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

Diploma Thesis in Information Systems Engineering

27 February 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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Abgabe der Arbeit:	**27. Februar 2023**

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(Karl Christian Lautenschläger)
Dresden, 27 February 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- problem: gap in knowledge, too expensive, too slow, a deficiency, superseded technology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.

Schlingmann et al. [2] of the Agricultural Industry Electron- ics Foundation AEF, one of the major industry associations, are investigating the concept of cooperative agricultural ma- chinery using Inter-Vehicular Communication (IVC). One of the often-mentioned use cases is precisely this exchange of cultivated areas. Arguing that only 30 covered by wireless connections [3],

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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

Given that there are many different agricultural technology companies worldwide and a 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 (AEF) was founded to develop and implement electronic standards in the agriculture industry. By creating common standards and protocols, the AEF enables interoperability between Agricultural Technologies.

TThe 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 projects. Among these is also the WIC. The associated project group WIC develops and standardizes solutions for Machine-To-Machine (M2M) communication between cooperating agricultural machines.

For this purpose, the authors name the following use cases:

- **Real-Time Machine-to-Machine Control** is the exchange of control data under real-time conditions with defined latency policies. This use case enables leader-follower scenarios where agricultural machines follow a leading agricultural machine at a lateral and longitudinal distance. Throughout this thesis, I will refer to Real-Time Machine-to-Machine Control as Agricultural Platooning Service.

- **Streaming Services** are communications that stream video from remote cameras and monitors at a high data rate and low latency. The authors estimate the distance between the communication participants to be less than 100 m. As a result, this data is available on another agricultural vehicle and can be analyzed and processed there. I will refer to Streaming Services as Agricultural Streaming Services in this thesis.

- **Process Data Exchange** describes the exchange of process data. One example is the exchange of already sprayed field areas to prevent multiple spraying of fertilizers and pesticides on the same field area by different machines. According to the authors, this WIC use case requires long-range technologies because agricultural fields worldwide can be vast.

- **Fleet Management & Logistics** is the potential retrieval of data from the ongoing agricultural process. This information can influence economic or agronomic decisions of agricultural enterprises or service companies and is therefore required in a Farm Management Information System (FMIS). Since not all agricultural machines may be connected to the FMIS, the WIC project group is looking at how to use M2M communications to bridge the missing communications infrastructure until the data reaches a machine that can connect to the FMIS.

- **Road Safety** describes a use case which is already a project between the European Telecommunication Standard Institute and the AEF. Since agricultural vehicles are repeatedly underestimated in their size and speed by other road users when they suddenly turn off the field onto the road, the other road users need to be warned in this situation. In this way, smart technologies in cars and motorcycles can brake these vehicles in advance and prevent possible accidents.

Considering that I investigate the Suitability of modern 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 WIC use cases Real-Time Machine-to-Machine Control and Streaming Services. Throughout this thesis, I will refer to real-time machine-to-machine control as Agricultural Platooning.

2.2 Related Work

AEF Vorgehen

Lösungen Technologien

Bekannte Arbeiten

Bekannte Forschung zur WIC habe ich in meiner Studienarbeit [1] und in **Beyond** zusammengefasst.

Supported by the AEF, **klingler** thus conducted a feasibility study for the use of IEEE 802.11p in an agricultural environment. They tested Received Signal Strength, delay, and goodput of IEEE 802.11p. The result of the study was a maximum distance of 1700 m since no further data could be exchanged after Line-of-Sight (LOS) was lost.

Additional RSS reductions decreasing channel quality were due to the size and shape of the agricultural machinery, in particular harvesters.

FendtPlatoon took a different approach and used IEEE 802.15.4 to exchange the relevant control data for a leader-follower system in which an unmanned tractor can follow another one. Still, the authors state that their system does not offer a wider range.

AEF Papers

Kein Cellular 11p Klingler FCC 802.15.4 Zhang LoRa

Claas Ivan Schmolnik

Außerhalb der AEF Platooning: There are also more developments in the field of wireless infield communication from the industry. In this context, Thomasson et al. [3] describe the John Deere Machine Sync and Case IH V2V systems as follows:

John Deere Machine Sync enables the WIC uses cases Process Data Exchange and Agricultural Platooning Service. Liu et al. [4] have extended the system to use Combine Harvesters, adding that the Machine Sync system is based on Metzler, Flohr, and Hoeh [5]'s patent. Smolnik, Lücke, and GmbH [6] adds thats John Deere Machine Sync is only available for a subgroup of John Deere machine types and can't be used with machines of other brands.

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

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

Also currently on the market is the Raven Autonomy™ Driver Assist Harvest Solution [2] system from Raven Industries. This system allows the harvester to take control of a Transport Machine (TM) from a distance of 70 m. The harvester then automatically guides the TM into the perfect position to load the harvested crop onto the TM via the spout. Once the harvesting and loading process is complete, the driver of the TM retakes control.

A comparable system is CartACE from AgLeader [3]

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

Aufbau:

WIC Umsetzungen:

Klingler 802.11p Elektrische Deichsel Fendt Beyond Sensing ???

John Deere Machine Sync Raven Machine Sync Cellular networks

cellular network coverage AEF paper

Wifi 6 Outdoorcommunication

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 [7].

The authors consider the fundamental use of cellular networks as very problematic because, according to [8], 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.

In collaboration with Klingler, Blobel, and Dressler [9], the authors investigated IEEE 802.11p technology for WIC in agricultural scenarios. Experiments revealed that data could be exchanged over a maximum range of 1700 m. 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 high range, data rate, and possible latencies make IEEE 802.11p a good technology for WIC according to Schlingmann et al. [7].

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

[2] https://ravenind.com/products/autonomy/driver-assist-harvest-solution Accessed: 2/5/2023

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

are reserved for Intelligent transportation systems now. The lower 45 MHz have been released for unlicensed operations [10].

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

2.3 Wireless Lans according to IEEE 802.11

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

According to Kauffels [11] 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 [12] 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. [13] 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 (V2X) nach den Autoren im 5.9 GHz frequency spectrum

HT, VHT, HE - phy

Kauffels [11] defines the following three basic architectures for IEEE 802.11.

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

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

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

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

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

Sauter [12] adds, that usually Ethernet is used to link APs in within an ESS. But according to the author this can be replaced by a wireless connection, which is called wireless bridge.

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 [12] 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 (OFDM) can be used in the 2.4 GHz frequency band. the author explains OFDM as following. OFDM 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 OFDM symbols over the individual OFDM subcarriers. The distance between the "highs" of the subcarriers is specified as subcarrier spacing and corresponds to the reciprocal symbol length. 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 [13].

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

Bandwidth

Modulation and Coding Scheme

In order to encode as many bits as possible on one OFDM symbol, different MCSs can be used. These MCSs for the IEEE 802.11 standards are based on Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM). [11]. The smallest MCS is binary PSK and encodes 1 bit per symbol. IEEE 802.11ax has the most complex

MCS of 256-QAM IEEE 802.11ac to 1024-QAM and thus now encodes 10 bit per symbol [14]. In the V2X range, so can MCSs from binary-PSK to 256-QAM.

In order to encode as many bits as possible on one OFDM symbol, different MCSs can be used. The MCSs for the IEEE 802.11 standards are based on PSK or QAM. [11]. The smallest MCS is Binary - PSK and encodes 1 bit per symbol. IEEE 802.11ax has the most complex MCS of 256 - QAM IEEE 802.11ac to 1024 - QAM and thus now encodes 10 bit per symbol [14]. In the V2X range, so can MCSs from binary-PSK to 256- QAM.

An imaginary, theoretical transmission channel is usually specified as a square-wave signal in the frequency domain with the limits of both minimum and maximum amplitude and cut-off frequency. Kauffels [11] defines the roll-off factor as a cosine-shaped flattening of the square signal between 0 and 1. In addition, the author points out that QAM can generate high roll-off factors, so that signals interfere significantly more with adjacent channels.

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

Forward Error Correction

Nevertheless bit errors can occur during the transmission. In this regard, [11] mentions and explains FEC as a technique to reduce bit errors during transmission. FEC adds redundant bits to the data. The receiver uses these redundant bits to check the integrity or correct errors of the received data. The proportion of non-redundant transmission bits is defined in Coding Rate (CR)

explain cr ?? Cite??

To achieve this, binary convolutional coding (BCC) is used mandatory since the IEEE 802.11n standard [14] [15]. Syafei et al. [15] add that it is optionally possible to use low-density parity-check (LDPC). The authors state that LDPC can achieve a better channel capacity performance. This is also confirmed by Afaqui, Garcia-Villegas, and Lopez-Aguilera [14], who point out that LDPC also generates higher computational cost.

IEEE 802.11ax stations must support LDPC when using on the IEEE 802.11ax standard under the following conditions [14] **standard_ieee_2021**:

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

IEEE 802.11ax achieves CR of 1/2, 2/3, 3/4, and 5/6 **standard_ieee_2021**. Similarly, IEEE 802.11p uses the BCC technique, which has been superseded by LDPC in its successor IEEE 802.11ax [13] [16]. Yacheur, Ahmed, and Mosbah [16] argue that this step was important, as LDPC offers better error correction possibilities for higher communication ranges greater than 50 m.

Together with the MCS, the FEC CR form a physical layer specification. This is named after the standard and includes the possible expressions for MCS values and CR of the standard. For IEEE 802.11ax, this results in the HE-MCS index values in Table 2.1

HE-MCS index	MCS	CR
0	Binary PSK	1/2
1	Quadrature PSK	1/2
2	Quadrature PSK	3/4
3	16-QAM	1/2
4	16-QAM	3/4
5	64-QAM	2/3
6	64-QAM	3/4
7	64-QAM	5/6
8	256-QAM	3/4
9	256-QAM	5/6
10	1024-QAM	3/4
11	1024-QAM	5/6

Table 2.1 – HE-MCA index table nach **standard_ieee_2021**

Symbol length, GI, subcarrier spacing reciprocal

Wellenausbreitung, Überlagerungseffekte, Reflexsion, Reflexsion nicht bei Metall

Knauffel OFDM PHY

Guard Interval

Pulimamidi, Nulu, and Tahernezhadi [17] 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[18]. Similarly, Inter Carrier Interference is caused by time-varying channel a longer OFDM symbol duration, that just as an interference with the following OFDM symbol can arise [19].

About the Guard Interval Pulimamidi, Nulu, and Tahernezhadi [17] 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: BERECHNET SICH ALS: NAHTLOSER ÜBERGANG

longer GI WIfi 6 Outdoor Communication

Parameter einführen?

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

Since IEEE 802.11n, a shortened GI of 400 ns is usable, which increases the maximum data rate from 270 Mbit/s to 300 Mbit/s compared to the usual GI of 800 ns [12]. IEEE 802.11ax supports GIs 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 GI genannt. Außerdem steht in den genannten Quellen nur die OFDM symbol length von 12.8 µs aufgeführt.

Dual Carrier Modulation

In order to introduce additional robustness DCM can be applied to the physical layers of IEEE 802.11ax and IEEE 802.11bd according to Jacob et al. [13]. The authors describe DCM 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.

standard_ieee_2021 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 (BW) of 20 MHz is displayed in Figure 2.1. It demonstrates that when using DCM, the receiver minimum input sensitivity can be lower than without using DCM. The effect on the receiver minimum input sensitivity increases as the HE-MCS value increases.

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

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

standard_ieee_2021 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 DCM is only optional in the IEEE 802.11ax standard and can only be used for HE-MCS-0, HE-MCS-1, HE-MCS-3 and HE-MCS-4 for 1…2 spatial transmission streams **standard_ieee_2021**.

Extended Range

Since IEEE 802.11ax the Extended Range Mode exists, which defines the new HE ER SU Physical layer convergence protocol data unit (PPDU) as physical layer amendment **standard_ieee_2021** [14]. Deng et al. [20] explains that the HE ER SU PPDU format is intended to extend the range of a single station to access point

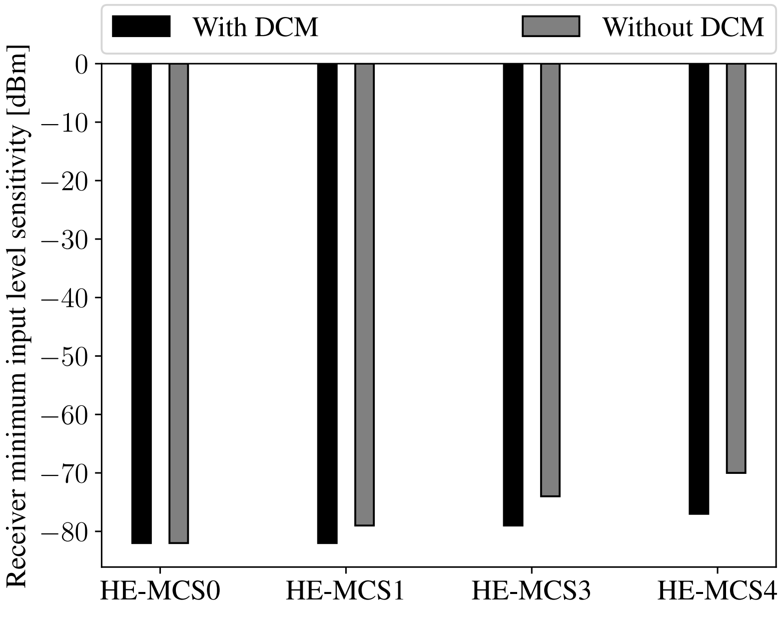

Figure 2.1 – Receiver minimum input level sensitivity for different HE-MCS values according to **standard_ieee_2021**, where packet error rate (PER) is less than 10 %

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 **standard_ieee_2021** [13], to guarantee reliable transmission for longer ranges.

The IEEE 802.11ax **standard_ieee_2021** standard defines that the HE ER SU PPDU 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 DCM.

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

Jacob et al. [13] adds that this extended range mode is also available for 802.11bd.

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 MIMO - systems. Sauter [12] describe the idea behind MIMO 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 **standard_ieee_2021**. Since data can be sent simultaneously via each MIMO stream, the theoretical data rate can thus increase proportionally depending on the usable streams.

MU-MIMO DCM only appicable, when RU contains only data for one user. **standard_ieee_2021** 607 not applicable with DCM NUM_STS = Number of Spatial Streams $n_{ss} = NUM\_STS/(1 + STBC)$

Space-Time-Block-Code (STBC)

abbas sagt zudem, dass MIMO dazu genutzt werden kann, um die Qualität des empfangenen Signals zu verstärken. Das geschieht in Form von spatial diversity und STBC.

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 **Santumon**. STBC is a technique used in Wi-Fi networks to improve the reliability and robustness of wireless communications. STBC encodes multiple redundant copies of data at the transmit side, which are transmitted in different spatial streams to reduce the effects of fading and interference. At the receiver side, these multiple copies are combined to improve the signal quality and increase the data rate. This results in a more reliable and efficient wireless communication system, with improved data transfer speed and reduced error rates. STBC in Wi-Fi networks improve the reliability and robustness of wireless communications. Here, **Stamoulis** has investigated the potential effect of STBC on Wi-Fi. Their simulations showed thatSTBC can increase the range and robustness for IEEE 802.11a. In addition, the authors concluded that STBC increases the Signal Noise Ratio (SNR) in nearly all cases at the same throughput or even allows higher MCS values to be used, thus allowing a higher throughput at the same SNR.

[12] Reichweite und throughput higher wegen better SNR in Range

IEEE 802.11ax stations use STBC when applying on the IEEE 802.11ax standard under the following conditions **standard_ieee_2021**:

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

HE Capabilities nur so gut, wie das schlechteste Glied

standard_ieee_2021 607 not applicable with DCM

MAtthew gast 11n STBC is only support in one fifth of the Wi-Fi CERTIFIED n devices. Group addressed frames

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

Kauffels [11] 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 SSID to test the presence of the AP. To get an AP in range, the probe-frame can also contain a broadcast SSID that causes all nearby APs to respond. The response of an AP to the probe frame is the probe-response frame, which contains the same information as a beacon frame. With the information from the beacon frame, a station can start the authentication process.

For this process, Kauffels [11] names the two methods Open System Authentication and Shared Key Authentication. Sauter [12] explains that Open System Authentication is based on a device making an authentication request to the AP. If the AP answers with a positive status in the Authentication Frame, the station is included in the BSS. The actual encryption and authentication is then performed by the Wi-Fi Protected Access (WPA) functions. The author points out that Shared Key Authentication is no longer used today.

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

Sauter [12] explains that DCF is based on the media access method Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). In CSMA/CA 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 (DIFS) 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 (ACK) frame. The DIFS ensures that an ACK 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 DIFS, 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 ACK 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 (NAV) 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 2.2, 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 AP may occur.

Um das hidden station problem zu umgehen kann eine Station nach Sauter [12] Point coordinator ohne Wettbewerb mit optionaler Priorisierung

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 [12] 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

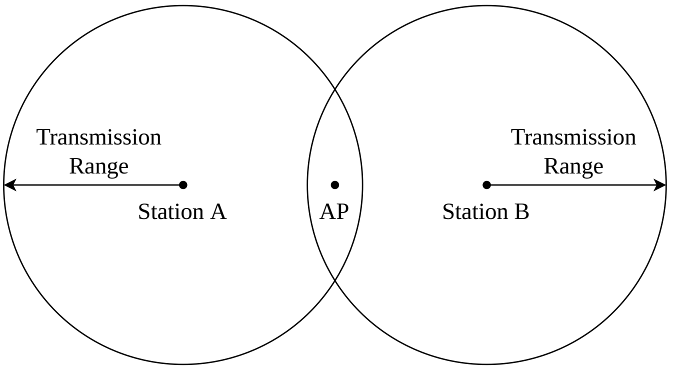

Figure 2.2 – Hidden Station Problem

MAC Header

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

Sauter [12] 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 (802.11ac) and operates in the 5 GHz frequency range [21].

According to Perahia and Gong [22], 802.11ac is a further evolution of IEEE 802.11n, where 802.11ac adds to the known bandwidth of IEEE 802.11n of 40 MHz the bandwidths 80 MHz,160 MHz and the interrupted bandwidth of 80 MHz + 80 MHz.

nach Sauter [12] ist die Aufspaltung in zwei 80 Mhz Kanäle sehr nützlich, wenn das frequenzband reservierte Regionen enthält. Dadurch kann ein 160 Mhz breiter Kanal um eine reservierte region des frequenzbandes gebaut werden.

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

As declared by Abdelrahman, Mustafa, and Osman [23], 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 [21] were able to demonstrate that 802.11ac with a range of over 60 m enables a longer indoor communication range than previous IEEE 802.11 standards.

new Physical Layer Very High Throughput (VHT) Physical Layer

80 Mhz

Beamforming

IEEE 802.11ax - Wi-Fi 6

The 6th generation of WLAN is IEEE 802.11ax (802.11ax). Khorov et al. [24] reveals what has changed from 802.11ac to 802.11ax. For this, the authors make the following statements.

802.11ax uses the same bandwidths in the 5 GHz range and can also operate in the 2.4 GHz frequency range with a maximum bandwidth of 40 MHz. Similar to DL MU transmission, 802.11ax enables UL MU transmissions. These can also use Orthogonal Frequency-Division Multiple Access (OFDMA) in addition to the already known MIMO of 802.11ac. OFDMA groups the orthogonal frequency subcarriers into Resource Unit (RU)s, which can be selected by the transmitter for optimal transmission to the receiver. This increases the Signal-to-Interference-plus-Noise Ratio (SINR).

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

MIMO und OFDMA MU Streams

BSS Coloring

Backward Kompatibilität über CTS Reservierungen.

Tabelle Vergleich

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

Table 2.2 – Comparison of IEEE 802.11ac and IEEE 802.11ax

2.4 Harvest and Loading Processes as a Use Cases for WIC

The Forage harvester has proven to be an essential agricultural machine for harvesting and loading forage. Seifert, Grimm, and Schurig [25] define a forage harvester as an agricultural loading machine for nearly all types of animal feed. By mounting different cutting and loading devices, a forage harvester can load the following animal feed, according to the authors: Hey, Straw, Corn, Grass and Clover.

In the harvesting and loading process, a TM typically drives alongside or behind the Forage Harvester (FH) so that the FH can load the harvested goods onto the trailer of the TM using the spout. Drivers operate both machines and try to keep the speed and distance so that the spout only throws the harvested goods into the trailer of the TM. An image of a harvesting and loading process for corn can be seen in Figure 2.3.

Taking a corn harvest scenario as an example, key figures can be looked up in [26], 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 2.3, are dependent on the Plant Population Density (PPD) and show the large amount of forage harvested by a FH every hour.

The harvesting and loading processes are examples of the use of an agricultural Platooning Services as described by Zhang et al. [27]. This Platooning Service creates a leader and follower system where an uncrewed agricultural machine follows a leading operated agricultural machine. For the harvesting and loading process, a

Figure 2.3 – Forage Harvester (FH) and TM while

Kennzahlen	PPD 20 t/ha	PPD 30 t/ha	PPD 50 t/ha
Required TMs	5	7	10
Harvesting performance volume [m^3/h]	285.7-333.3	428.6-500.0	595.7-695.0
Harvesting performance TM loads [1/h]	5.7 - 6.7	8.6 - 10.0	11.9 - 13.9
Harvesting performance mass [t/h]	100	150	208.5

Table 2.3 – Key figures from [26] of corn harvest of a FH with a working width of 6.2 m in a 80 ha-field in regard to PPD

Platooning service could be used as follows. The operated FH, as a leader, sets the path and speed and transmits the data via WIC to the TM. Based on the path and speed data of the FH, TM follows unmanned with a longitudinal and lateral offset, as Figure 2.4 displays.

This Platooning Service positions the TM optimally to the FH so that the forage can be loaded ideally from the FH onto the TM.

Figure 2.5 shows that the number of workers in the agriculture domain is declining. Because fewer and fewer workers are working in agriculture, the use of platooning services for harvest and loading processes can save and free up labour for other activities [4].

As stated in Table 2.3, already ten drivers for the TMs are needed in the corn harvest process with a high PPD.

Using an agricultural Platooning Service, each TM can drive unmanned in the field leading to a smaller number of workers needed in the corn harvest process.

Smolnik, Lücke, and GmbH [6] adds that platooning services at the platoon level can reduce the workload of drivers so that they can focus on optimally adjusting the machines. In addition, TMs can be guided to the FHs in a targeted manner so that logistics processes in the field can be improved.

At the same time, the harvest and loading processes are examples of the video streaming WIC use case. During these harvest and loading processes the spout of the FH must be controlled to set the loading position of the forage into the trailer of the TM.

According to Murcia [29], 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 of the

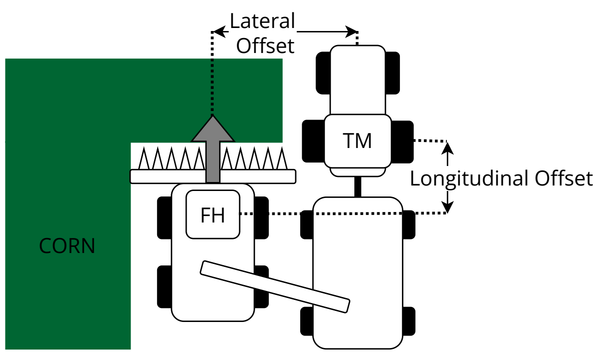

Figure 2.4 – Lateral and longitudinal Offset between the two agricultural machines FH and TM in a corn harvest scenario

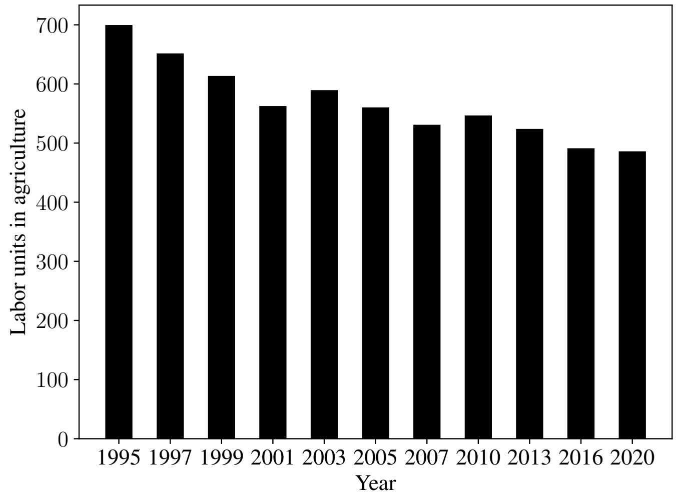

Figure 2.5 – Decrease in the agricultural labor force in Germany based on the data from [28]

trailer accordingly. The author describes Autofill - systems from Claas and Intellifill - systems from CNH Industrial as examples of spout guidance systems.

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

Chapter 3

Analyzing Corn Harvest Process Data

To gain a better insight into requirements of the WIC use cases Platooning and Streaming Services, I analysed process data of a corn harvest scenario as the example for I collected GPS tracks of a FH and two to three TMs harvesting corn on a field in Germany on two days in September. For this, I placed tablets in the driver's cabs of a FH and three TMs, 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 FH and the TMs 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.

After that, I anonymized 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.

The goal of analysing the corn harvest data was to investigate the machines moving in the working scenarios relative to each other. The speed and distance of the machines in tracked data of harvest platoons 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.

I had to develop an intelligent algorithm to detect harvest platoons in the Harvest Process data. It can detect them in the recorded process data.

For this purpose, I built a dashboard with the Python framework *Dash*[4]. In the dashboard, I initially plotted all the positions in a polyline for each machine on a map. A 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 TMs are displayed next to the FH. For the chosen time interval, the distance and velocity difference between the selected TMs and the FH were plotted in graphs as time histories.

In the dashboard, I could get an overview of the machine's behaviour before, during, and after the overloading scenario. In the overview, it can be seen that a FH is nearly always in the overloading process with a TM. In doing so, the FH may occasionally stay in the same place if the cutter is clogged or there is a transition of TMs where a full TM moves away from the FH and a empty TM catches up to the FH to take over the forage.

A TM is in a platoon with a FH if it is close to the FH and they are moving at nearly the same speed. During a turning manoeuvre on the field, the distance between TM and FH increases. Since both machines have different curve radii in a turning manoeuvre, a different speed can be observed on both machines to finish turning simultaneously. This also describes Smolnik, Lücke, and GmbH [6] 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. The machines again drive closely and nearly at the same speed to harvest and overload forage.

Furthermore, sometimes another TM can be close to the FH. This TM is empty and waits to work with the FH in the next platoon. For that purpose, the empty TM drives close behind the current platoon at the same speed so as not to catch up even closer to the platoon and be ready in the close vicinity.

Based on these observations above, I developed an intelligent algorithm for detecting platooning scenarios. It uses a weighted sum of distance and speed difference between FH and TM 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 TM leaves the field via one of the field exits to bring the crop to a farm building. Via a check if a TM 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 FH and TM was exceeded. These data points are also relevant to the requirements because at the beginning of an agricultural platooning service, the FH, as the leader of the system, must be able to guide an empty TM to the appropriate position for overloading.

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

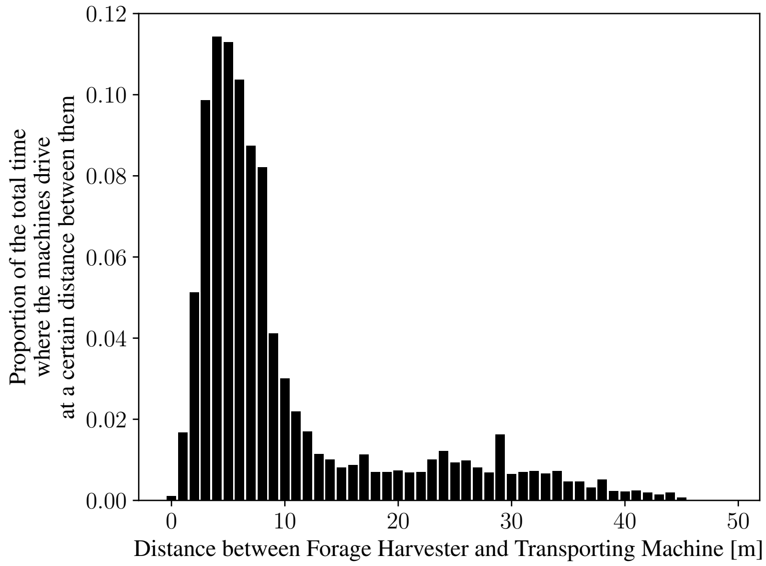

Figure 3.1 – Distribution of time proportions where a given distance was between FH and TM in a harvest platoon scenario.

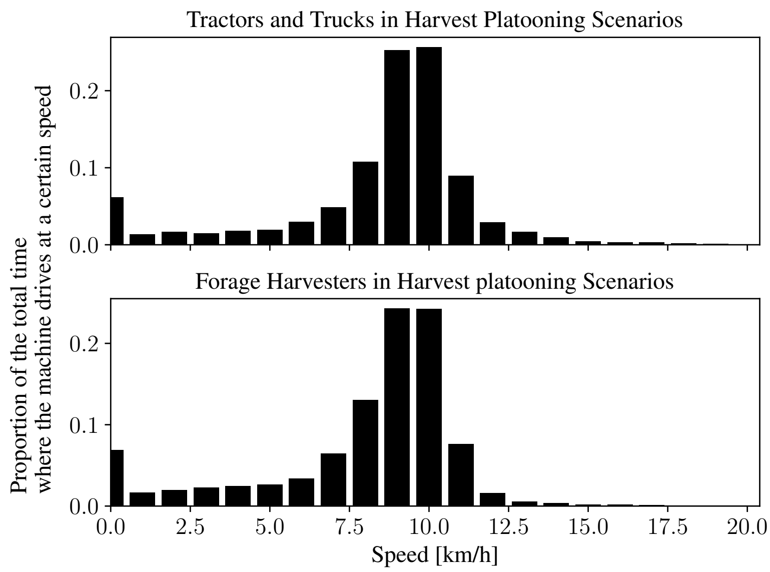

Figure 3.2 – Distribution of time proportions where FH and TM drove with a certain speed in a harvest platoon scenario

For the detected data points of the platooning services from recorded data of the corn harvest, the proportion where the FH and TM move in a specific distance is shown in Figure 3.1. For the same data points, the proportion in which FH and TM move at a given speed is available in Figure 3.2.

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

Smolnik, Lücke, and GmbH [6] 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 FH and TMs in the corn harvesting platooning scenario often travel at a speed of approximately 10 km/h. This speed is significantly higher than the average speed of 5.6 km/h of a FH in an entire corn harvesting process from [26]. 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 [26]. Nevertheless, the recorded data shows that a platooning service in agriculture must also be designed for higher speeds.

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

Klingler, Blobel, and Dressler [9] investigated the suitability of IEEE 802.11p for WIC. The authors detected that shadowing effects occur in the harvest scenario. The authors explain the effect because another tractor or the spout of the FH was in Line-of-sight (LOS). I reviewed the recorded position data to get an overview of where a TM is in the overloading process relative to the FH. The relative bearing is

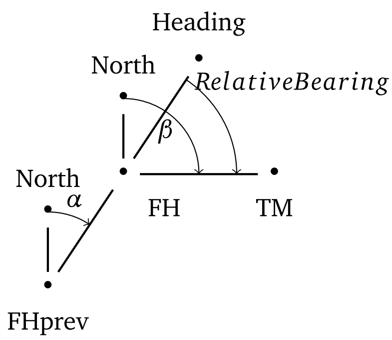

Figure 3.3 – Relative bearing between FH and TM which is calculated using the previous location of FH by using β and α for Equation 3.1

the angle between B and the heading of point A. Using the previous position of the FH, the relative bearing between FH and TM can be calculated with the angles α and β in Figure 3.3 as:

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

Assuming that the FH does not move backwards, we can see from the relative bearing in which angle from the FH the TM is located. The result is displayed in Figure 3.4. It can be observed that the TM is mainly close to the FH at an angle of $30° \dots 150°$ at a distance between $0\,\mathrm{m} \dots 10\,\mathrm{m}$.

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

Another notable fact is that the TM hardly ever stayed to the left of the FH. Since the FH often made left turns, the crop was usually already harvested to the right of the FH so that the TM could drive there without running over the crop. On rare

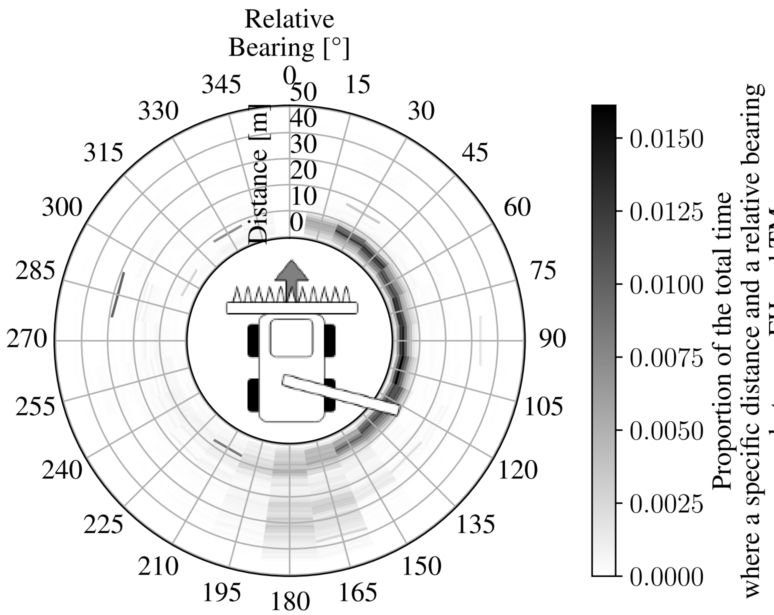

Figure 3.4 – Distribution of time proportion at specific distances and relative bearings between FH and TM

Figure 3.5 – FH and TM start cutting a new field section

occasions, the TM was also to the left of the FH. 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 requirements of a harvest and loading process. More data from around the world needs to be analyzed to make a general statement. The low rainfall this year has already set 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?

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

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**.

QUESTIONS open 7 Möglichkeiten outdoor wifi was für Effecte

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

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 (PER) in regards to SNR. 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

Bei der Wahl der Network Simulator Wifi 6 Implementierungen

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

Im **ns3manual** 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 [5]. 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 [6].

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 PPDU 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.

Netsimulyzer 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 Programmen.

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

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

Das NetSimulyzer ns-3 module[7] 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[8]

6.1 Data Rate

When do I write the evaluation of the data rate? emidiately after the graph?

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 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 to allow the use higher HE-MCS values, which don't support long range transmissions due to path loss and shadowing effects. Every node is eqipped with a Wi-Fi NetDevice with the following parameters: GI of 3200 ns, a bandwidth of 20 MHz and 2 spatial streams. A Constant Rate Wifi Manager is used to set a constant data rate according to the fixed HE-MCS for data, non-uniform and control data transmissions. The used frequency band is 2.4 GHz or 5 GHz as higher frequencies are less resistant to shadowing and fading and a higher data rate is not needed for the WIC use cases. The Wi-Fi Netdevices operate in the frequency channels specified in Table 6.1, which can be used for outdoor Wi-Fi communication in Germany **GermanLaw**.

UDP explanation?

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 0.000 000 1 s. This packet interval sorgt dafür, 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.

[7] **https://github.com/usnistgov/NetSimulyzer-ns3-module Accessed: 24.02.2023**.
[8] \url {**https://github.com/usnistgov/NetSimulyzer} Accessed: 24.02.2023**.

BW	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 BWs of the IEEE 802.11 standard [30], which can be used for outdoor communication **GermanLaw**

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 and the confidence interval with a confidence level of 95 % is calculated.

Überprüfung, Phy-Monitor, Theoretical DataRates

Guard Interval

atteninuation of bandwidth : 800ns : 94 % 89 % 80 %

Factors apply for MCS0 but may also apply later

DataRate for STBC

STBC and DCM * 2 payload / half data rate

But Latency? Latency is always based on Data Rate and Robustness

Data Rate and Robustness als related to oneanother

Robustness?

6.2 Robustness

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

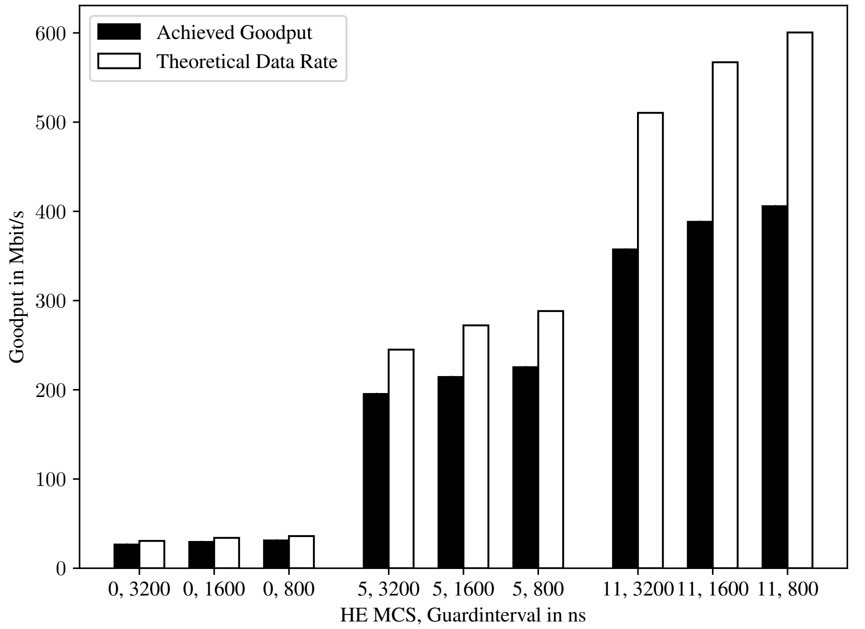

Figure 6.1 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with 2 MIMO streams and a bandwidth of 80 MHz in regards to the number of MIMO streams and the chosen MCS and CR

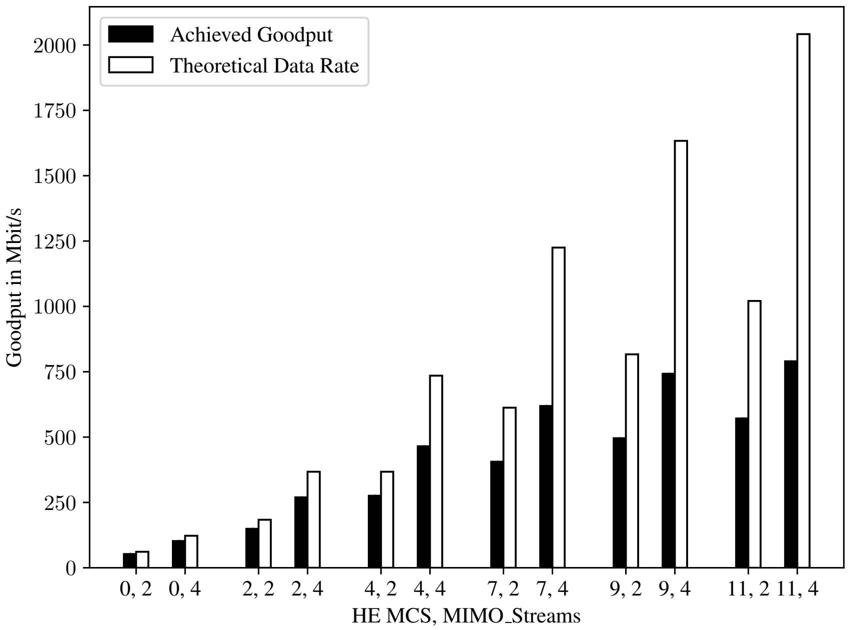

Figure 6.2 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with a GI of 3200 ns and a bandwidth of 80 MHz in regards to the number of MIMO streams and the chosen MCS and CR

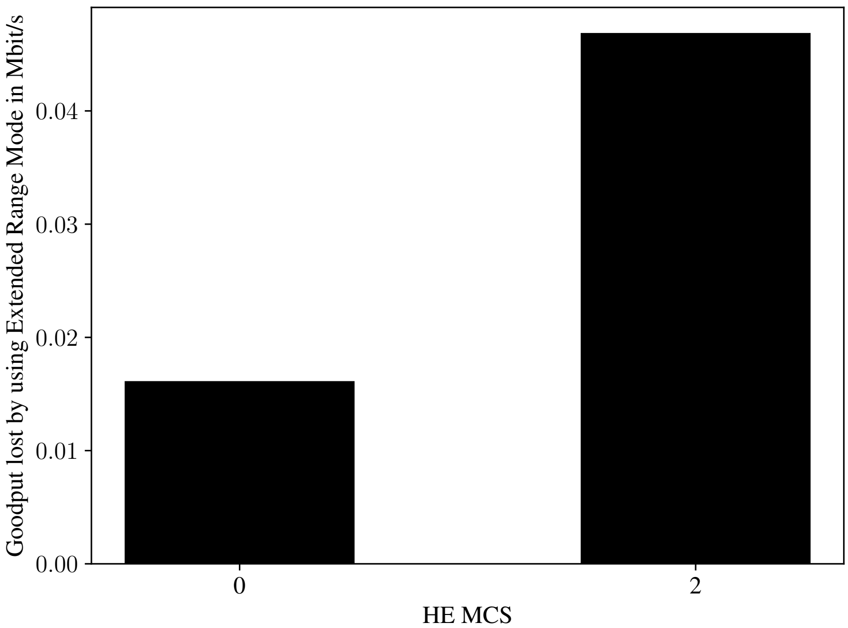

Figure 6.3 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with a GI of 3200 ns and a bandwidth of 20 MHz in regards to the number of MIMO streams and the chosen MCS and CR

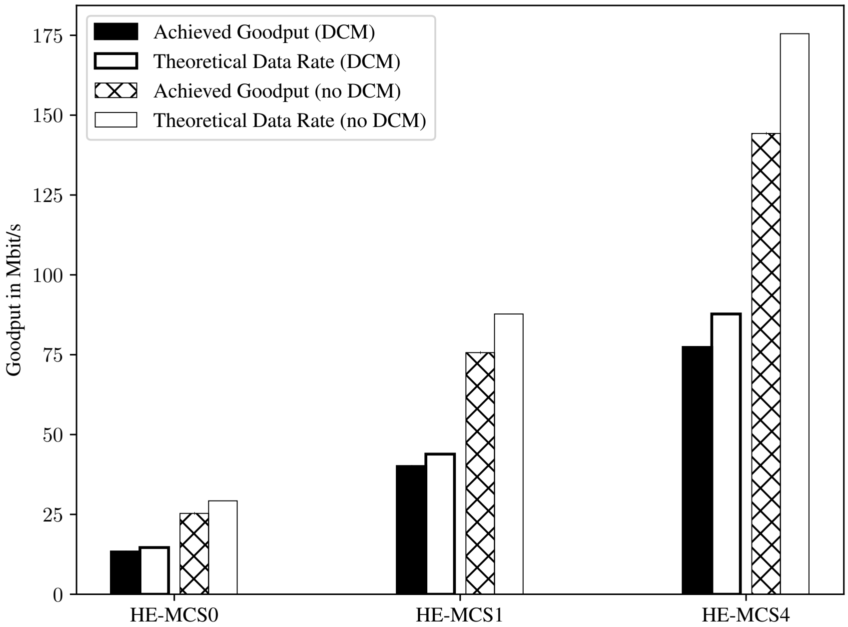

Figure 6.4 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a BW of 40 MHz and 2 spatial streams in regards to the number of the chosen HE-MCS value and whether DCM is enabled

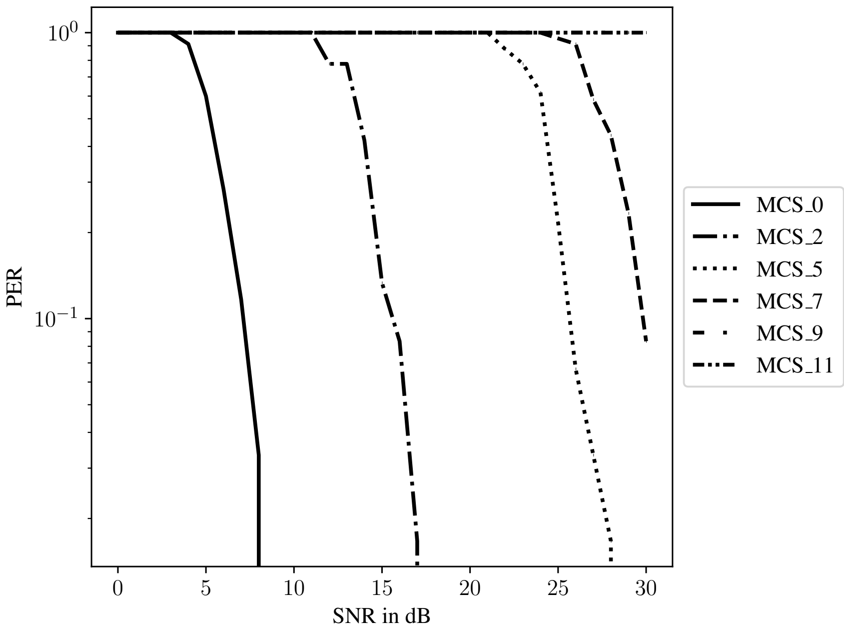

Figure 6.5 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with a GI of 3200 ns and a bandwidth of 40 MHz in regards to the number of the chosen MCS and CR and whether DCM is enabled

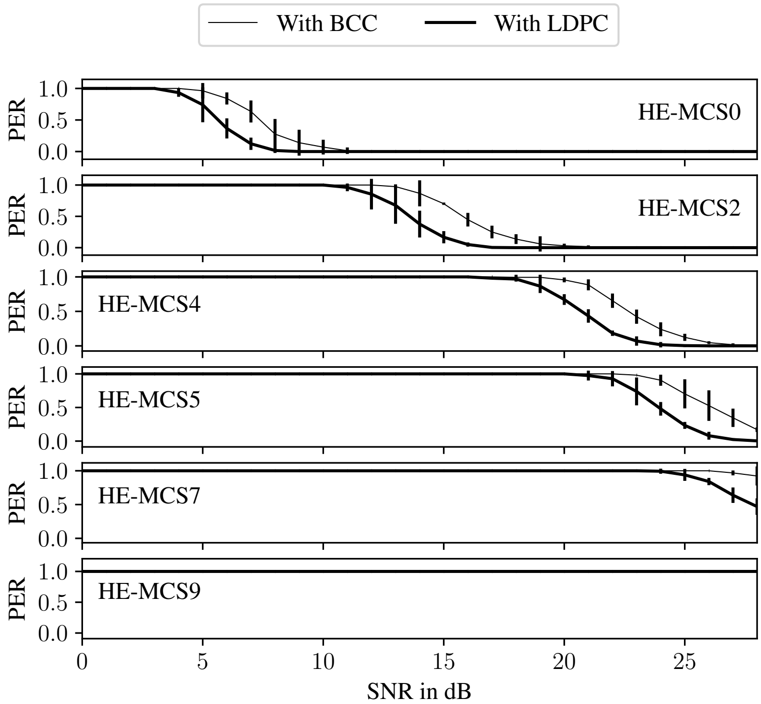

Figure 6.6 – Simulated PER in regards to SNR for chosen HE-MCS values and whether LDPC or BCC is enabled for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a bandwidth of 20 MHz and 2 spatial streams

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

Auf different paper stützen?

6.3 Platooning Services

Packetsize **(**fendtPlatoon) 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** 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

Figure 6.7 – Achieved Goodput and theoretical Datarate of two WiFi 6 stations in Ad-Hoc Mode with a GI of 3200 ns and a bandwidth of 40 MHz in regards to the number of the chosen MCS and CR and whether DCM is enabled

Rebroadcast by Count? additional Traffic

MANET Service discovery

Visualisierung Netsimulyzer

Farbcodes

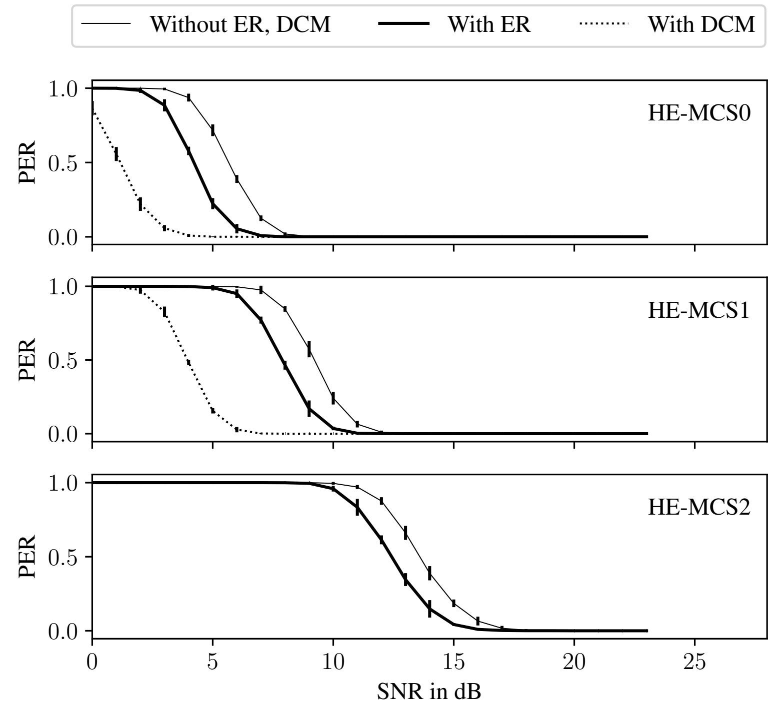

Figure 6.8 – Simulated PER in regards to SNR for chosen HE-MCS values and whether Extended Range or DCM is enabled for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a BW of 20 MHz and 2 spatial streams

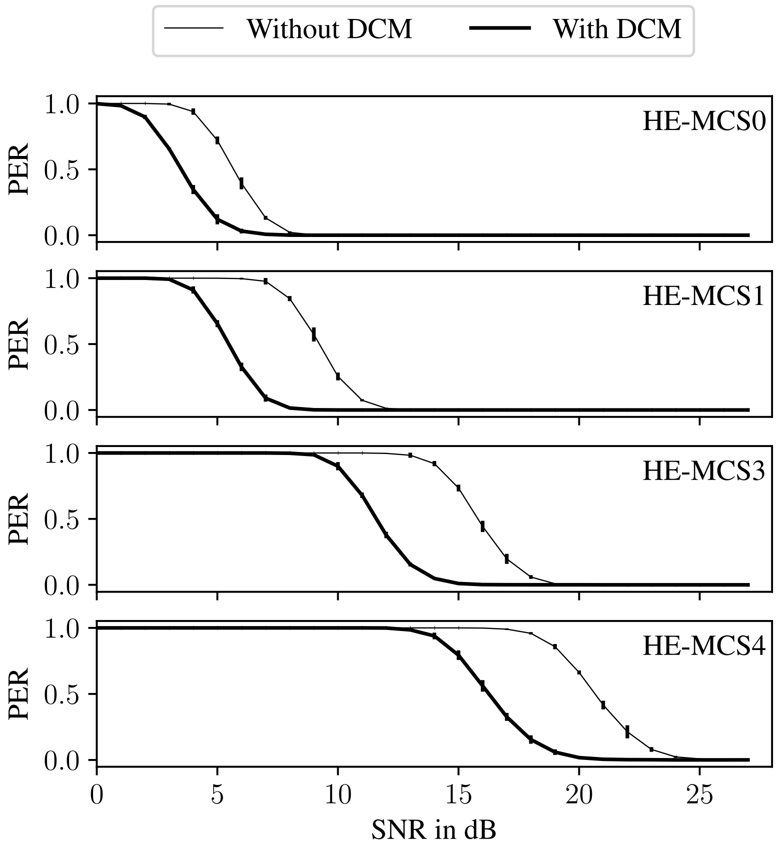

Figure 6.9 – Simulated PER in regards to SNR for chosen HE-MCS values and whether DCM is enabled for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a BW of 20 MHz and 2 spatial streams

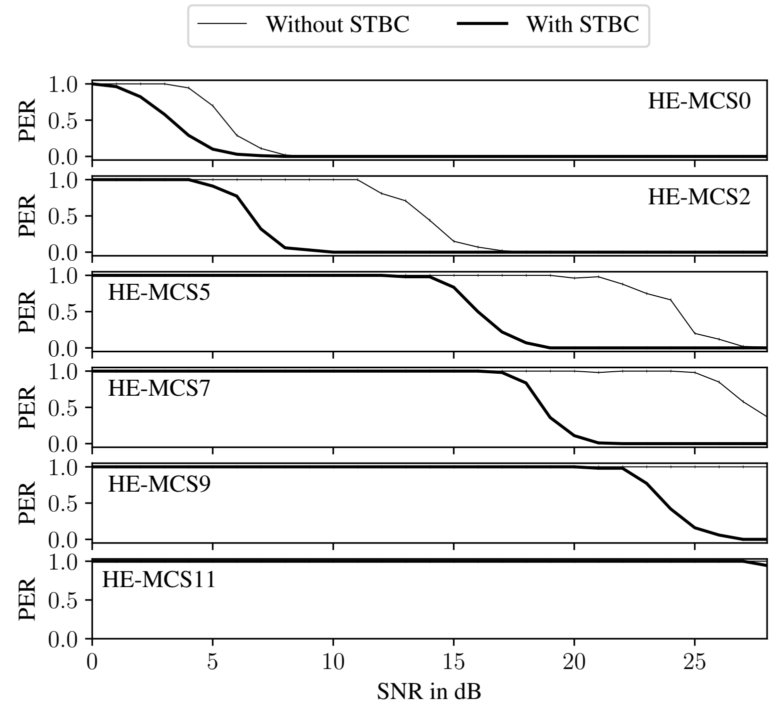

Figure 6.10 – Simulated PER in regards to SNR for chosen HE-MCS values and whether STBC is enabled for IEEE 802.11ax physical layer parameters of a GI of 3200 ns, a BW of 20 MHz and 2 spatial streams

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

802.11ac	IEEE 802.11ac
802.11ax	IEEE 802.11ax
ACK	Acknowledgement
AEF	Agricultural Industry Electronics Foundation
AP	Access Point
BCC	binary convolutional coding
BSS	Basic Service Set
BW	bandwidth
CR	Coding Rate
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
DCF	Distribution Coordination Function
DCM	Dual Carrier Modulation
DIFS	Distributed Coordination Function Interframe Space
ESS	Extended Service Set
FEC	Forward Error Correction
FH	Forage Harvester
FMIS	Farm Management Information System
GI	Guard Interval
IBSS	Independent Basic Service Set
LDPC	low-density parity-check
LOS	Line-of-sight
M2M	Machine-To-Machine
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
NAV	Network Allocation Vector
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
PCF	Point Coordination Function
PER	packet error rate
PPD	Plant Population Density

PPDU	Physical layer convergence protocol data unit
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RU	Resource Unit
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal Noise Ratio
SSID	Service Set Identifier
STBC	Space-Time-Block-Code
TM	Transport Machine
V2X	Vehicle-to-everything
WIC	Wireless-Infield Communication
WPA	Wi-Fi Protected Access

List of Figures

List of Tables

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Todo list