance between Transport Machine and Forage Harvester 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 different speed 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 Transport Machine can sometimes be close to the Forage Harvester. This Transport Machine is empty and waits to work with the Forage Harvester in the next platoon. For that purpose, the empty Transport Machine drives

[6]https://dash.plotly.com/introduction Accessed: 5.12.2022

close behind the current platoon at the same speed to not catch up even closer to the platoon and be ready in the vicinity.

Based on the above observations, I developed an intelligent algorithm for detecting platooning scenarios in the recorded harvest process data. It uses a weighted sum of distance and speed difference between Forage Harvester and Transport Machine to detect the platooning scenarios.

For verification purposes, I displayed the found platoons scenarios on the map and confirmed the algorithm's functioning.

Additionally, I implemented the following further verification method. I observed that a fully loaded Transport Machine leaves the field via one of the field exits to bring the crop to a farm building. Via a check, if a Transport Machine has left the field and thereby passed the exit after leaving a platoon, wrongly recognized platoons can be discarded.

After the platoons scenarios were correctly detected, I included the data points before each platoons scenario till a maximum distance of 50 m between Forage Harvester and Transport Machine was exceeded. These data points are also relevant to the requirements because at the beginning of an agricultural platooning service, the Forage Harvester, as the system leader, must be able to guide an empty Transport Machine to the appropriate position for overloading.

For the detected data points of the platooning services from recorded data of the corn harvest, the proportion where the Forage Harvester and Transport Machine

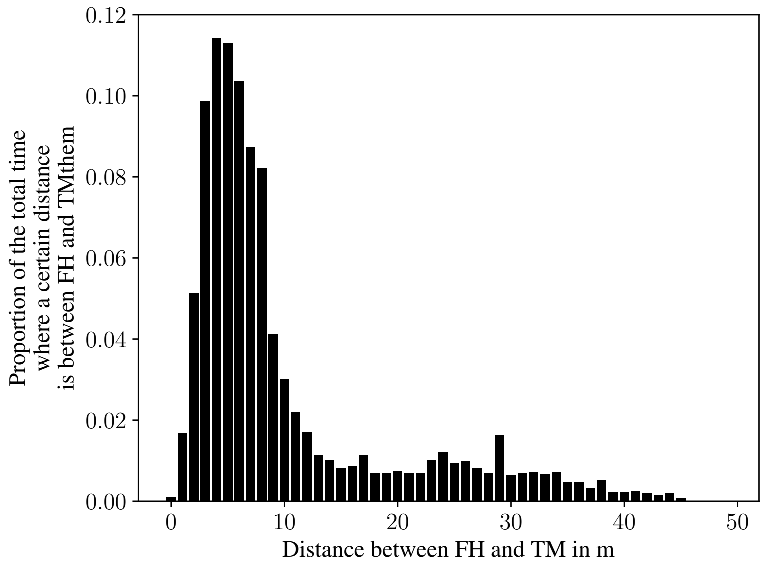

Figure 3.1 – Distribution of time proportions where a given distance was between Forage Harvester (FH) and Transport Machine (TM) in a harvest platoon scenario.

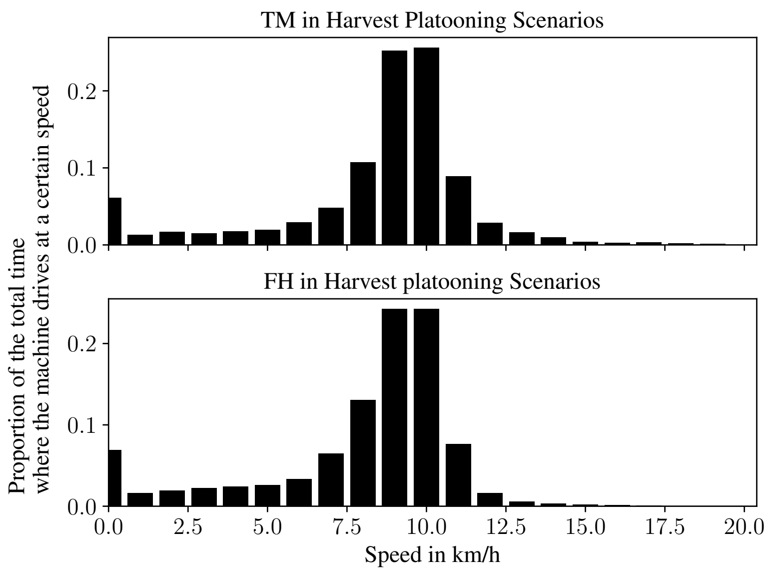

Figure 3.2 – Distribution of time proportions where Forage Harvester (FH) and Transport Machine (TM) drove with a certain speed in a harvest platoon scenario

move in a specific distance is shown in Figure 3.1. For the same data points, the proportion in which Forage Harvester and Transport Machine move at a given speed is available in Figure 3.2.

These analysing results show that the Transport Machine and the Forage Harvester 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 3.2 is that the Forage Harvester and Transport Machines 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 Forage Harvester 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 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 3.2 is a local maximum at a speed of 0 km/h. In a harvest platoon scenario, Forage Harvester and Transport Machine 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 , 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 Forage Harvester worldwide and thus should have expertise in the topic.

Klingler, Blobel, and Dressler [34] investigated the suitability of IEEE 802.11p for Wireless-Infield Communication. The authors detected that shadowing effects occur in the harvest scenario. The authors explain the effect because another tractor or the spout of the Forage Harvester was in Line-of-sight. I reviewed the recorded position data to get an overview of the Transport Machine's position relative to the Forage Harvester in the overloading process. The relative bearing is the angle between B, and the heading of point A. Using the previous position of the Forage Harvester, the relative bearing between Forage Harvester and Transport Machine can be calculated with the angles α and β in Figure 3.3 as:

$$Relative\_Bearing = \beta - \alpha, \tag{3.1}$$

Assuming that the Forage Harvester does not move backwards, the relative bearing describes the relative angle from the Forage Harvester to Transport Machine. The result is displayed in Figure 3.4. It can be observed that the Transport Machine is mainly close to the Forage Harvester at an angle of 30° . . . 150° at a distance between 0 m . . . 10 m.

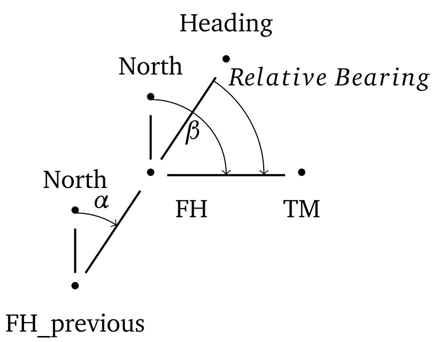

Figure 3.3 – Relative bearing between Forage Harvester and Transport Machine which is calculated using the previous location of Forage Harvester by using β and α for Equation 3.1

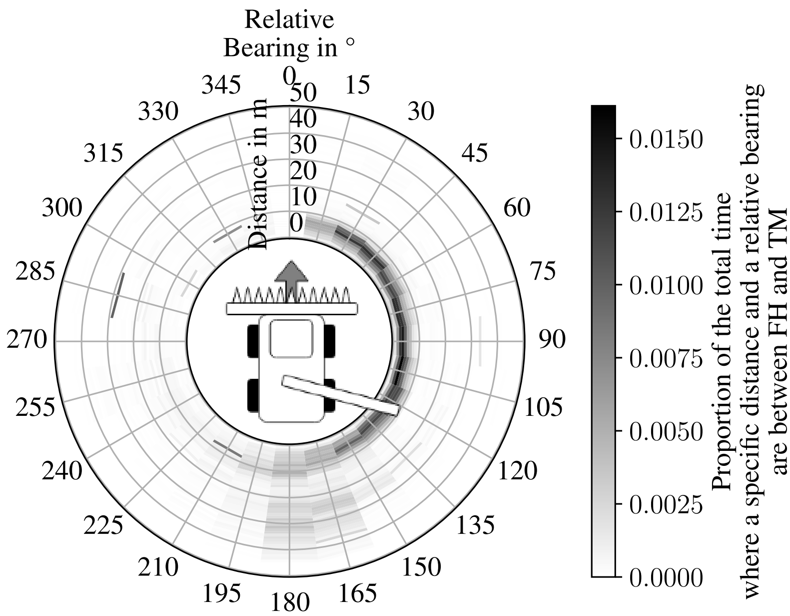

Figure 3.4 – Distribution of time proportion at specific distances and relative bearings between Forage Harvester (FH) and Transport Machine (TM)

In addition, it is noticeable that the machine can also be directly behind the Forage Harvester. This driving behind each other is common when a new part of the field is being cut in harvesting, as shown in Figure 3.5. When there is a greater distance between Transport Machine and Forage Harvester, the Transport Machine is usually behind the FH at an angle of 157.5°... 187.5°. At these moments, the Transport Machine is empty and closes up to the Forage Harvester to operate in a new platooning Service together.

Figure 3.5 – Forage Harvester (FH) and Transport Machine (TM) start cutting a new field section

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

The results reveal only a first impression of the harvest and loading process requirements. More data from around the world must be analyzed 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. To make a general statement, I should use data from different years because they can reveal different initial field conditions.

Heading Annahme Vorwärts Fahrt. Ansonsten Überprüfen und nochmal Einzelfahrt plotten und anschauen. Wie oft dreht sich das Heading ? Möglicherweise Rückwärtsfahrt erkennen? Oder WIC Requirements erwähnen?

Chapter 4

Field Measurements

Netcat not working no interval but connection setup easy. maybe something else iperf run unlimited?

Setup

HardwareListe machen E-Mail Excel

Blockschaltbild

John Deere T-Serie T6 T5 Großer Anhänger HW 80 Verlängerungskabel

Describe Mistakes?

Chapter 5

Developed architecture / System design / Implementation / ...

- describe everything you yourself did (as opposed to the fundamentals chapter, which explains what you built on)
- start with a theoretical approach
- describe the developed system/algorithm/method from a high-level point of view
- go ahead in presenting your developments in more detail
- recommended length: approximately one third of the thesis.

Chapter 6

Simulation

Seite 77 von 93 02 simulation.pdf Propagation Model: Two Ray Ground only mathematics Rappaport Jakes Model Three Log Distance

Data Simulation

QUESTIONS open 7 Möglichkeiten outdoor wifi was für Effecte

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

Im folgenden möchte ich den Einfluss der verschiedenen Parameter auf die Robustheit und den Goodput untersuchen. Da wie beschrieben, die vorhandene Technik nicht gezielt angesteuert werden kann, um die Einflüsse der Parameter zu untersuchen, wird eine Simulation durchgeführt. Weitere Vorteile, sind die flexibilität und die Möglichkeit verschiedene Communication Protocol und network protocols zu simulieren **ComparativeStudyKumar**.

OmarHESurvey unterscheidet dabei für die Simulation von HE wireless networks zwischen Link-Level Simulations and System-Level Simulations. Beide Methoden erklären die Autoren, wie folgt.

Link-Level Simulations untersuchen den Autoren nach die performance des HE physical layer für verschiedene physical layer parameter als packet error rate in regards to Signal Noise Ratio. Als Beispiel nehmen die Autoren die Simulation von **201** für PER in regards to SNR and chosen MCS.

Für System-Level Simulation benötigt es Abtractionen des physical und des MAC layers, um auf dieser Basis ein system close to real zu simulieren.

Für die Simulation von Wifi gibt es bereits verschiedene Tools, wie z.B. Matlab, ns-2 und ns-3, OMNeT++ oder Qualnet.

SimulationWifiMesh Ns-3 wurde bereits in **ComparativeStudyKumar** und **SimulationWifiMesh** verwendet für die Simulation von Wi-Fi networks. und ist daher für die Simulation von Wifi 6 geeignet. Da ns-3 eine Open Source Software ist, die auch für die Simulation von 802.11ax geeignet ist, wird diese für die Simulation verwendet. Die Simulation wird in der Programmiersprache C++ durchgeführt.

ns-3 Network Simulator

Warum nicht was anderes GNS3, MININET, ... ?

Bei der Wahl der Network Simulator Wifi 6 Implementierungen

In the doc folder of [38] findet man die folgenden Informationen über ns-3. 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 procide an open, extensible network simulator for research and educational use. Ns-3 scripts can be written in C++ or Python. ns-API Python uses models in C++ build system Cmake

ATM no pre-built libraries and packages for operating systems

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.

Für die aktuelle Version ns-3.37 wird IEEE 802.11ax als Standard im Infrastructure und Adhoc Mode unterstützt [7]. Jedoch ist die Unterstützung für den 802.11ax standard noch nicht vollständig. So kann man bereits DCM und STBC konfigurieren, jedoch findet man die den Kommentar in Zeile 496 von der Datei he-ppdu.cc, dass diese noch nicht in der aktuellen Version 3.37 für beachtet werden [8].

Bei der Untersuchung der Implementierung von 802.11ax in ns-3, fällt auf, dass die Implementierung von 802.11ax in ns-3 auf, dass bereits eine HE ER SU Physical layer convergence protocol data unit Preamble implementiert ist, welche jedoch nie genutzt wird und man den Extended Range Mode den nicht aktivieren kann. Die Implementierung von 802.11ax in ns-3 ist also noch nicht vollständig und es gibt noch einige offene Punkte, die in der Zukunft noch implementiert werden müssen.

Black, Gamboa, and Rouil [39] haben eine 3D Visualisierung von ns-3 entwickelt, welche die Simulationen in 3D visualisiert, um die ns-3 simulation scenarios greifbar zu machen. Die grafische Erweiterung der Autoren besteht aus zwei open source

[7] `https://www.nsnam.org/docs/models/html/wifi-design.html` Accessed: 24.02.2023

[8] https://www.nsnam.org/docs/models/html/wifi-user.html Accessed: 24.02.2023

Programmen. Das NetSimulyzer ns-3 module [9] lässt sich in die ns-3 Simulation integieren und baut über die spezifizierten Funktionen und Configurationen eine JSON Datei. Diese beinhaltet alle benötigten Daten für die Visualisierung in der NetSimulyzer [10]

6.1 Data Rate

Using ns-3 I built a simulation 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 eqipped with a Wi-Fi NetDevice with the following parameters: Guard Interval 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-Modulation and Coding Scheme 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 Wireless-Infield Communication use cases. The Wi-Fi Netdevices operate in the frequency channels specified in **??**, which can be used for outdoor Wi-Fi communication in Germany [40].

As the Wi-Fi standard implements ACKs for every packet, every lost packet is repeated until it is received or the number of retrys is exceeded. Platooning Services are time critical and therefore the number of retrys 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 µs. This packet interval sorgt dafür,

[9] https://github.com/usnistgov/NetSimulyzer-ns3-module Accessed: 24.02.2023
[10] `https://github.com/usnistgov/NetSimulyzer` Accessed: 24.02.2023

bandwidth	Channel number 2.4 GHz	Channel number 2.4 GHz
20 MHz	1	100
40 MHz	3	102
80 MHz	-	106
160 MHz	-	114

Table 6.1 – Frequency Channels numbers for 2.4 GHz and 5 GHz for the different bandwidth (BW)s of the IEEE 802.11 standard [41], which can be used for outdoor communication [40]

dass nach Start der Simulation the packet queue of the client is never empty. 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.

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 [17].

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. According to **ClassReference**, the WifiTxVector instance describes all parameters of the transmission in acordance to the TXVECTOR field of the IEEE 802.11 standard [17]. 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.

Überprüfung, Phy-Monitor, Theoretical DataRates

Guard Interval (GI)

In the first simulation I varied the Guard Interval of the Wi-Fi Netdevices for different HE-Modulation and Coding Scheme values. The results are shown in **??**. The achieved goodput is plotted against the theoretical data rate for the different Guard Interval values. The theoretical data rate is always higher than the achieved goodput of the UDP applications, because the channel is used for ACK and Adhoc Beacon transmissions as well. Due to these additional transmissions the goodput is lower than the theoretical data rate.

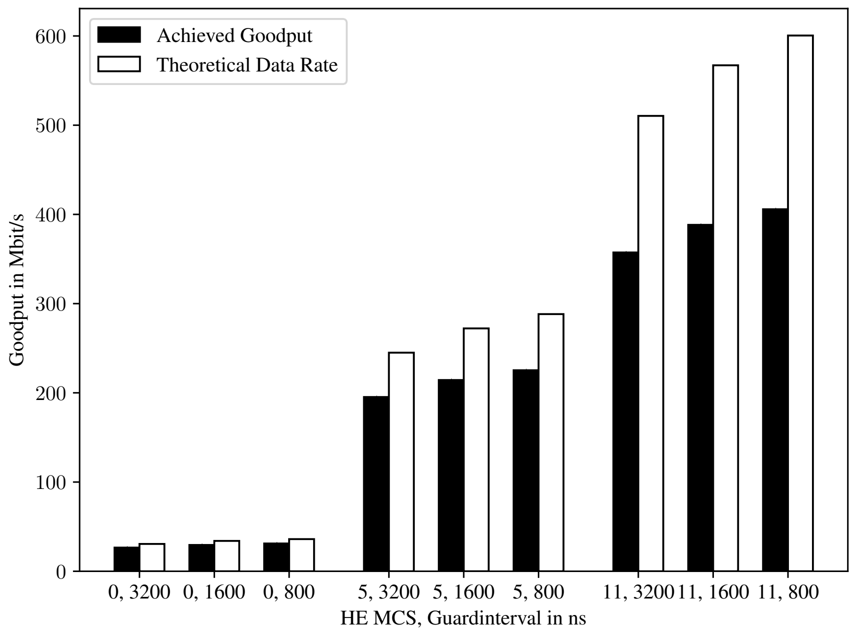

Figure 6.1 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with 2 Multiple Input Multiple Output (MIMO) streams and a bandwidth of 80 MHz in regards to the number of Multiple Input Multiple Output (MIMO) streams and the chosen HE-Modulation and Coding Scheme (MCS) value

As the Guard Interval length increases the achieved goodput deceases. This effect can be characterized by the aforementioned formula. The bandwidth attenuation for the possible Guard Interval lengths is displayed in **??**. The effect of the bandwidth attenuation for the different Guard Interval lengths can be observed in the mean achieved goodput in **??**, where the decrease of the mean goodput reflects the bandwidth attenuation of the decreasing Guard Interval length. A similar effect can be observed whit higher HE-Modulation and Coding Scheme values. **Pravinkumar Patil** similiar sgi and lgi. **Prasad** not similiar sgi and lgi.

Prasad, Patil, GI, Umgang mit Falschaussagen?

Guard Interval	Mean achieved goodput	bandwidth attenuation
800 ns	31.15 Gbit/s	94 %
1600 ns	29.47 Gbit/s	89 %
3200 ns	26.52 Gbit/s	80 %

Table 6.2 – bandwidth (BW) attenuation and mean goodput for HE-Modulation and Coding Scheme0 in regards to Guard Interval (GI) length

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 ER SU PPDU format is not used in ns-3 version3.37.

As I was using the ConstantRateWifiManager, all paramter 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 [17] are 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.

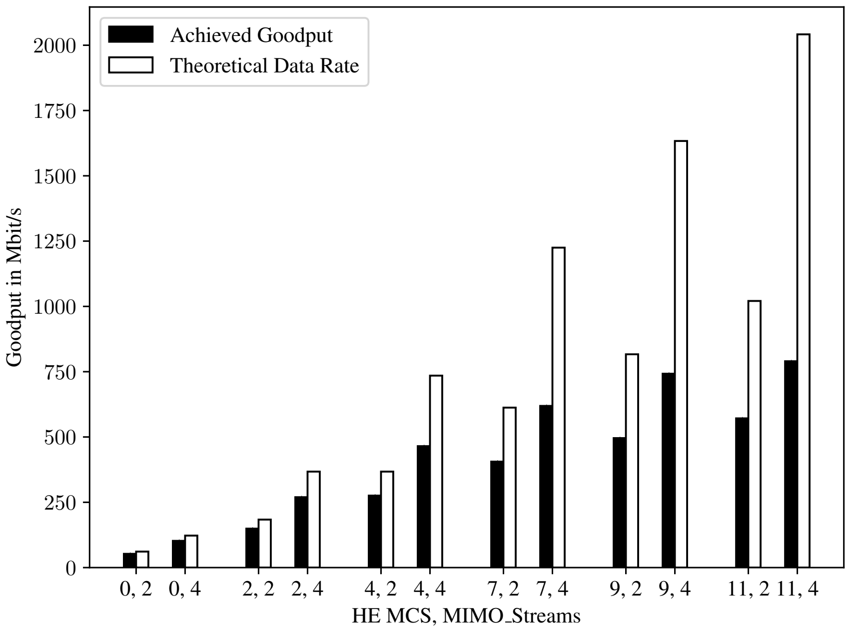

Figure 6.2 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with a Guard Interval (GI) of 3200 ns and a bandwidth of 80 MHz in regards to the number of Multiple Input Multiple Output (MIMO) streams and the chosen HE-Modulation and Coding Scheme value

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-Modulation and Coding Scheme value is less than 3 and d) the bandwidth is 20 MHz.

The results of the simulation are shown in **??**, where the lost achieved goodput is plotted against the theoretical data rate for the different HE-Modulation and Coding Scheme 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

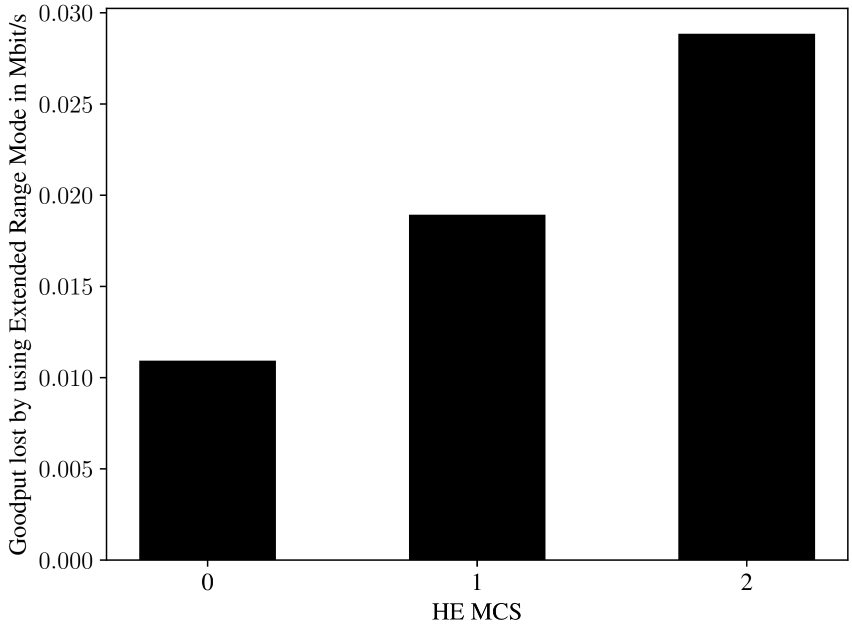

Figure 6.3 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with a Guard Interval (GI) of 3200 ns and a bandwidth of 20 MHz in regards to the number of Multiple Input Multiple Output (MIMO) streams and the chosen HE-Modulation and Coding Scheme value

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

Dual Carrier Modulation (DCM)

Using the Dual Carrier Modulation in the IEEE 802.11ax physical layer has also an effect on the achievable goodput. As aforementioned, the Dual Carrier Modulation is not supported by ns-3 version 3.37. Therefore, I implemented the Dual Carrier Modulation 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-Modulation and Coding Scheme values 0, 1, 3 and 4, where Modulation and Coding Scheme is allowed. Using Dual Carrier Modulation, the receiver would apply maximum likelihood decoding to decode the original payload with a higher probability.

The results of the simulation are shown in **??**, where the lost achieved goodput is plotted against the theoretical data rate for the different HE-Modulation and Coding Scheme values. The theoretical data rate while using Dual Carrier Modulation is half of the theoretical data rate without Dual Carrier Modulation, which complies with the IEEE 802.11ax standard [17].

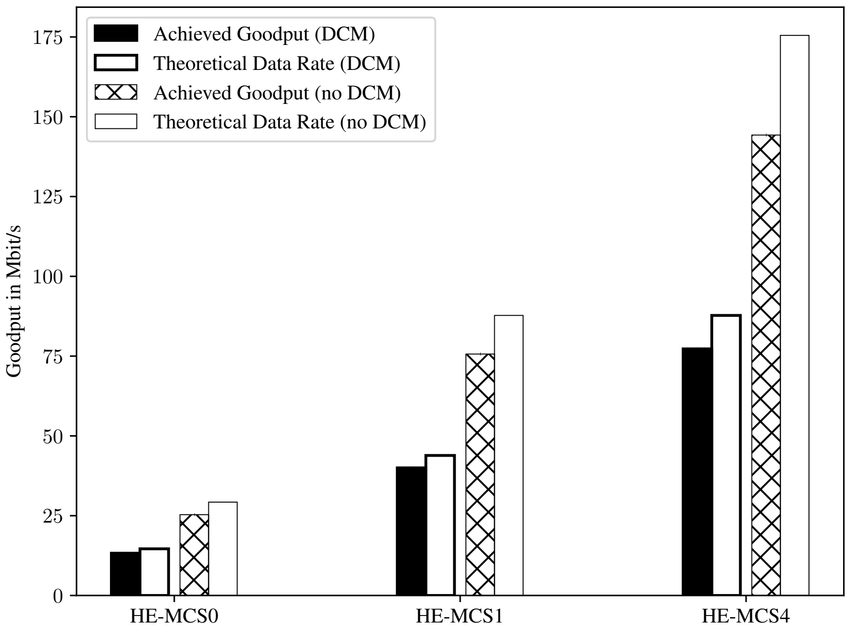

Figure 6.4 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with for IEEE 802.11ax physical layer parameters of a Guard Interval (GI) of 3200 ns, a bandwidth (BW) of 40 MHz and 2 spatial streams in regards to the number of the chosen HE-Modulation and Coding Scheme (MCS) 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 Dual Carrier Modulation 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 procudure 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 Space-Time-Block-Code. As mentioned, ns-3 version 3.37 does not support the Space-Time-Block-Code for the IEEE 802.11ax standard. Therefore, I reduced the number of Multiple Input Multiple Output streams from two to one, when the Space-Time-Block-Code is enabled. Space-Time-Block-Code 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 **??**, where the lost achieved goodput is plotted against the theoretical data rate for the different HE-Modulation and Coding Scheme values. The theoretical data rate while using Space-Time-Block-Code is half of the

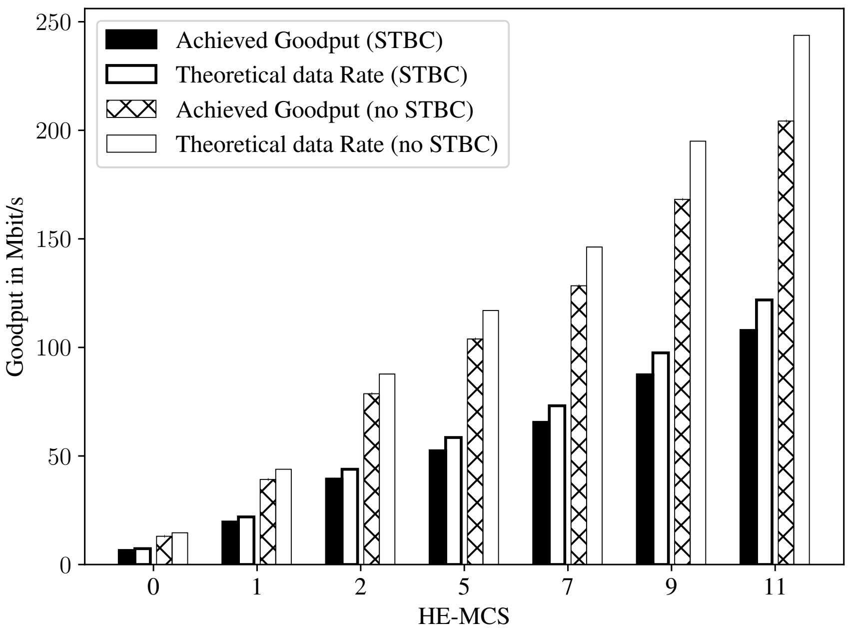

Figure 6.5 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with for IEEE 802.11ax physical layer parameters of a Guard Interval (GI) of 3200 ns, a bandwidth (BW) of 40 MHz and 2 spatial streams in regards to the number of the chosen HE-Modulation and Coding Scheme (MCS) value and whether Space-Time-Block-Code (STBC) is enabled

Error bars goodput lost

Through the new IEEE 802.11ax standard [17], the Wi-Fi standard has been extended to support more Multiple Input Multiple Output streams or higher Modulation and Coding Scheme values and use low-density parity-check compulsory for the aforementioned configurations. The effect of more Multiple Input Multiple Output streams is already known from **Lot of stuff**. low-density parity-check no new effect for data rate, but more robustness which results in a lower packet error rate. Robustness?

6.2 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. The MATLAB WLAN Toolbox [11] 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.

Why Matlab? Why not ns-3?

[11] `https://de.mathworks.com/products/wlan.html?s_tid=AO_PR_info`

Since Release R2019b [12], 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/HESUExample [13] to simulate the packet error rate of point-to-point IEEE 802.11ax networks for a specified Signal Noise Ratio values.

example?

First, I set the IEEE 802.11ax physical layer parameters using the wlanHEConfig object, where I define the following default parameters:

- Guard Interval of 3200 ns
- bandwidth of 20 MHz
- 2 spatial streams
- 2 transmit antennas
- Dual Carrier Modulation disabled
- Space-Time-Block-Code disabled
- low-density parity-check enabled
- HE-Modulation and Coding Scheme of 0
- Coding Rate of 1/2
- Extended range mode disabled

use table?

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 six different channel models for IEEE 802.11ax networks, named TGax-A, TGax-B, TGax-C, TGax-D, TGax-E, and TGax-F.

As I want to simulate outdoor scenarios, I chose the TGax-F channel model, which is suitable for outdoor scenarios. The wlanTGaxChannel model supports configuring the bandwidth, the number of transmit and receive antennas, which I set equal to the configuration of the wlanHEConfig object. [40] 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. Additional parameters are left at their default values as they are not relevant for outdoor scenarios.

The simulation runs the following procedure for each specified Signal Noise Ratio value.

[12] https://de.mathworks.com/help/wlan/release-notes.html

[13] https://de.mathworks.com/help/wlan/ug/802-11ax-packet-error-rate-simulation-for-single-user-format.html

First, the WLAN Toolbox generates a random packet of the specified length of 1000 Byte, which is used to create a Wlan waveform based on the physical layer parameters specified in the wlanHEConfig object using the wlanWaveformGenerator function. The generated waveform is then passed through the configured wlanTGax-Channel to simulate the channel. The output of the channel model is the received waveform, where the channel model adds noise to the transmitted waveform based on the specified Signal Noise Ratio value.

The received waveform is then passed through the wlanWaveformDecoder function to decode the received waveform.

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 packet error rate in regards to the Signal Noise Ratio. The results in **??** show that the packet error rate decreases with higher Signal Noise Ratio for all HE-MCS values. The packet error rate decreases at lower Signal Noise Ratio values for lower HE-MCS values.

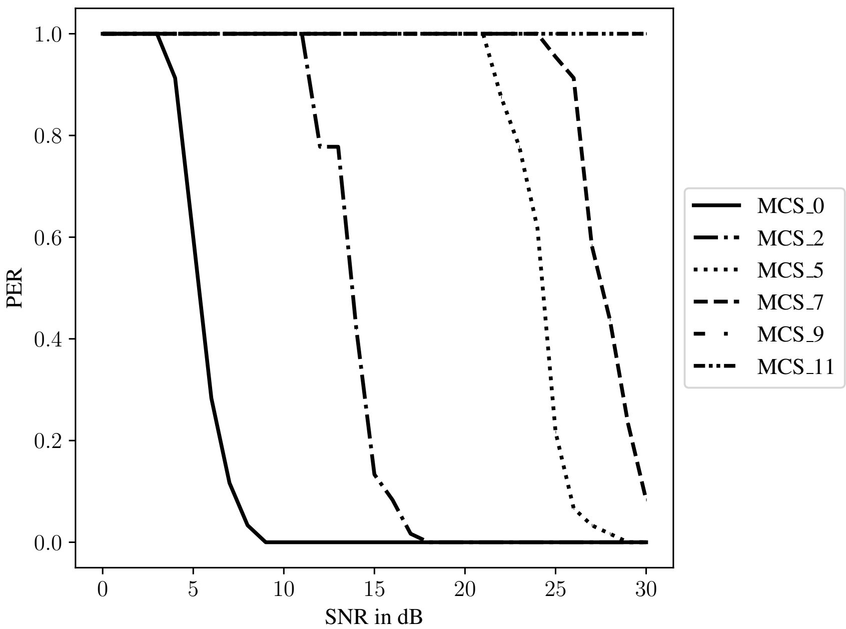

Figure 6.6 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with a Guard Interval of 3200 ns and a bandwidth of 40 MHz in regards to the number of the chosen Modulation and Coding Scheme and Coding Rate and whether Dual Carrier Modulation is enabled

Forward Error Correction (FEC)

Another parameter that influences the packet error rate is the choice of the forward error correction (FEC) procedure. In order to analyse the influence of the FEC procedure on the packet error rate, I simulated the packet error rate in regards to the Signal Noise Ratio for HE-MCS 0 . . . 9 and whether low-density parity-check or binary convolutional coding is enabled. For higher HE-MCS values binary convolutional coding can be used as low-density parity-check is compulsory, so no comparison of the Forward Error Correction procedures is possible.

The results are displayed in **??**. The packet error rate decreases with higher Signal Noise Ratio for both Forward Error Correction procedures for all HE-MCS values as expected. Using low-density parity-check instead of binary convolutional coding decreases the packet error rate for all HE-MCS values at lower Signal Noise Ratio values.

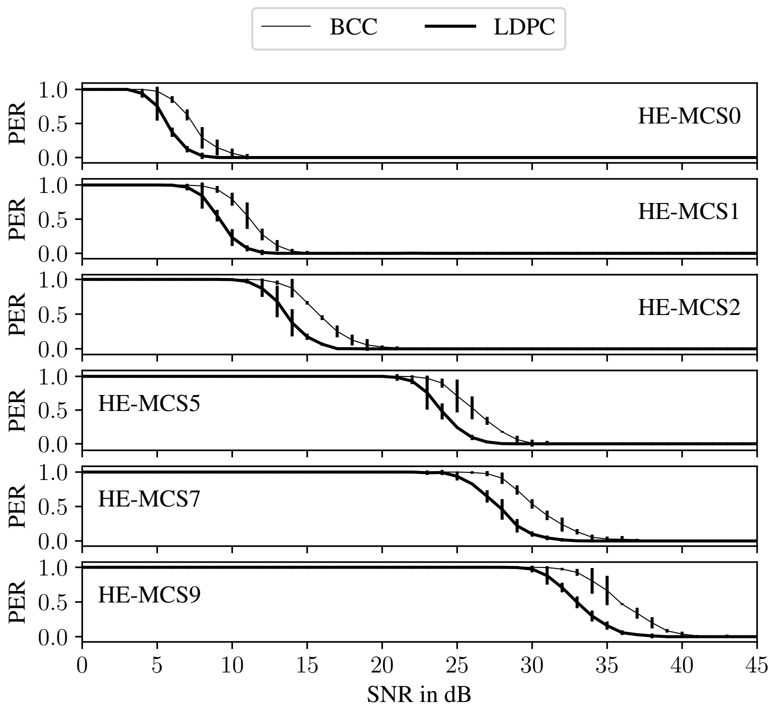

Figure 6.7 – Simulated packet error rate in regards to Signal Noise Ratio for chosen HE-Modulation and Coding Scheme values and whether low-density parity-check or binary convolutional coding is enabled for IEEE 802.11ax physical layer parameters of a Guard Interval of 3200 ns, a bandwidth of 20 MHz and 2 spatial streams

Guard Interval (GI)

patil effect

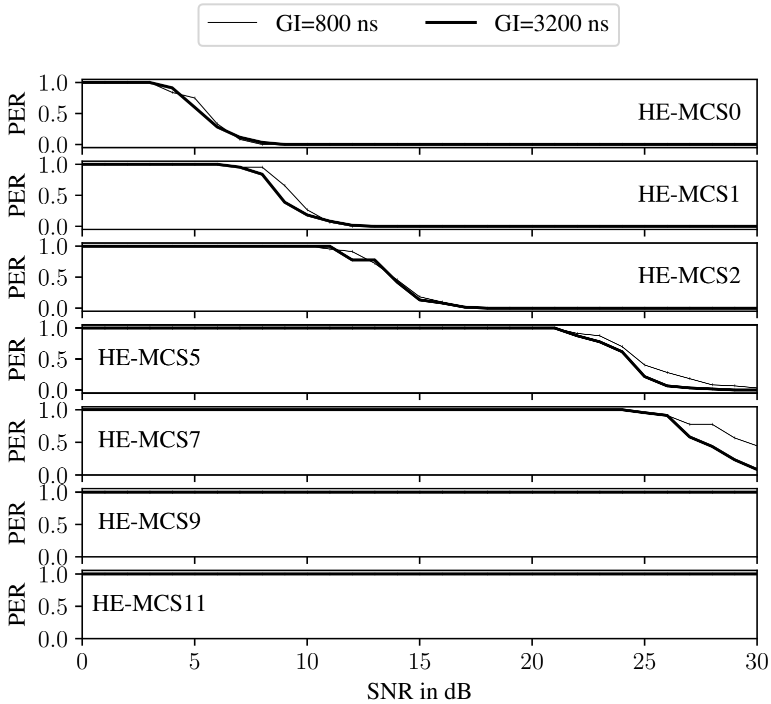

Figure 6.8 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with a Guard Interval of 3200 ns and a bandwidth of 40 MHz in regards to the number of the chosen Modulation and Coding Scheme and Coding Rate and whether Dual Carrier Modulation is enabled

cite others seane old??

Dual Carrier Modulation (DCM)

Next, I simulated the packet error rate in regards to the Signal Noise Ratio and whether Dual Carrier Modulation is enabled for the specfied HE-Modulation and Coding Scheme values. Dabei habe ich für die SImulation die möglichen HE-MCS 0,1,3 and 4 aus dem IEEE 802.11ax Standard verwendet.

The results indicate, that using Dual Carrier Modulation can achieve the same packet error rate at lower Signal Noise Ratio values compared to not using Dual Carrier Modulation. Dual Carrier Modulation also influenced the packet error rate to decrease at lower a Signal Noise Ratio for all specified HE-MCS values. The results are visualized in **??**.

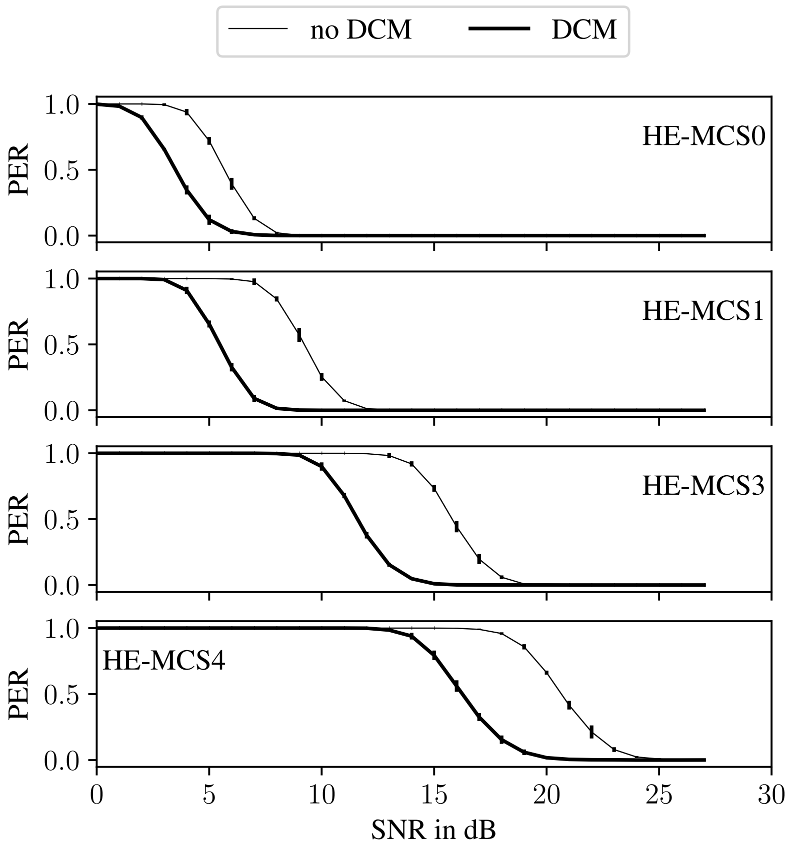

Figure 6.9 – Simulated packet error rate in regards to Signal Noise Ratio for chosen HE-Modulation and Coding Scheme values and whether Dual Carrier Modulation is enabled for IEEE 802.11ax physical layer parameters of a Guard Interval of 3200 ns, a bandwidth of 20 MHz and 2 spatial streams

Ryu, Lee, and Kang [42] and Park, Sung, and Ko [43] conducted a similar simulation, where they analyse the bit error rate in regards to the normalized Signal Noise Ratio and whether Dual Carrier Modulation was enabled for rayleigh fading channels. Both authers wraped two Quadrature Phase Shift Keying modulated symbols into one 16-Quadrature Amplitude Modulation symbol. As Quadrature Phase Shift Keying modulates 2 bit per symbol, the infomation of two Quadrature Phase Shift Keying modulated symbols can be transmitted in one 16-Quadrature Amplitude Modulation symbol, which encodes 4 bit. The authors transmit the 16-Quadrature Amplitude Modulation symbols and a redundant copy of the 16-Quadrature Amplitude Modulation symbols via orthogonal subcarriers. At the receiver the authors combine the copies and retrieve the transmitted information using the Maximum likelyhood criterion. The results of the author show that a better bite error rate can be achieved while applying Dual Carrier Modulation than sending the information via two Quadrature Phase Shift Keying or 16-Quadrature Amplitude Modulation modulated symbols without Dual Carrier Modulation.

name PER 0.5 Some paper use 0.1 PER and mention the SNR improvement 4 db improvement

Extended Range (ER)

For a HE-MCS 0 and 1 the Extended Range range mode can be applied additional to Dual Carrier Modulation, when one spatial stream is used [17]. In order to analyse the impact of the Extended Range mode, I set the physical layer parameters to a Guard Interval of 3200 ns, a bandwidth of 20 MHz and one spatial streams. For He-MCS 0, 1 and 3 I run simulations, where I enabled the Extended Range mode and compared the packet error rate to the packet error rate of the same HE-MCS values without Extended Range mode. The results in **??** indicate , that the packet error rate is influenced by the Extended Range mode. The packet error rate decreases with at lower Signal Noise Ratio for all HE-MCS values when Extended Range is enabled. Additionally, I simulated the impact of applying the Extended Range mode and Dual Carrier Modulation for the allow HE-MCS values 0 and 1. Applying Dual

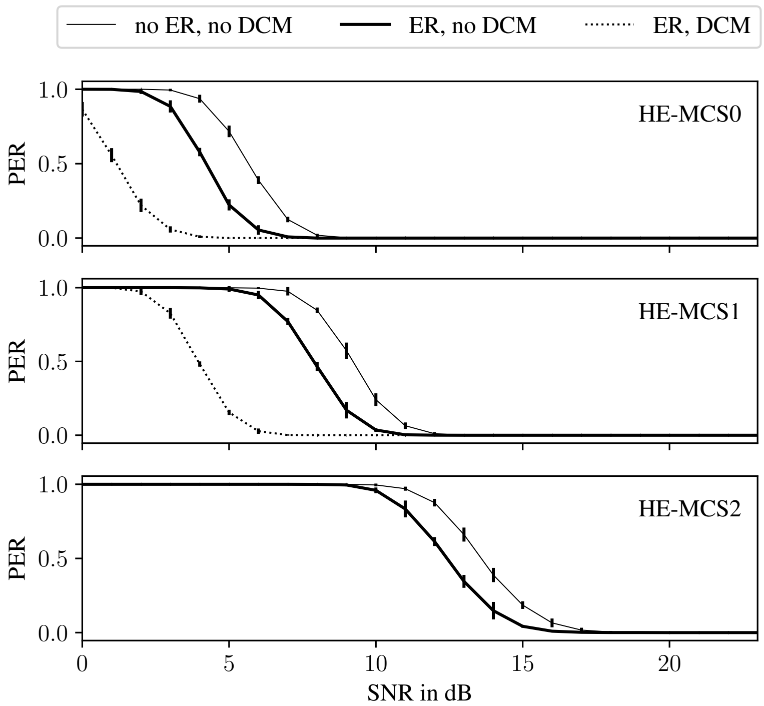

Figure 6.10 – Simulated packet error rate in regards to Signal Noise Ratio for chosen HE-Modulation and Coding Scheme values and whether Extended Range or Dual Carrier Modulation is enabled for IEEE 802.11ax physical layer parameters of a Guard Interval of 3200 ns, a bandwidth of 20 MHz and 2 spatial streams

Carrier Modulation additionally makes the transmission more robust and decreases the packet error rate at even lower Signal Noise Ratio as it is displayed in **??**.

Jacob et al. [14] conducted a simulation, where they analysed the effect of Dual Carrier Modulation and Extended Range on the packet error rate for IEEE 802.11bd in vehicular environments to the transmission range. The authors found out, that the using Dual Carrier Modulation and Extended Range can increase the transmission range for Line-Of-Sight by 65 % for a packet error rate greater than 0.1. After additional analysis with higher vehicle densities, the authors remark, that using Dual Carrier Modulation and the Extended Range mode cause channel congestion in CSMA/CA based networks with low bandwidths. The authors conclude, that the Extended Range mode and Dual Carrier Modulation 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 [44]. The researchers state, that using Dual Carrier Modulation and the Extended Range mode results in better packet error rate performance at lower Signal Noise Ratio values in Line-Of-Sight and non Line-Of-Sight scenarios.

Space-Time-Block-Code (STBC)

Fixed Wifi 6 devices: 4 Streams, 2.4, 5.0 Ghz Fixed Wifi bd devices: 1 Stream, 5.9 Ghz,

Leave it open for future work? look for different chips?

Auf different paper stützen?

6.3 Platooning Services

Packetsize 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 weißen 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 Transportmachine sein.

Service Discovery

Rebroadcast by Count? additional Traffic

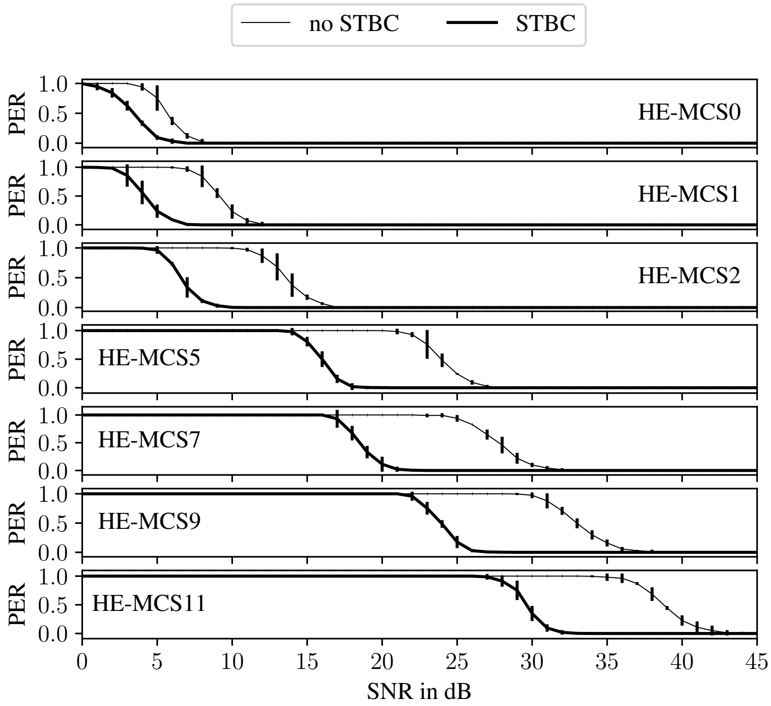

Figure 6.11 – Simulated packet error rate in regards to Signal Noise Ratio for chosen HE-Modulation and Coding Scheme values and whether Space-Time-Block-Code is enabled for IEEE 802.11ax physical layer parameters of a Guard Interval of 3200 ns, a bandwidth of 20 MHz and 2 spatial streams

MANET Service discovery

Visualisierung Netsimulyzer

Farbcodes

Chapter 7

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 8

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

List of Figures

List of Tables

Bibliography

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