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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

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Abgabe der Arbeit: **19. 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 19 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

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

List of papers:

In this chapter I discuss the fundamentals required for understanding the different approaches in this thesis using. I will repeat some 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. In order to understand the upcomming ESP-Now protocol we have to take a look at the Data Link (DL) layer in 802.11. It is the second layer of the OSI model of computer networking illustrated in Table 3.1.

refrence to table below

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.
- Independent BSS
  A network without a central station, where the network topology can flexible change over time. The communication is 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.

3.1.1 IEEE Frame Structure

- Image of 802.11 frame structure PHY and MAC header
- Image of MAC header
- Image of frame control field of MAC in MAC header
- Image of frame control field of MAC in MAC header

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

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29

FC	Duration	Address 1	Address 2	Address 3	SC	Address 4

Figure 3.1 – MAC header in a WLAN frame

3.1.2 DL-Layer in 802.11

- why is it important for us
- how works the DL layer
- was ist BC, was Unicast
- was sind frames
- how the Application layer

3.1.3 Physical layer

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.

3.1.4 IEEE 802 Stuff

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 (up to 4) to increase data rates

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.

3.2 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 Platform

ESP32 Kosten in € 2021 aufführen? Link? Datum?

is discussed below Section 3.3.3 has promising properties for the realisation of a low level protocol.

3.3 Light protocols

In this chapter I give you a short introduction about stage lighting protocols that are already in use. After that I will discuss why I choosed the ESP Platform and which modifications I made to get the improvements I was looking for in the requirements.

use passive voice

DMX-512A

Digital Multiplex (DMX), is the current industry standard for stage lighting. It is based on Controller Area Network (CAN), therefore it uses wires.

All devices, called fixtures, are daisy chained together.

Picture of topology

A fixture is a lighting instrument, 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. Since DMX is unidirectional we can assume that fixtures generally only receive or forward (daisy chain) control signals sent from the control console. In this thesis I equate it with a node or an entity receiving a signal.

I or we? It should be I...

Show Hardware e.g. DMX Plug

A channel in the event technology is to distinguish between e.g. a WiFi channel.

Each FIXTURE is assigned at least one, but usually several CHANNEL, which are the payload containing in a packet to all FIXTURES. Each fixture knows which CHANNEL is intended for it. Each channel consists of one byte. 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.

Bild von fixtures verteilt auf channel

A universe can contain a set of 512 Channel. If there is a need of more channels one needs more DMX universes. Due to the fact that a DMX universe always has its own bus, starting from its own controller, this can lead to inconveniences.

3.3.1 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

3.3.2 ESP32 Hardware

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

The chip ESP32 is quite common in DIY projects around everything from home automation to light installations. The chip supports the

3.3.3 ESP-Now

- Range
- Properity
- Reverse-Engineering
- related work
- cheap chip
- 2.4 GHz (cheap)
- How does ESP-Now match the requirements from the motivation
- Frame Format
- Vendor specific frame
- gaps in the documentation

3.3.4 ESP-Now vs Art-Net Baseline

- Network stack diagram
- baseline

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)

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 3.3.1 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??

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

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

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

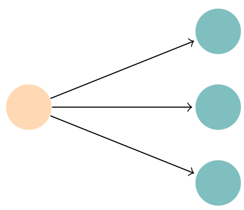


Figure 4.1 – Topology of the Slim Unicast

4.1.3 Rapid Repetition

- simple
- redundant
- fast
- cite paper from tolja
- 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%

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

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 Media Access Control (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?

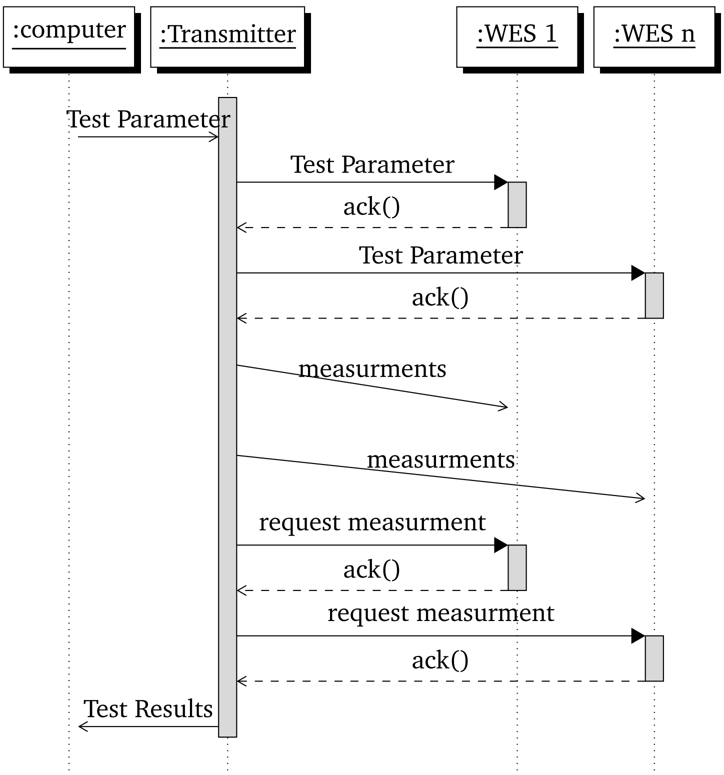
```
void addFixtureToPeerList(const uint8_t *mac_addr)
{
  if (esp_now_is_peer_exist(mac_addr)) return;

  peer_info.channel = 1;              // 1-14
  peer_info.ifidx   = ESP_IF_WIFI_STA; // Station mode
  peer_info.encrypt = false;          // not needed
  memcpy(peer_info.peer_addr, mac_addr, 6);

  esp_err_t status = esp_now_add_fixture(&peer_info);
  if (ESP_OK != status)
  {
    Serial.println("[ERROR] Could not add fixture");
```

```
  }
  else
  {
    Serial.println("[OK] fixture added");
  }
}
```

fix colorscheme omf code examples

4.2.2 Collecting measurment results

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



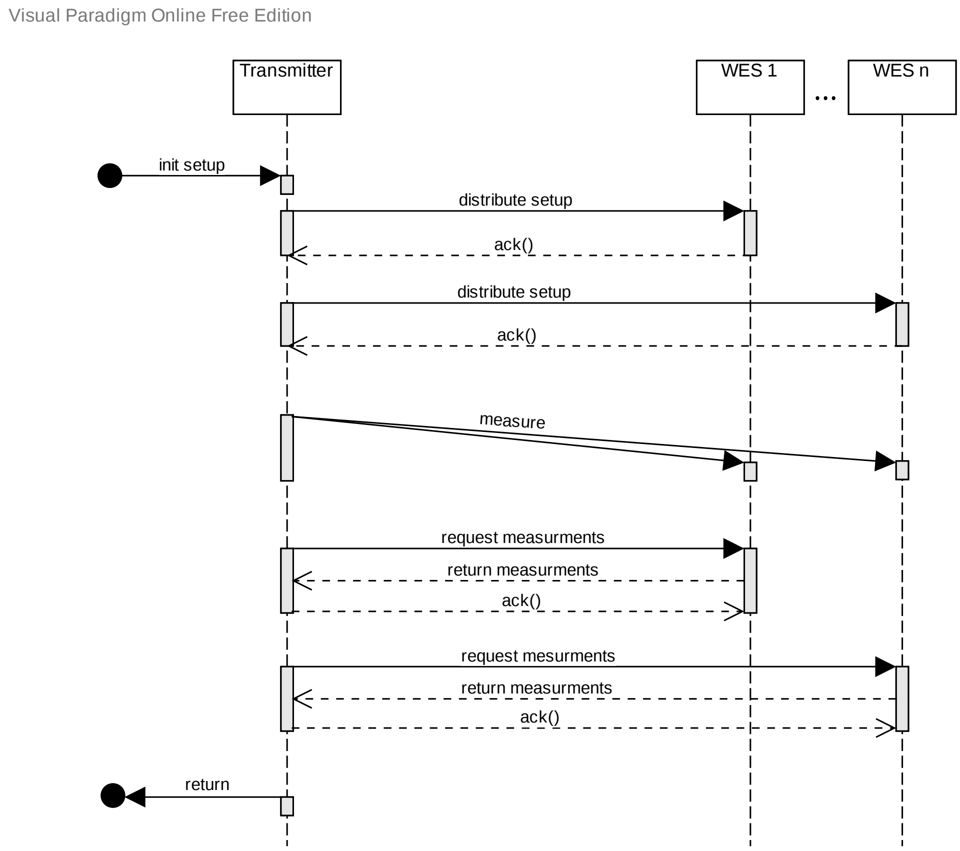


Figure 4.2 – Sequence diagram of the measurment

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
CAN	Controller Area Network, *when referring to the bus protocol*
DL	Data Link
DMX	Digital Multiplex
DSSS	Direct Sequence Spread Spectrum
FHSS	Frequency Hopping Spread Spectrum
IEEE	Institut of Electrical and Electronics Engineers
IP	Internet Protocol
MAC	Media Access Control
MCU	Microcontroller Unit
MIMO	Multiple Input-Multiple Output)
OFDM	Orthogonal Frequency Division Multiplexing)
OSI	Open Systems Interconnection
STA	Station
UDP	User Datagram Protocol
WES	Wireless Endsystem

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