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Evaluation of protocols for control stage lighting

Bachelor Thesis in Computer Engineering

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Evaluation of protocols for control stage lighting

Bachelor Thesis in Computer Engineering

vorgelegt von

Maximilian W. Gotthardt

geb. am 13. July 1993
in Berlin

angefertigt in der Fachgruppe

Fachgebiet Telekommunikationsnetze

Institut für Telekommunikationsnetze
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Abgabe der Arbeit: **28. Februar 2022**

Erklärung

Ich versichere, dass ich die Arbeit ohne fremde Hilfe und ohne Benutzung anderer als der angegebenen Quellen angefertigt habe und dass die Arbeit in gleicher oder ähnlicher Form noch keiner anderen Prüfungsbehörde vorgelegen hat und von dieser als Teil einer Prüfungsleistung angenommen wurde.
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(Maximilian W. Gotthardt)
Berlin, den 28 February 2022

Abstract

about 1/2 page:

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

In the field of lighting and stage technology, the challenge of controlling the individual installations, called 'fixtures', quickly and without complications is a recurring one. Established solutions are realized via cables.

However, due to the progress in radio technology, wireless solutions are becoming more and more common. Therefor is often expensive hardware needed. Parallel to this there is a fast growing market around creative and individually developed DIY projects, which have found their own niche. Durch niedrigpreisige While most commercial solutions still rely on expensive and complex wired control, it is particularly suitable for smaller projects to experiment with the new wireless technologies. In this thesis I try to implement a wireless solution, which does not need an IP-Layer using the popular platform ESP and the properitary protocol ESP-NOW to distribute the light information to each fixture. ESP-Now instead works more like an direct radio communication.

Kurzfassung

- kabellose lösungen werden interessant
- chips werden günstiger
- für kleine projekte leider sehr teuere Hardware
- 802.11 wird als standard benutzt
- protokolle wie art-net könnten optimiert werden
- esp plattform bietet interssante möglichkeiten, wegen der geringen kosten der chips und esp-now
- entwicklung einer plattform die esp-now nutzt
- verschiedene ansätze studiert, wie broadcast und unicasts
- mit jeweils unterschiedlichen modifikationen

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.

In the subject area
====
In the field of lighting and stage technology, the challenge of controlling the individual installations, called 'fixtures', quickly and without complications is a recurring one. Established solutions are realized via cables.

1.1 Motivation/Requirements

- Reliability
- .. and why 100% Reliability is not important (pyrotechnics)
- Lower latency
- Synchronisation
- higher update frequency
- Range

1.2 Challenges

- low cost
- (ESP Platform)
- DIY community

1.3 Problemstatement and Contribution WICHTIG

- open source available on github [link]
- thought-provoking impulse for different approaches
- Protocol auf DL Layer/App Layer Ebene
- Art-Net baseline
- simulativ und experimentel untersucht

1.4 Thesis Outline

- A First Implementation and Evaluation of the IEEE 802.11aa Group Addressed Transmission Service

  unsosliced Repetition

  blockack

- Evaluation of Error Control Mechanisms for 802.11b Multicast Transmissions

  packet loss rate

  ARQ, FEC

- ESP-NOW communication protocol with ESP32

  ESP-NOW details

- The Working Principles of ESP32 and Analytical Comparision of using Low-Cost Microcontroller Modules in Embedded Systems Design

  why the ESP32 is superior over arduino

- Adaptive Cross-Layer Protection Strategies for Robust Scqalable Video Transmissions Over 802.11 WLANs
- Voice Capacity of IEEE 802.11b, 802.11a and 802.11g Wireless LANs

Chapter 2

Related Work

- Wie der und der in Paper so gezeigt hat
- Auch Ding et al haben versucht
- ...
- 10 Paper
- halbe seite

Foo and bar [1] are of equal value. Thus, any can be used.
According to [2]

Wireless solutions for stage lighting are growing fast.

2.1 References

What follows is just a very quick refresher on how to use references. It is not a guide on scientific writing in general, nor copyright and plagiarism in particular. Please refer to an actual guide on technical writing and scientific practices to make sure you understand how, where, and when to cite.

Simply speaking, proper scientific writing has to deal with two closely related (but not identical) concepts:

a) Copyright

b) Plagiarism

Do not confuse the need for properly citing your sources as something related to copyright. Questions of (a) copyright or the corresponding national equivalent deal with who has the right to reproduce a certain text excerpt, an image, or something similar. Questions of (b) plagiarism deal with who came up with a certain idea or

insight, e.g., a certain finding, a certain concept, or a certain way of illustrating a concept. By way of analogy, consider a car: after buying a car you have the right to (a) do whatever you want with it, but you still cannot claim that you (b) invented it. Conversely, properly (b) crediting who invented your neighbor's car does not give you the right to (a) use it. Put yet another way, problem (a) is a legal one: to be allowed to publish a scientific work you (or, rather, your publisher) needs to have permission to reproduce it – or suffer legal consequences like heavy fines. Problem (b) is an academic one: claiming someone else's ideas as one's own is plagiarism; similarly, re-selling old ideas as new ones is self-plagiarism. Both incur heavy penalties like exclusion from schools and professional associations or being blacklisted from publishing with scientific outlets for any number of years.

You will need to address both problems in writing your thesis. Problem (a) can be addressed in two ways: First, by creating original content (that is, text or figures) yourself, which is always preferable as this gives you the freedom to present the content your way. Second, by obtaining a license to reproduce content (e.g., by way of buying a license or adhering to the terms of an existing copyleft license). Problem (b) can be addressed in two ways: First, presenting original ideas and insights (as you will do when presenting own results). Second, by clearly pointing out the (primary) source of an idea. The latter is the topic of this section.

In brief, use references whenever you cite from related work (either directly or indirectly), or when you build on related work (this includes their way of illustrating a particular concepts, in text form as well as in the overall design of a figure). Also use references to point a reader to related work. Clearly distinguish between these uses. Make it very clear which part of a statement a reference belongs to. Compare the following three, vastly different uses (where the cited idea appears in **boldface**):

- "**Foo and bar are of equal value. Thus, any can be used.**" [2], [3]
- According to [2] and [3], **foo and bar are of equal value, and any can be used**.

versus

- "**Foo and bar are of equal value**" [2], [3]. Thus, any can be used.
- According to [2] and [3], **foo and bar are of equal value**. From this it follows that any can be used.

versus

- Foo and **bar** [2], [3] are of equal value. Thus, any can be used.
- Foo and **bar** (detailed in [2] and [3]) are of equal value. Thus, any can be used.

versus

- **Foo** [2] and **bar** [3] are of equal value. Thus, any can be used.
- **Foo** (detailed in [2]) and **bar** (detailed in [3]) are of equal value. Thus, any can be used.

Never typeset a reference after the final full stop of a paragraph (or sentence) and expect your reader to figure out which part of the paragraph is an indirect citation and which part is original (i.e., your own) work. When paraphrasing longer passages of text, use an indirect citation. Make sure to clearly point out when you are finished paraphrasing, like so: *According to Akyildiz et al. [2], Foo and Bar can be characterized as follows. They are big. They are bright. The authors further argue that one can be substituted for the other. In the following I will go on to prove that this is not true.*

When citing more than a few pages worth of text, point the reader to the specific part you are referring to in your citation, like so: *In recent years, an increasing number of cyclists are switching from air filled tires to cement filled ones [4, Table IV].*

If a figure or a table is closely based on another one, make sure to cite its source, preferably in its caption, like so: *Figure 1 – the relation of ravens and writing desks (based on [4, Figure 42])*. Be aware that, while there is a well-established convention on how to illustrate a verbatim quote of text (by using quotation marks), there is no well-established convention for indicating that an image was copied verbatim. Thus, when citing a figure or table, you must explicitly state whether it was copied verbatim, ed, or whether it served as inspiration for your own.

Do not cite URLs. Content found there is not peer reviewed and it is likely to change during the lifetime of your work. For pointing a reader to interesting websites, use footnotes – but trust your reader to know how to use a web search engine.

Your text reads nicer if you do not use citations as a substitute for nouns (like this section did). Instead of *The benefits of cement filled tires has been shown by [2]*, consider writing *Akyildiz et al. [2] have shown the benefits of cement filled tires*. The `textcite` command makes this straightforward.

Make sure to read your bibliography section (that is, the typeset list of references) after you are done adding all citations to your text. Does it contain all information needed to uniquely identify to references you used? Do not trust BibTeX files you find on the web: Digital libraries frequently have their contents wrong, are missing information, or are using different field names than your bibliography style expects (leading to missing information in the typeset bibliography). To give a few examples: Check the authors' list (making sure all authors are listed in the same order and in the same way they are listed in the publication). Check the conference location (it's most likely not "New York, New York"). Check the publisher name (many digital libraries use a field that is not typeset by your bibliography style; have a look at the demo

bibliography in this template for how to deal with that). Check the page numbers (many digital libraries put "1–5" here despite the paper starting at a later page – or despite it not having any page numbers to begin with). Check the conference name, put its parts in a logical order, and lose the "in proceedings of" (it's not "Mobicom, in proceedings of, 1999 series MobiCom99" but "5th ACM International Conference on Mobile Computing and Networking (MobiCom 1999)".

triple-check all references

Chapter 3

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.

don't get what methods and techniques i was using

In this chapter the fundamentals required for understanding the different approaches in this thesis using are explained. This contains basic knowledge of the physical- and data link layer, which are located in the first and second layer of the Open Systems Interconnection (OSI) Model..

refrence to table below

In order to understand the upcomming ESP-Now protocol we have to take a look at the Data Link Layer (DL) layer in 802.11. It is the second layer of the OSI model of computer networking illustrated in Table 3.1.

Rewrite introduction in chapter Fundamentals!

Application layer
Presentation layer
Session layer
Network layer
Data Link layer
Physical layer

Table 3.1 – OSI model

3.1 IEEE 802.11 Specification Family

The Institut of Electrical and Electronics Engineers (IEEE) 802 is a family of standards dealing with area networks different kinds.

- 802.11 Wireless Local Area Network (WLAN)
- 802.15.1 Wireless Personal Area Network (WPAN)
- 802.15.4 Low-rate WPAN (LR-WPAN)
- 802.16 Wireless metropolitan area network (WMAN)

For this thesis is the focus set to the 802.11, because of the accessability and wide functionality. There are two Basic Service Set (BSS) defined:

- Infrastructure BSS
  A central element manages the network and all the traffic goes through. Every Station (STA) must always communicate via the Access Point (AP) and never directly - exceptional: Direct Link Mode. An initial association must take place to use this BSS. This is the most common mode a WLAN is used.
- Independent BSS
  A network without a central station, where the network topology can flexible change over time. The communication happens directly between the Wireless Endsystems. Efficent routing can became a problem in more complex topologys.

WES in AdHoc correct?

The most common use in 802.11 is the Infrastructure mode, which is commonly used in office and home enviroments.

3.1.1 Physical layer

In this thesis we sould take a breef look into the Physical Network Layer (PHY) of the IEEE 802.11 standard, which is the first layer of the OSI model 3.1. This layer provides mechanical, electrical and other functional tools to activate or deactivate physical connections, maintain them and transmit bits over them. These can be, for example, electrical signals, optical signals (fiber optics, lasers) or electromagnetic waves (wireless networks). There are several complements to the 802.11 standard:

- 802.11b
  supports larger bitrates with Direct Sequence Spread Spectrum (DSSS) or Frequency Hopping Spread Spectrum (FHSS) as modulation from 1Mbit/s to 11Mbit/s. It uses the 2.4 GHz ISM band.

- 802.11a and 802.11g
  with Orthogonal Frequency Division Multiplexing) (OFDM) data rates are increased up to 54 Mbit/s. Where 802.11a is in the 5GHz ISM band 802.11g uses the 2.4GHz ISM band.

- 802.11n
  It also uses OFDM and improves with additionaly Multiple Input-Multiple Output) (MIMO), channel bonding and frame aggregation to increase the bandwidth and decrease the overhead. Using 2.4 GHz and 5GHz ISM band.

- 802.11ac
  Support of wider channel and out of it higher bitrates. It also includes features like Multi-User MIMO. It only uses the 5 GHz ISM band.

- 802.11ax
  Like 802.11ac but with additional use of the 6GHz ISM band and better power control. Also called WiFi6.

In this thesis the rather basic 802.11b is used with a transmission rate of 1Mbit/s.

3.1.2 Data Link Layer

The DL Layer is the second lowest layer of the OSI Model 3.1 and is split in two sublayers. The Locig Link Control (LLC) sublayer which multiplex protocols over the MAC layer while transmitting and to de-multiplex the protocols while receiving. LLC provides the hop-to-hop flow and error control, allows multipoint communication over networks and it also adds frame sequence numbers. But in this thesis we focus on the other data link sublayer.

The Media Access Control (MAC) includes network protocols that regulate how multiple computers share the physical transmission medium they use. Without regulation, collisions and data loss would occur in the shared medium if several WES were to transmit simultaneously. The MAC Protocol Data Unit is additional added inside of the PHY Payload. It contains the MAC Header and encapsulated in it the MAC Service Data Unit (MSDU).

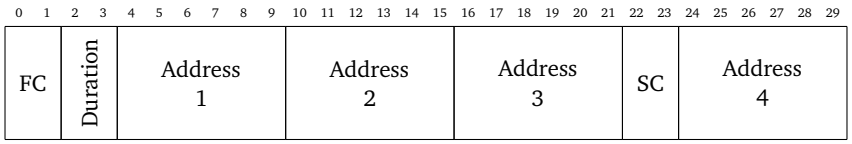


Figure 3.1 – MAC header of a WLAN frame

Payload and FCS are missing

- **Frame Control Field:** Discribes the Type of frame:

  - 00 Manegement Frame
  - 01 Control Frame
  - 10 Data Frame

- **Duration:** Contains the Network Allocation Vector (NAV) value, specifies the transmission time required for the frame. In order to save power to save energy, WES can defer access to the medium for this duration
- **Address fields:** Certain address fields are specified by the relative position of the address field. Not every address field is needed by certain frames.
  - Basic Service Set Identifier (BSSID)
  - Source Address
  - Destination Address
  - Transmitting STA Address
  - Receiving STA Address
- **Sequence Control:** Sequence number of the current frame modulo 4096.
- **MAC Payload:** The actual payload information of the MAC layer. The actual payload can differ, because the headers of the LLC and ip etc. has to be subtracted.
- **Frame Check Frequence:** The sender calculates the checksum for the entire data block and appends it to the end of the block.

802.11ac and later using frame aggregation in order to reduce overhead.

3.1.3 Carrier Sense Multiple Access/Collision Avoidance

shot explaination of CSMA/CD

Multiple Access/Multiplexing: When Signals to/from different users share a common channel using time division methods (TDM/TDMA, CSMA)

eigene Worte

DSSS: Usage of multiple antennas Direct Sequence Spread Spectrum. Spreading of the signal over a given bitsequence PN

Addressing

In a LAN environment, devices are logically separated using 48-bit globally unique MAC addresses: example In IPv4 networks (e.g. Internet), nodes are logically separated using 32-bit globally unique IP addresses: example

Routing

- Routing in a (W)LAN is based on MAC addresses, never IP addresses.
- A router (e.g. integrated with an access point) performs mapping between

these two address types:

Address allocation
• MAC addresses are associated with the hardware devices.
• IP addresses can be allocated to (W)LAN devices either on a
permanent basis or dynamically from an address pool using the Dynamic Host Configuration Protocol (DHCP).

Mesh networks
are able to relay frames from one device to another. • Provide coverage extension over multiple hops (e.g. Internet access) • Sufficient address information is required to be able to relay data from a source device to the ultimate destination (IP or MAC address). This can be used to extend the range from on Wireless Endsystem (WES) to another WES over some other WES. Since range isn't a critical parameter in this thesis, it hasn't to be further discussed.

Beacon Frames
contain the channel information found during passive scanning. Probe request are used in acting scanning.

Backoff:
random time delay to avoid collisions

DIFS/SIFS:
Delay between transmissions used for Carrier-sense multiple access with collision avoidance (CSMA/CA)

3.1.3.1 Unicast

The link layer unicast is used to send data over an single hop to the target WES destination. The link layer of each WES checks the destination MAC address in the link layer header and discards the frame if the destinatin address does not match its own address.

Unicast is by default reliable.
E.g. the AP wants to transmit a packet to one specific WES
When the Unicast reaches the destination WES an acknowledgement frame is send back after the Short Inter Frame Spaces (SIFS) + backoff.

when to explain CSMA/DC?

If the acknowledgement is not successfully received by the sender, the sender will repeat the transmission for a given number. When the number is exceeded,

the packet could not be delivered. If the number is set to zero, the unicast can be considered as non-reliable.

example

complete figure UC

Figure 3.2 – Unicast Transmission

3.1.3.2 Broadcast

If a packet should be received from all WES's it can be distributed as broadcast. The MAC address of the destination address in the link layer is set to the common broadcast address, which is ff:ff:ff:ff:ff:ff.
In contrast to unicast, broadcast is not reliable. This is mainly because the packet is addressed to all nodes at the same time, and if link layer acknoledgements would be used, the acknoledgements would be sent by all nodes at the same time, because there is no mechanism in which order acknoledges should be answered. In addition, the sender of a broadcast does not know how many WESs he is addressing the packet to in the first place. Retransmitting acknoledgements would lead to massive collision and loss of acknoledgements. E.g. management information in a WLAN is sent in a broadcast mode, because it has to reach every WES and isn't worth to be acknoleged.

complete figure BC

Figure 3.3 – Broadcast Transmission

3.1.3.3 Multicast

Mutlicast explain multicast mac address

When the same packet should be transmitted to multiple WES's, but not to all, multicast can be used. Transmitting the same packet multiple times via unicast is wasteful. There are different approaches to realize acknowledgements for mutlicasts, they differ mainly by the respective field of application.

examples for multicast ack + related work

Level 2 multicast is often used for large files in audio or video streams, where a big amount of data is distributed and multiple clients listen simultaneously.

complete figure MC

Figure 3.4 – Multicast Transmission

3.2 Light protocols

There are several lighting protocols that are used. The field of application ranges from wired CAN buses over ethernet cables to wireless WLAN networks. To give a short insight, some of the most important protocols are explained below.

3.2.1 DMX-512A

Digital Multiplex (DMX) 512A, is the current industry standard for stage lighting. It is based on Controller Area Network (CAN), therefore it uses wires. Physically is the DMX protocol transmitted over a differential pair of lines using the RS-485 voltage levels. The bus signal is updated with $\frac{1}{50}$Hz. According to the specification are XLR-5 type connectors are to be used.

image der connectoren

Show Hardware e.g. DMX Plug

The endsystems are called fixture because it's most likely a lighting installation which is mounted somewhere, this could be a moving-head, fresnel, spotlight, stroboscope or any other light installation. It could also be a fog machine that emits fog on an appropriate signal.

All devices are daisy chained together visualized in 3.5. The DMX controller is in the begin of each chain. The receiving endsystems, are chained behind each other from output to input. A terminator, specified in the DMX specification, is to be connected to the final output.

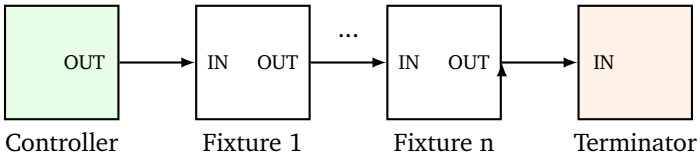


Figure 3.5 – Block Diagram of an DMX Universe

The hole chain is called DMX-Universe and can contain a set of 512 channel. If there is a need of more channels one needs more DMX universes - each channel consists of one byte. Due to the fact that a DMX universe always has its own bus, starting from a new controller can lead to inconveniences.

A channel in the event technology is to distinguish between e.g. a WiFi channel. Each endsystem is assigned at least one, but usually several channels. Every endsystems knows which channel is intended for it, this must to be preset.

For example: An RGB-LED spotlight could have three channels, one for each color. Due to the resolution of one byte, the individual colors can (theoretically) be controlled in 256 different intensities. If the Channel 0-56 are already used, it could be set to channel 57, 58, 59. Any other free channel range would also be possible, provided it is connected. There exist hardware with automatic-address-assignment.

Bild von fixtures verteilt auf channel

Since DMX is unidirectional it can be assumed that the endsystems generally only receive or forward (daisy chain) control signals sent from the control console. This is a major limitation of DMX, beside of the rather small universe size. It is also not reliable, the use of fire installations is therefore considered too dangerous.

3.2.2 Art-Net

- 2.4 or 5GHz
- DMX-Like
- related work

Due the limitation of 512 channel for each universe there where protocols implemented using the Art-Net also called Art-Net DMX is

3.3 ESP Platform

- Why ESP Platform
- whats is the alternative
- chip shortage for Arduino
- price gab to esp32 dev boards

Almost every 802.11 capable Microcontroller Unit (MCU) could be picked for this research. But there are several reasons why the ESP Platform from Espressif is a valid choice. There are several chips provided by Espressif with WiFi specifications, these chips are very affordable () and althrough the ongoing chip crysis (2021) there are easy to get, in contrast of the also very popular Chips from the manufacturer Arduino, which are also more expansive. Espressif supports an own development IDF to flash the chips, with minor tweeks it's also to use the Arduino IDE.
However the properitary protocol ESP-Now which, just supported in the ESP Ecosystem, is discussed below Section 3.3.2 and has promising properties for a solid and fast realisation of a low level protocol.

ESP32 Kosten in € 2021 aufführen? Link? Datum?

3.3.1 ESP32 Hardware

- reasons to pick
- availability due chipcrysis
- cheap chip
- Range
- Properity
- Reverse-Engineering
- related work
- 2.4 GHz (cheap)
- Bild vom chip

The chip ESP32 is quite common in DIY projects around everything from home automation to light installations. The chip is delivered with several development boards. The chip is promoted with:

this is cited from: link zum esp32 datasheet

- 802.11 b/g/n with up to 150 Mbps
- Wifi Multimedia (WMM)
- Immediate Block ACK
- Automatic Beacon monitoring (hardware TSF)
- Virtual Wi-Fi Interfaces
- Simultaneous support for Infrastructure Station, SoftAP, and Promiscuous modes
- Bluetooth v4.2 BR/EDR and Bluetooth LE specifications
- Xtensa® single-/dual-core 32-bit LX6 microprocessor(s)
- Advanced Peripheral Interfaces: GPIO, ADC, DAC, touch sensors, hall sensor, SPI, I2S, I2C, UART, CAN, RMT (TX/RX), Motor/LED PWM

add picture of an ESP layout

3.3.2 ESP-Now

- How does ESP-Now match the requirements from the motivation
- 250 payload
- gaps in the documentation

ESP-NOW is a properitary protocol developed by Espressif. ESP-NOW is widely used in smart light, remote controlling, sensor, etc.. It is a conectionless protocol, so the WES's are in Ad-Hoc mode insted of STA. It is just supported with the ESP8266, ESP32 and ESP32, these are all chipsets from Espressif, but they are compatible with each other. Because of this, a ESP-Chip as gateway is needed to interact from the outside to the ESP-NOW network.

cite ESP documentation website

Through the hardware limitation of the boards it can just be used on the 2.4 GHz frequncy band. ESP-NOW allows 10 ESPs for pairing with encryption and up to 20 without encryption. Espressif promises throuput of up to 30MBit/s with UDP transmissions over the air and a possible range of up to 1km. However *Roberto Pasic [5]* measured a range of the unmodified onboard antenna of the ESP32 and just got a *Roberto Pasic [5] stable commication up to 190m in open field*.

The ESP-NOW protocol has a focus on low power consumption. A connectionless communication between WES's not only saves energy during the authentication process, Additionally, is the commonication the the properties of the ad-hoc mode, direct and not over a second access point. The protocol has a limitation of a limeted payload of 250 byte for each transmission. It also has a much less overhead, which results in shorter airtime, less disturbances and also less power consumption through the antenna (latter is not relevant for this thesis). There is no TCP/IP header to be transmited. For very small payloads, this offset can become dispropotional.

The default ESP-NOW bit rate is 1 Mbps it uses a channelwidth of 20MHz, there is no double channel (40Mbit/s or higher) used. But e.g. the low energy, high range protocol Long Range Wide Area Network (LoRaWAN) suffers from a to slow throuput for this application.

To undersant what ESP-NOW does it needs to take a look to the vendor-specific action frame transmiting ESP-NOW data.

visualized in 3.2.

cite somehow the ESP-NOW documentation pdf: ESP-IDF Programming Guide: ESP-NOW, source: `https://docs.espressif.com/projects/esp-idf/en/latest/esp32/api-reference/network/esp_now.html`

- **MAC Header:** As ESP-NOW is connectionless, the MAC header differs from that of standard frames.
- **Category Code:** The Category Code field is set to the value(127) indicating the vendor-specific category.

MAC Header	Category Code	Org.	Random Values	Vendor Specific Content	FCS
24	1	3	4	7 ~ 255	4

Table 3.2 – ESP-NOW Frame Format

- **Organization Identifier:** The Organization Identifier contains a unique identifier (0x18fe34), which is the first three bytes of MAC address applied by Espressif.
- **Random Value:** The Random Value filed is used to prevents relay attacks.
- **Vendor Specific Content:** The Vendor Specific Content contains vendor-specific fields (table 3.3)
- **Frame Check Sequence:** Used for error correction in layer 2.

Inside of the ESP-NOW frame 3.2 is the vendor specific content visualized in 3.3.

Element ID	Length	Org. Identifier	Type	Version	Body
1	1	3	1	4	7 ~ 250

Table 3.3 – Vendor Specific Action Frame

- **Element ID:** The Element ID field is set to the value (221), indicating the vendor-specific element.
- **Length:** The length is the total length of Organization Identifier, Type, Version and Body.
- **Organization Identifier:** The Organization Identifier contains a unique identifier(0x18fe34), which is the first three bytes of MAC address applied by Espressif.
- **Type:** The Type field is set to the value (4) indicating ESP-NOW.
- **Version:** The Version field is set to the version of ESP-NOW.
- **Body:** The Body contains the ESP-NOW data.

this is cited from espressif manual!!

It is worth to mention, that the vendor specific content 3.2 is allowed to contain up to 255 byte, but the sum over all values in 3.3 if the body would contain the maximum of 250 bytes, leads to a total of 260 bytes. The values are from the documentation of ESP-NOW from Espressif. They also claim, that broadcast is not supported in ESP-NOW, but it is. It seems that the documentation isn't complitly finished (or translated).

3.3.3 ESP-Now vs Art-Net Baseline

subsection can be on a wrong position!

remove newpage command

- Network stack diagram
- baseline

ESP-NOW Baseline Artnet should be moved to Design part??

Chapter 4

Proposed Approach

- 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.

Starting from the ESP-Now protocol, different approaches can be chosen to route the control signals to the fixtures. In the following I will present different approaches, which are also investigated experimentally.

4.1 Design

- Specification of the protocols
- analytic results (simulierte Ergebnisse)
- Ad-Hoc complexity of topology is not a problem, because of its simple star structure.

In this chapter there are different approaches presented and discussed. There are several specifications to go through and some details of the implementation.

4.1.1 Slim Unicast

- topology

- Network stack
- re transmissions
- reliability
- tolja calculation sheet for 802.11
- wireshark measurements

Art-Net Section 3.2.2 makes use of the Internet Protocol (IP) and the User Datagram Protocol (UDP) for routing and controlling the transmissions. The most similar approach using ESP-Now insted of Art-Net is cutting the Layer above the Data Link Layer. It is more like a direct transmission between sender and fixture, saving some overhead. In the Application layer is the Art-Net replaced with the Slim-Unicast, controlling the order and timing of the repetitions.

ist Slim-Unicast auf sender-seite nicht anders zu behandeln als auf empfängerseite?

Art-Net	Slim-Unicast	Slim-Broadcast
UDP		
IP		
802.11 DL/Unicast	802.11 DL/Unicast	802.11 DL/Broadcast
802.11b/g/n PHY	802.11b/g/n PHY	802.11b/g/n PHY

Table 4.1 – OSI Layer of Slim Unicast and Broadcast

Fehlt hier nicht ESP-Now?

An intuitive way is to send the most recent signal to all fixtures via Round Robin. The sender node selects a fixture after each other and transmits all the needed channel to it.

Discuss the inimportance of order of round robin in unicast

calculation of the estimated transmission time of unicasts

One benefit of the unicast is the support of acknoledgements. So the reliability should be very good. Unfortunately the ESP-Now protocol does not allow to control the number of retransmissions before the packet is discarded. Synchronisation of all devices is also expensive, because every fixture has to wait after the successfull receiving of his packet until the last fixture received his packet too. This is further discussed in Section 4.1.4.

move to buffering delay??

$$t_{bestcase} = N \cdot (t_{transmission} + 8 \cdot t_{ack})$$
$$t_{worstcase} = N \cdot (t_{transmission} + 1 \cdot t_{ack})$$

The idea of the unicast is, that a transmission to each device is very fast, because the transmitted payload is very small (1-25 Byte). However, since we are sending many small packets, it can be assumed that we will be sending a lot of overhead. So we playing off reliability against transmission speed.

Man kann transmissions skippen, wenn eine fixture keine veränderten daten erhält

reference to unicast topolgy in fundamentals

4.1.2 Slim Broadcast

- topology
- efficiency
- for how many nodes it does make theoretical a difference

The ESP-Now protocol supports both unicast and broadcast. Instead of transmitting every unicast after each other, we transmit a broadcast with the payload of all channels at the same time to all fixtures. If we need more than 250 channel we have to send to broadcasts to transmit all information to all fixtures. To achieve this we need to tell each fixture in advance his channel. A fixture with a channel above 250 needs to modulo to get the broadcast ID.

Notwendig?

$$315 \mod 250 = 1$$
$$315/250 = 65$$

Insead of transmitting to several fixtures after each other we just transmitt to all fixtures at the same time. This solves the problem of synchronization for less than 250 channel. For more than 250 each fixture has to wait until the last broadcast is arrived, even if he must be discarded because the required channel has already been arrived in a previous broadcast. Through less overhead there is an estimated difference when a specific amount of fixtures is reached.

Grafik die zeigt, wie der Broadcast besser performt, sobald eine bestimmte zahl fixtures erreicht ist

4.1.3 Rapid Repetition

- simple
- redundant
- fast
- cite paper from tolja

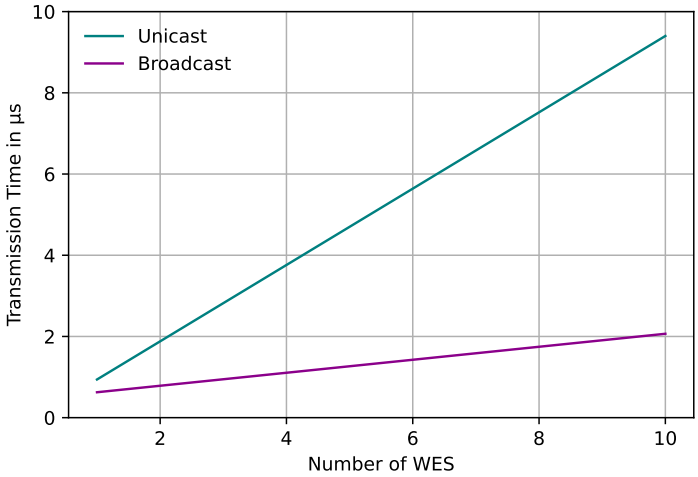


Figure 4.1 – Transmission Time of Unicast vs Broadcast

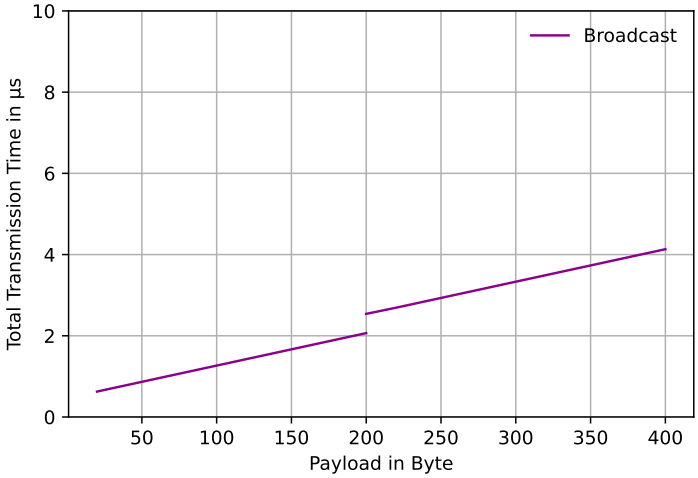


Figure 4.2 – Transmission Time of Unicast vs Broadcast Analytis

- explain why its only relevant for BC?

The ESP-Now broadcast does not support acknoledgements. So we can't retransmit a packet to the fixture, which is not arrived successfully. In case of broadcast we had to transmit the hole broadcast or an unicast to each fixture wich does not send back the acknoledgement.

Since this is very cumbersome to implement, it is a good approach to simply repeat each broadcast.

Cite paper A First Implementation and Evaluation of the IEEE 802.11aa Group Addressed Transmission Service

This is called rapid repetition.

Is Rapid Repetition a appropriate name? Unsosliced Repetition is better siehe Paper?

The idea is, that we can push the reliability wich each redundant retransmission.

The estimated reliability of a fixture with average success ratio (SR) of 83% without Repetition has to be 83%. If we increase the number of Rapid Repetitions (RR) we can roughly estimate:

$$SR_{RR}(RR) = 1 - (1 - SR)^{RR+1} \tag{4.1}$$

RR von 0 beginnen

grafische Darstellung RR=[0,1,2,3,4], für einen guten und einen schlechten Knoten 83% und 95%

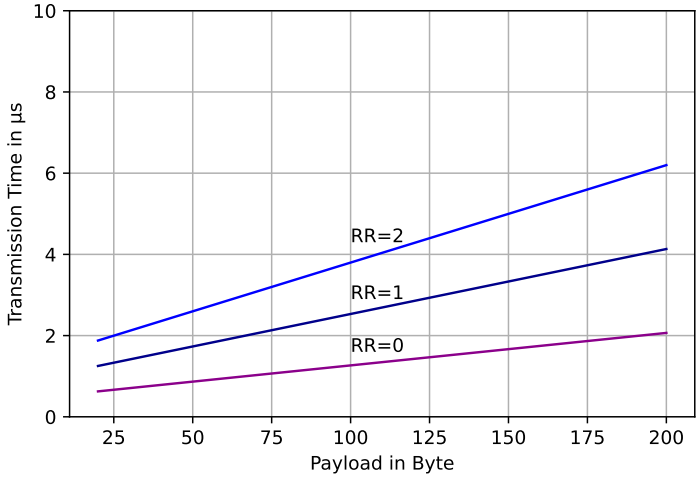


Figure 4.3 – Transmission Time with with different Rapid Repetitions

We have to figure out how many repetitions we should transmit in order to find the best balance between reliability and latency/update ratio. This hardly correlates with the overall success ratio in the (test-)setup.

(test-)setup: kann man das so schrieben?

4.1.4 Delayed Repetition

- when to perform repetition
- buffering delay
- explain why its only relevant for BC?

To push the idea of rapid repetion even further, we should take a look to temporarily occuring disturbances.

Figure of bad channel time

4.2 Implementation

- ESP programming
- code examples
- python script

for later use: ESP-NOW User Guide, V1, source: https://www.espressif.com/en/support/documents/

4.2.1 ESP Programming

- broadcast unicast
- IDF/Arduino
- IDE & ESP hardware flashing
- setup devices

Unfortunally in the documentation of the ESP-protocol is written, that broadcast is not supported but actually it is. Insted of adding the MAC Address of a fixture, we can use ff:ff:ff:ff:ff:ff to add a peer with the broadcast MAC.

has this a proper name, like broadcast address?

```
1 void addFixtureToPeerList(const uint8_t *mac_addr)
2 {
3   if (esp_now_is_peer_exist(mac_addr)) return;
4
5   peer_info.channel = 1;                // 1-14
```

```
6   peer_info.ifidx   = ESP_IF_WIFI_STA; // Station mode
7   peer_info.encrypt = false;           // not needed
8   memcpy(peer_info.peer_addr, mac_addr, 6);
9
10  esp_err_t status = esp_now_add_fixture(&peer_info);
11  if (ESP_OK != status)
12  {
13    Serial.println("[ERROR] Could not add fixture");
14  }
15  else
16  {
17    Serial.println("[OK] fixture added");
18  }
19 }
```

fix colorscheme omf code examples

4.2.2 Collecting measurment results

- Collecting values
- state machine
- python script
- saving values
- digital encoding e.g.: 777477472717

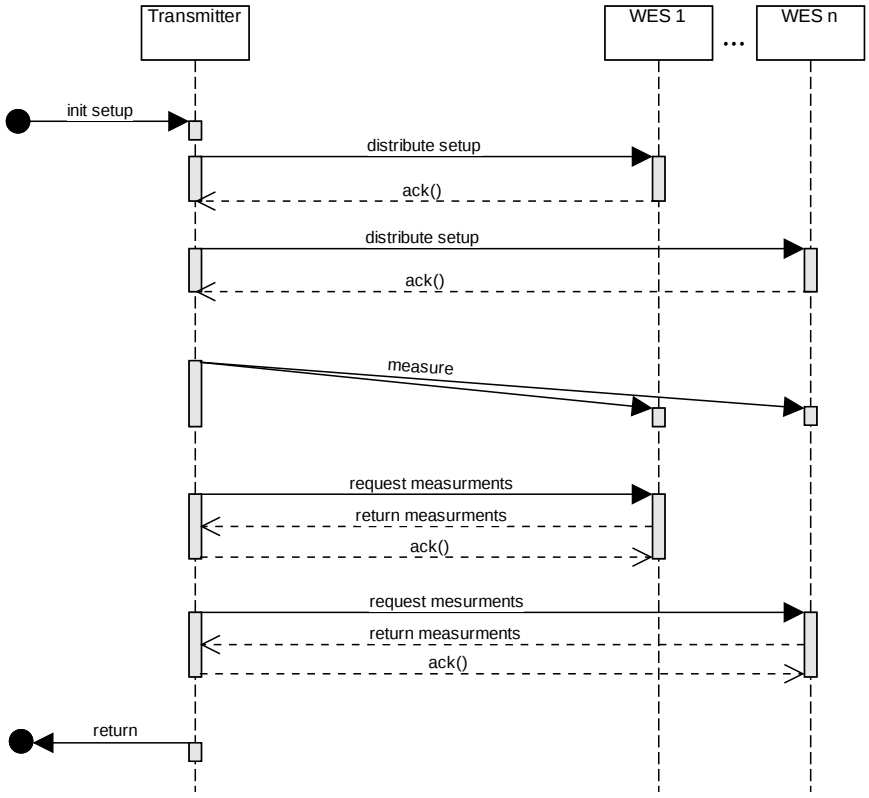
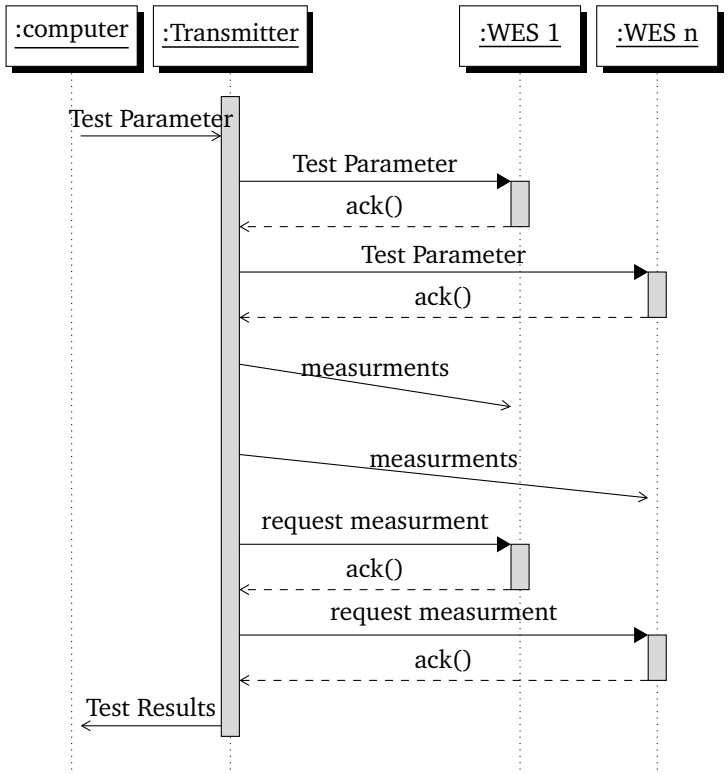


Figure 4.4 – Sequence diagram of the measurment


:computer
:Transmitter
:WES 1
:WES n
Test Parameter
Test Parameter
ack()
Test Parameter
ack()
measurments
measurments
request measurment
ack()
request measurment
ack()
Test Results

Chapter 5

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.

Keep in Mind

- metrics (SR, Latency, ...)
- compare with art-net all the time

5.1 Methodic

- Testbed
- Collect Data
- Seqence Diagram to explain

5.2 Protocols under Study

-

Unicast vs Broadcast

Rapid Repetition

Delayed Repetition

Grouping

5.3 Results

Difference between Results and Discussion?

- Grafen miteinander verlgeichen?
- Which method had the best results?

Chapter 6

Conclusion & Discussion

- 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.

Why not 5GHz -> to expensive.

List of Abbreviations

AP	Access Point
BSS	Basic Service Set
BSSID	Basic Service Set Identifier
CAN	Controller Area Network, *when referring to the bus protocol*
CSMA/CA	Carrier-sense multiple access with collision avoidance
DL	Data Link Layer
DMX	Digital Multiplex
DSSS	Direct Sequence Spread Spectrum
FHSS	Frequency Hopping Spread Spectrum
IEEE	Institut of Electrical and Electronics Engineers
IP	Internet Protocol
LLC	Locig Link Control
MAC	Media Access Control
MCU	Microcontroller Unit
MIMO	Multiple Input-Multiple Output)
MSDU	MAC Service Data Unit
NAV	Network Allocation Vector
OFDM	Orthogonal Frequency Division Multiplexing)
OSI	Open Systems Interconnection
PHY	Physical Network Layer
SIFS	Short Inter Frame Spaces
STA	Station
UDP	User Datagram Protocol
WES	Wireless Endsystem
WLAN	Wireless Local Area Network

List of Figures

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Bibliography

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Todo list