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

Diploma Thesis in Information Systems Engineering

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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:	**23. Dezember 2022**

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(Karl Christian Lautenschläger)
Dresden, 23 December 2022

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- problem: gap in knowledge, too expensive, too slow, a deficiency, superseded technology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

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 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 standardize this interoperability w[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.

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

The authors mention that the AEF is currently working on other issues. Among them is also the WIC. In the associated project group WIC, solutions for Machine-To-Machine (M2M) communication between cooperating, agricultural machines are to be developed and standardized.

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.
- **Streaming Services** are communications that stream video from remote cameras and monitors at a high data rate and low latency. As a result, this data is available on another agricultural vehicle and can be analyzed and processed there. The authors estimate the distance between the communication participants to be less than 100 m.
- **Process Data Exchange** describes the exchange of process data. One example is the exchange of already sprayed field areas in order to prevent multiple spraying of fertilizers and pesticides on the same field area by different machines. According to the authors, long-range technologies must be used here because agricultural fields around the world can be very large.
- **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 be used to brake the 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

Außer AEF Platooning:

OMNiDRIVE Raven Industries Technology? Starfire In einem Manual? Machine Sync Starfire 6000 - SF1 Gen4 4240 Display Autotrac 300 CartACE Nothing named?

AutoSync Trimble m-ASC

Außer AEF Video Streaming:

OcuSync Lightbridge DJI Mavic Herelink

What is it? 2.4 GHz? But is it Wifi?

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 [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 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 [5], 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. [3].

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 [6].

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 [7] 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 [8] considers IEEE 802.11 also to be an implementation of Ethernet with the help of wireless radio technologies. The author lists the extensions to the original standard, which range from 802.11b, 802.11g, 802.11a, 802.11n, 802.11ac to the latest enhancement 802.11ax. The different IEEE 802.11 standards can operate in the 2.4 GHz - , 5 GHz and 6 GHz - frequency band.

Kauffels [7] 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 [8] 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.

Sauter 2022 Ad-Hoc Infos

The further development of IEEE 802.11 is accompanied by a constant change of the physical layer. Sauter [8] 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. 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". For the modulation and demodulation the FFT and IFFT are used respectively. Kauffels [7] states, that OFDM can be used in the 5 GHz frequency band since IEEE 802.11a.

Convolutional encoders are used to increase redundancy. This enables Forward Error Correction (FEC), which can distribute a bit sequence over the OFDM subcarriers in such a way that an original bit sequence can be decoded at the receiver even in the event of interference. Kauffels [7]

Various Modulation and Coding Scheme (MCS)s can be selected in the physical layer in order to transmit as many bits as possible in the signal. These MCSs are based on Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM). Kauffels [7] 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.

Viel aus gleichem Lehrbuch Quellen? / Lieblingsautor /

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 [7] 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. The author recommends increasing the frequency spacing between transmission channels.

Symbol length, GI, subcarrier spacing reciprocal

Wellenausbreitung, Überlagerungseffekte, Reflexsion, Reflexsion nicht bei Metall

Knauffel OFDM PHY

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 [7], 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 [8] 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 [7] 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 [7] names the two methods Open System Authentication and Shared Key Authentication. Sauter [8] 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 [8] 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 2.1, 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 [8] 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 [8] DCF oberbegriff für CSMA /CA

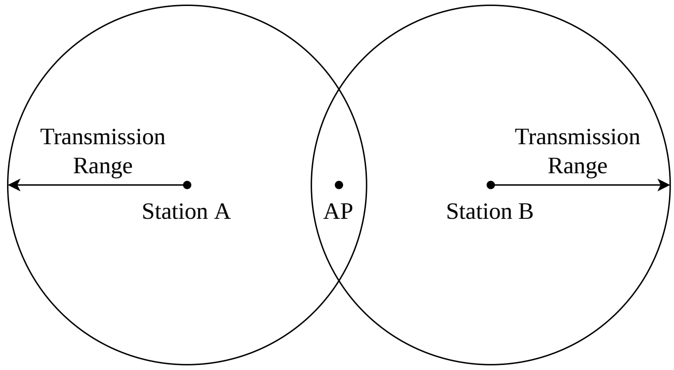

Figure 2.1 – Hidden Station Problem

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 [8] 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 [9].

According to Perahia and Gong [10], 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 [8] 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 Multiple Input Multiple Output (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 [11], 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 [9] 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. [12] 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. Guard Interval	0.8 µs	3.2 µs

Table 2.1 – Comparison of IEEE 802.11ac and IEEE 802.11ax

2.4 Harvest and Loading Processes as a Use Cases for WIC

Seifert, Grimm, and Schurig [13] 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 types of animal feed according to the authors: Hey, Straw, Corn, Grass and Clover. While harvesting and loading large quantities of forage, the Forage Harvester (FH) needs to load the harvested goods directly onto a Transport Machine (TM), which drives next to or behind the vehicle. Unlike the Combine Harvester, the FH cannot store the forage in the tank because the harvested volume is too large. Therefore, a TM always drives next to the forage harvester to take over and transport the harvest to the farm.

Taking a corn harvest scenario as an example, key figures can be looked up in [14], a standard reference book in agricultural literature. This book contains key figures of agricultural processes, which have been compiled by 80 experts. The key figures, which are shown in Table 2.2, 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 for the use of an agricultural platooning system as described by Zhang et al. [15]. This creates a leader and follower system where an unmanned agricultural machine follows a leading manned agricultural machine.

In a harvesting and loading process, the FH, as a leader, sets the path and speed and the TM follows unmanned with a longitudinal and lateral offset as it is displayed in Figure 2.2 This system positions the TM optimally to the FH, so that the foarge

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 2.2 – Key figures from [14] of corn harvest of a FH with a working width of 6.2 m in a 80 ha-field in regards to PPD

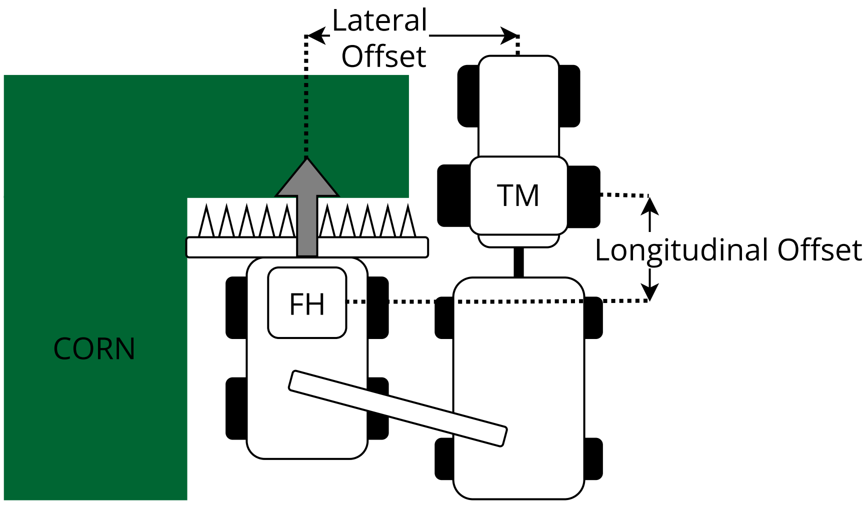

Figure 2.2 – Lateral and longitudinal Offset between the two agricultural machines FH and TM in a corn harvest scenario

can be loaded ideally from the FH onto the TM.

As stated in Table 2.2, already ten drivers for the TMs are needed in the corn harvest process with a high PPD. By using a leader and follower system based on the description of Zhang et al. [15], each TM can drive unmanned in the field leading to a smaller number of workers needed in the corn harvest process.

At the same time, the harvesting and loading processes are also examples of the video streaming use case. During these 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 [17], different spout guidance and control systems have been developed for this reason, which 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 trailer accordingly. The author describes Autofill - systems from

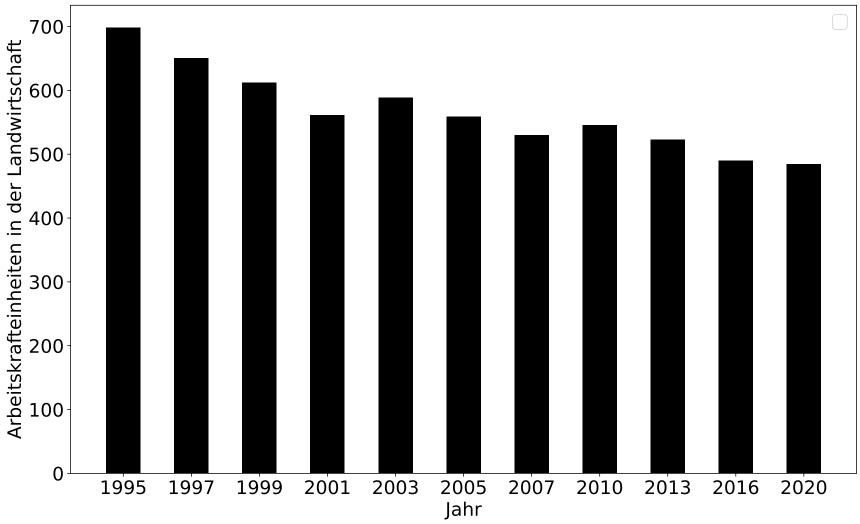

Figure 2.3 – Decrease in the agricultural labor force in Germany [16]

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 useful application of the video streaming use case in the harvesting process. If the driver of the TM can watch a livestream of the trailer's fill level, he is always 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 theWIC 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 the speed in a 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 position and speed of the FH and the TMs all day long. During breaks, the tablets continued to capture 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 delete data points of the log files where the recorded accuracy was not yet less than 2 m. When the accuracy of following data points was less than 2 m, 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, the areas were moved to a random location in the world.

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

To detect overloading of crops from FH to a TM in the Harvest Process, I had to develop an intelligent algorithm. It can detect overloading scenarios in the recorded process data.

For this purpose I started to build a Dashboard with the Python framework *Dash*[2]. 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 was able to get an overview of the behavior of the machines before, during, after the overloading scenario. In the overview, it can be seen that a FH is nearly always in the overleading 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.

Klingler, Blobel, and Dressler [5] 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 either another tractor or the spout of the FH was in the Line-of-sight (LOS).

To get an overview of where a TM is in the overloading process relative to the FH, I reviewed the recorded position data. The relative bearing is the angle between B and the heading of point A, as shown in Figure 3.4. I calculated the relative bearing

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

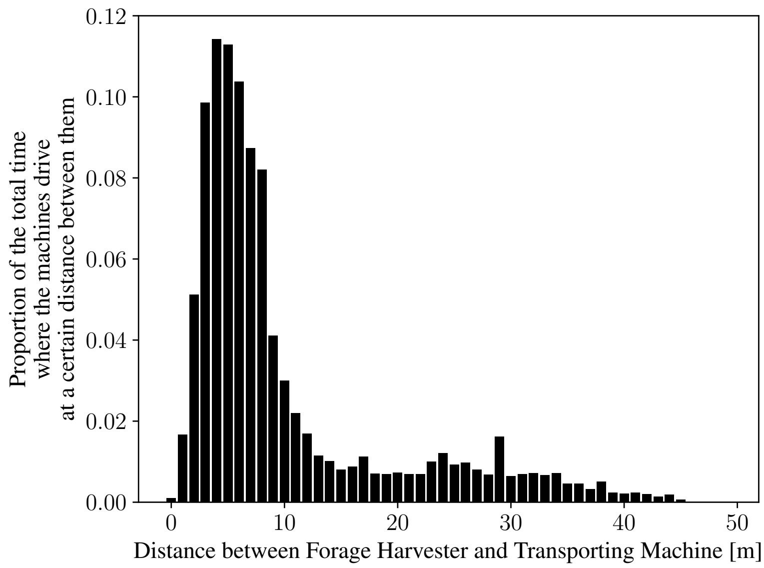

Figure 3.1 – Distribution of time proportions where a given distance was between FH and TM in a harvest platoon scenario.

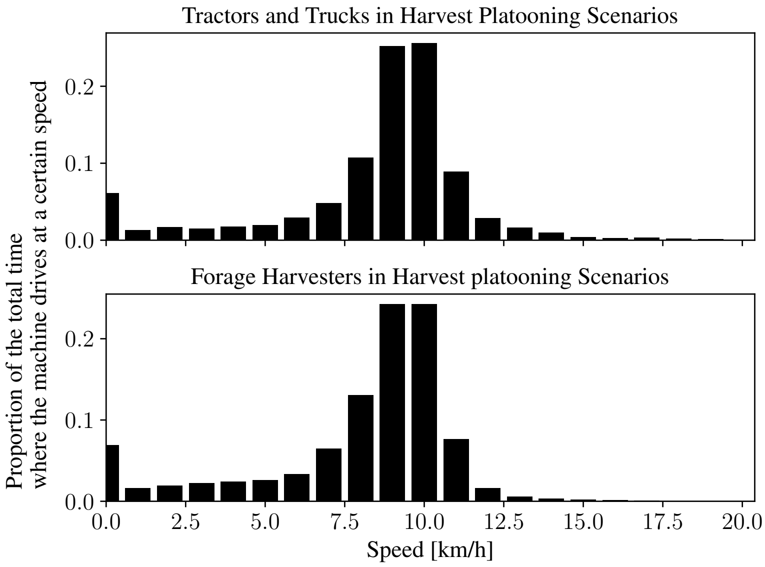

Figure 3.2 – Distribution of time proportions where FH and TM drove with a certain speed in a harvest platoon scenario

between the heading of the FH and the TM at each time point in the overloading scenario.

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

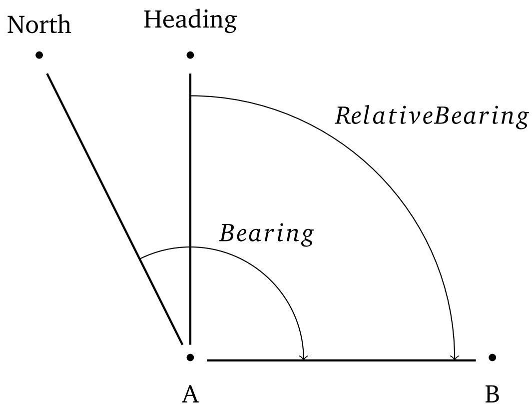

Figure 3.3 – Relative and True bearing between A and B

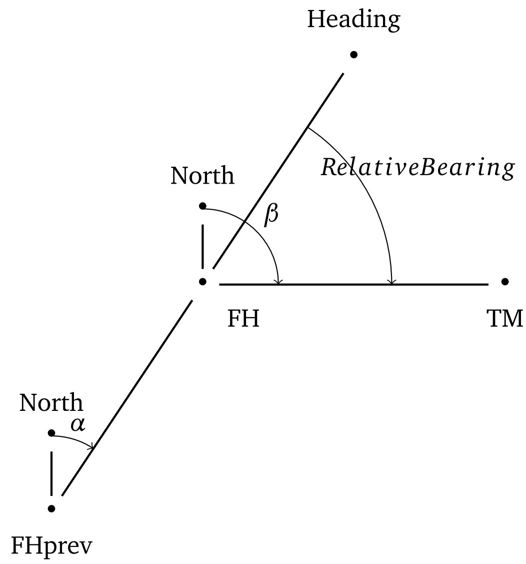

Figure 3.4 – Relative bearing between FH and TM which is calculated using the previous location of FH by the difference of β minus α

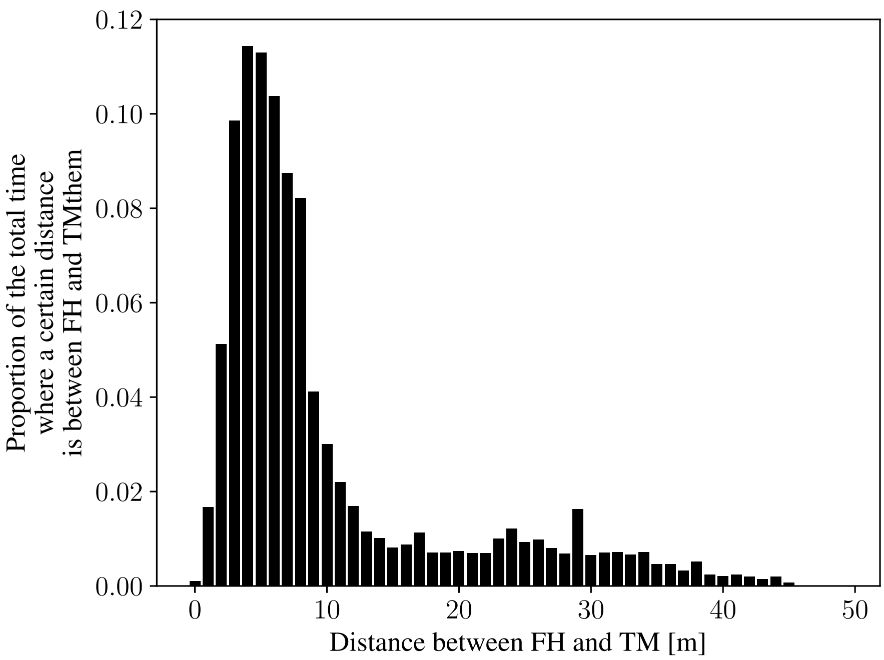

Figure 3.5 – Distribution of time proportion at specific distances and relative bearings between FH and TM

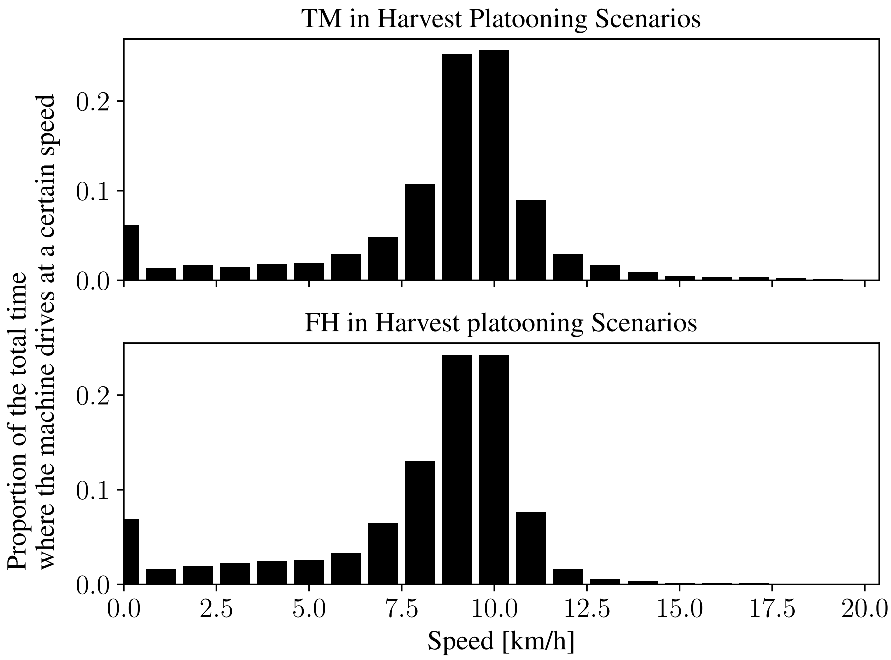

Figure 3.6 – Distribution of time proportion at specific distances and relative bearings between FH and TM

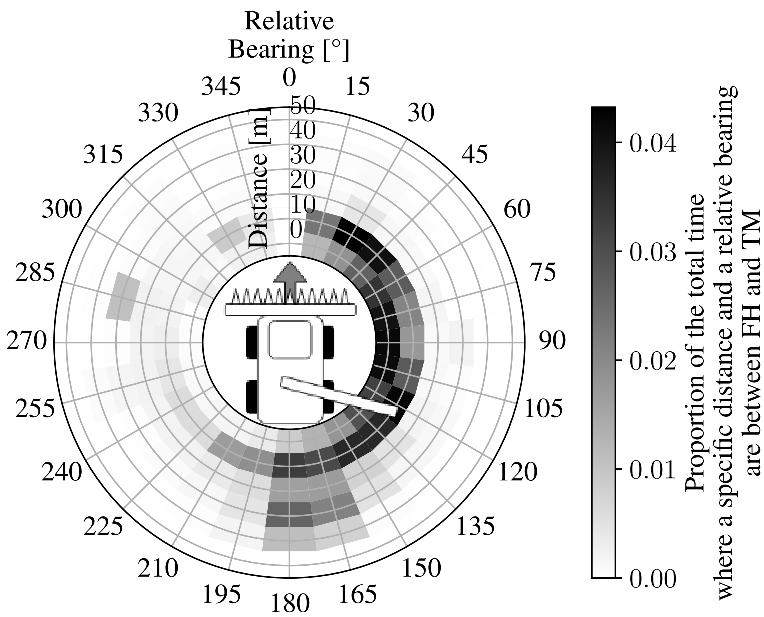

Figure 3.7 – Distribution of time proportion at specific distances and relative bearings between FH and TM

Figure 3.8 – Distribution of time proportion at specific distances and relative bearings between FH and TM

Figure 3.9 – Distribution of time proportion at specific distances and relative bearings between FH and TM

Chapter 4

Field Measurements

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

Propagation Model: Two Ray Ground only mathematics Rappaport Jakes Model Three Log Distance

Data Simulation

6.1 ns-3 Network Simulator

Bei der Wahl der Network Simulator Wifi 6 Implementierungen

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

According to **ns3manual** 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. An example for the

ns-3 erklären?

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.

List of Abbreviations

802.11ac	IEEE 802.11ac
802.11ax	IEEE 802.11ax
ACK	Acknowledgement
AEF	Agricultural Industry Electronics Foundation
AP	Access Point
BSS	Basic Service Set
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
DCF	Distribution Coordination Function
DIFS	Distributed Coordination Function Interframe Space
ESS	Extended Service Set
FEC	Forward Error Correction
FH	Forage Harvester
FMIS	Farm Management Information System
IBSS	Independent Basic Service Set
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
PPD	Plant Population Density
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RU	Resource Unit
SINR	Signal-to-Interference-plus-Noise Ratio
SSID	Service Set Identifier
TM	Transport Machine
WIC	Wireless-Infield Communication

WPA Wi-Fi Protected Access

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Bibliography

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Todo list