ANALYSIS AND OPTIMIZATION OF THE NETWORK THROUGHPUT IN IEEE 802.15.13 BASED VISIBLE LIGHT COMMUNICATION NETWORKS

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ANALYSIS AND OPTIMIZATION OF THE NETWORK THROUGHPUT IN IEEE 802.15.13 BASED VISIBLE LIGHT COMMUNICATION NETWORKS

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I dedicate this dissertation to my beloved family, who have instilled in me the desire to learn and helped me in everything great and small.

ABSTRACT

In recent years, commercialization of visible light communication networks have started. As a result, there are multiple groups working for their standardization. In this work, we focus on one of them, which is IEEE 802.15 Task Group 13 and their 802.15.13 Optical Wireless Personal Area Networks (OWPAN) standard draft. The network generated according to the draft is analysed for network load and an algorithm to improve network throughput is proposed. In 802.15.13 draft, the MAC protocol uses contention free and contention access periods. This paper investigates how those period lengths should be determined. Our suggested algorithm improves the performance of the network at least 5% in the case of variable network traffic up to 15 active users.

ÖZETÇE

Son yıllarda, görünür ışık iletişim ağlarının ticarileştirilmesi başlamıştır. Sonuç olarak, standardizasyonu için çalışan birden fazla grup var. Bu çalışmada, bunlardan biri olan IEEE 802.15 Görev Grubu 13 ve 802.15.13 Optik Kablosuz Kişisel Alan Ağları (OWPAN) standart taslağına odaklanıyoruz. Taslağa göre oluşturulan ağ, ağ yükü açısından analiz edilerek ağ verimini iyileştirmek için bir algoritma önermekteyiz. 802.15.13 taslağında, MAC protokolü çekişmesiz ve çekişmeli erişim dönemleri kullanır. Bu çalışma, bu dönem uzunluklarının nasıl belirlenmesi gerektiğini araştırmaktadır. Önerdiğimiz algoritma, değişken ağ trafiğinin 15 aktif kullanıcıya kadar olması durumunda ağ performansını en az 5% arttırmaktadır.

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Especially, I am appreciated to Dr.Mohammed Elamassie to help to my studies and share his experience with me .

ACRONYMS

CAP	contention access period
CFP	contention-free period
CRC	cyclic redundancy check
FCS	frame check sequence
GTS	guaranteed time slot
IFS	interframe space
MAC	medium access control
MCPS-SAP	medium-access-control common-part sublayer service access point
MLME-SAP	medium-access-control link-management entity service access point
MLME	medium-access-control link-management entity
MPDU	medium-access-control protocol-data unit
MSDU	medium-access-control service-data unit
OWC	Optical Wireless Communications
OWPAN	Optical Wireless Personal Area Network
PHR	physical-layer header
PHY	physical layer
PIB	physical-layer personal-area-network information base
PPDU	physical-layer data unit
PSDU	PHY service data unit
RS	Reed-Solomon
PD-SAP	service access point
SAP	service access point
SHR	synchronization header

OWPAN	Optical wireless personal area network
VLC	visible-light communication
Li-Fi	Light Fidelity
Wi-Fi	Wireless Fidelity
IoT	Internet of Things
CAN	Controller Area Network
RF	Radio Frequency
LAN	Local Area Network
TDM	Time Division Multiplexing
TDMA	Time Division Multiplexing Access
OFDM	Orthogonal frequency division multiplexing
FDM	Frequency Division Multiplexing
WDM	Wavelenght Division Multiplexing
SCM	Sub-Carrier Multiplexing
QAM	Quadrature Amplitude Modulation
WPAN	Wireless Personal Area Network
PM-PHY	Pulsed Modulation
PAM	Pulse Amplitude Modulation
HCM	Hadamard-coded modulation
LB-PHY	low bandwidth OFDM PHY
HB-PHY	high bandwidth OFDM PHY
OFE	optical front end
OCR	optical clock rate
RS	random slot
CW	contantion window
RC	rety count
IFS	inter frame space

TAIFS	Turn Around Interframe Space

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CHAPTER I

INTRODUCTION

1.1 Motivation

The spectrum crunch in traditional indoor radio networks has motivated the introduction of visible light communication (VLC) as an alternative wireless access solution. Consequently, VLC equipment vendors and research institutions have initiated relevant standardization efforts. The IEEE 802.15.13 Multi-Gigabit/s Optical Wireless Communications Task Group (TG13) is working on Physical (PHY) and Media Access Control (MAC) layer designs, which will deliver data rates up to 10 Gbit/s. The first draft of TG13 was finalized in 2019. As of May 2021, the group is in the final phase of standard preparation.

802.15.13 MAC protocol uses ”slotted Aloha” and ”reserved dynamic time slots” protocols simultaneously to provide the required quality-of-service (QoS) by resource reservation and achieve high resource utilization with multiplexing gain during the contention periods. However, reservation operation can significantly affect the behavior of the network. How to split time between reservation periods with reserved time slots and how to determine the number of reservation slots are crucial tasks of 802.15.13 MAC Network Coordinator.

The IEEE 802.15.13 MAC superframe consists of a contention access period (CAP) and a contention free period (CFP) [1]. In the CAP, each node transmits its packets to the coordinator using slotted Aloha protocol through contention with the other nodes. On the other hand, in the CFP, each node transmits its packets to any device in the network by using the guaranteed time slots (GTSs) dedicated to itself. In order to transmit packets in the CFP, a node transmits a request packet to the coordinator during the CAP. If the coordinator successfully receives the request packet, it allocates the GTS to the node according to its buffer or queue. Therefore, the performance of the CAP and that of the CFP are related to each other.

For the network coordinator, defining CAP duration is vital for the network data rate optimization. The CAP duration affects package drop rate and total throughput. The coordinator has to define the total number of CAP slots according to user numbers in the network. And then, it can decide the maximum CFP slots which can be assigned for each user according to the queue length of devices. High CFP slot numbers also cause more buffer and latency but more throughput. Thus, CFP duration is also vital for overall performance. In this work, we investigate how those period lengths and time slot numbers should be determined and optimized by the coordinator. According to a series of simulations, we further propose a heuristic algorithm to improve total network throughput efficiency.

In the literature, various techniques have been used to analyze and improve the performance of contention-based reservation protocols. D. Lee, *et. al.* proposed the use of Markov chains to model the distributed coordination function (DCF) for saturated stations [2]. Another method depends on the users in the network repeatedly updating information in order to reflect any changes in their data rates [3]. A similar approach is the modified packet transmission in the TDMA period to reduce transmission overhead [4]. Mean value analysis, which evaluates the average value of system variables, such as station transmission probability, collision probability, frame service time, can be used as well [5], [6], [7], [8]. The method in [5] evaluates the energy efficiency through computer-based simulations. In [6], the goodput[1] and delay is improved for high priority data by dividing the GTS length from historical packet size and adjusting values. In [7] and [8], the average frame service time and throughput is investigated to improve network efficiency based on Mean Value Analysis. Authors in [9] and [10], studied the delay performance of DRP (Distributed Reservation Protocol) with arbitrary reservation patterns in superframes.

[1]Goodput is the number of useful information bits that is delivered by the network to a particular destination per unit of time.

In [11], different transmission timing with a priority of packets is proposed to improve throughput. Most of the existing works however build upon simplified assumptions and do not include crucial parameters in practical deployment such as package drop, buffer, latency, and desired data rate for devices in the network which motivates our study.

1.2 The Overview of Visible Light Communications

In the beginning, cell phones were mostly used for voice calling or text messaging. The later introduction of smartphones marked the beginning of a new era in wireless communication. Nowadays, smartphones have all kinds of sensors and applications that facilitate daily communication, banking and healthcare [12]. These processes cause much more data confusion and transmission. For this reason, more bandwidth and faster devices are needed. This makes the frequency spectrum use below 5 GHz very intense and frequent. It doesn't leave much room for applications in this spectrum for future applications such as autonomous cars and smart cities [13]. Such problems have prompted scientists to find a new solution that can handle higher data rates and more data. The best candidate is the visible light. Because although visible light is frequently used in daily life, it is not used for communication. In addition, visible light communication has advantages such as usability, link-level security, higher bandwidth and frequency reuse. And, since 80% of people stay at home, it is considered to be quite helpful for data demand indoors [14].

Visible light was first used by the Romans for communication. The Romans communicated by reflecting sunlight onto each other through polished metal plates. In 1794, Claude Chappe developed a semaphore system from a series of towers equipped with mounted arms for communications. In the 19th and early 20th centuries, systems called heliographs were used to communicate with light. A helicograph is a system that uses sunlight to transmit morse code.

Graham Bell invented the modern telephone, using electrical signals to transmit sound. However, Bell described the photophone as one of the most important invention [15]. The photophone uses sunlight by vibrating the mirror to transmit sound. It was actually Graham Bell's idea that inspired fiber optic technology. In 1975, the first commercial fiber optic communication system was used. And in that year, the fiber optic communication system could operate at a bitrate of 45 Mbit/s. visible-light communication (VLC) is a form of optical communication that operates at a distance of two to three meters in the air, rather than using a cable-guided medium. In 2003, the term VLC was first coined by the Nakagawa Laboratory at Keio University in Japan [16]. Nakagawa Laboratory introduced the first VLC system at Keio University in 2000. Light emitting diodes (LEDs) are used to transmit the data.

The term Light Fidelity (Li-Fi) was first used by Herald Haas in 2011 [17]. Li-Fi is a bidirectional, high-speed and synchronous communication system like Wireless Fidelity (Wi-Fi) that uses Radio frequency for communication. Since the radio frequency spectrum is used very frequently today, it is inconvenient to use Wi-Fi signals in places where radio frequency is used intensely and vitally important such as airplanes. Because these signals create interference effect to each other. Therefore, Li-Fi offers a good solution in electromagnetic radiation sensitive areas. It also provides usability for Internet of Things (IoT). Using Li-Fi, speeds of up to 10 Gbit/s can be achieved, 250 times faster than super-fast broadband speeds [18].

1.3 Applications of Visible Light Communications

The things that make VLC more attractive are its high bandwidth, no health hazards, low power consumption, and practical use. Different application scenarios using VLC are as follows:

1.3.1 Vehicle to Vehicle Communication

VLC can be used for communication applications between vehicles via existing vehicle lights and traffic light infrastructure. These can be applications such as collision warning, pre-collision detection, emergency electronic brake lights, lane departure warning, stop sign motion assist, left turn assist, traffic signal violation warning and cornering speed warning. These applications require reliable availability with extremely low latency. VLC systems meet the low latency and reliable usability criteria required for such applications. In the [19], an outdoor VLC system using Controller Area Network (CAN) was proposed, and the proposed system used rear lights and headlights for communication.

1.3.2 Underwater Communication

RF waves are highly attenuated in seawater because seawater is conductive. Therefore, using VLC in underwater communication networks is a pretty good idea [20]. (UTROV) is another implementation of VLC in underwater communication. UTROV can be used to maintain oceans from observatories and conduct ocean surveys. In addition, UTROV can be deployed to ships and enable on-site inspections.

1.3.3 Hospitals

Hospitals have many devices and areas that are sensitive to electromagnetic waves, such as MRI scanners and x-ray service. VLC is very usable in such areas as it will not cause interference to the radio waves of other machines. In [21], a robot named HOSPI is proposed, which is used in hospitals and for transport duty. HOSPI's control system operates using the VLC and navigation sensors of robot into a building.

1.3.4 Visible light ID System

VLC can also be used as an identity system. For example, the address we are stay, can be coded with the visible light system and the address can be defined with VLC system. Similarly, the visible light identification system can be used in subways, hospitals and airports.

1.3.5 Wireless Local Area Networks (WLANs)

Using VLC is suitable for Local Area Network (LAN)s. In [22] an ultra-high speed full duplex LAN based on star topology using LED visible light communication is proposed.

This LAN is predicted to provide speeds of more than 10 Gb/s and has been tested for a large number of users. The reason the network is designed using a star topology is to enable it to serve a large number of users. The fiber is used in direct connection with each lamp. The proposed LAN uses hybrid access protocol such as Time Division Multiplexing (TDM) for bidirectional VLC transmission and Frequency Division Multiplexing (FDM) for uplink and downlink fiber transmission. The results of the proposed LAN provide high speed access for a large number of users. In [23], a 10 Mbps VLC wireless LAN system using white LEDs is proposed. Lighting system is used for downlink and infrared light is used for uplink. It is beneficial to use in high security office buildings and hospitals because visible light cannot go out from closed environments.

1.4 Architecture of Visible Light Communication

The lowest layer of the VLC system consists of the transmitter and receiver that make up the physical layer. Above the physical layer is the MAC layer and above it is the application layer. The reference model of the VLC communication system is shown in Fig. 1 [24]. Most VLC standards are simplified to just two layers (PHY and MAC).

1.4.1 Mac Layer

Common requirements for the Medium Access Control (MAC) layer are follows:

- Supporting mobility,
- Supporting dimming,
- Supporting visibility,
- Supporting security,
- Schemes for mitigation of flickering,
- Supporting color function,

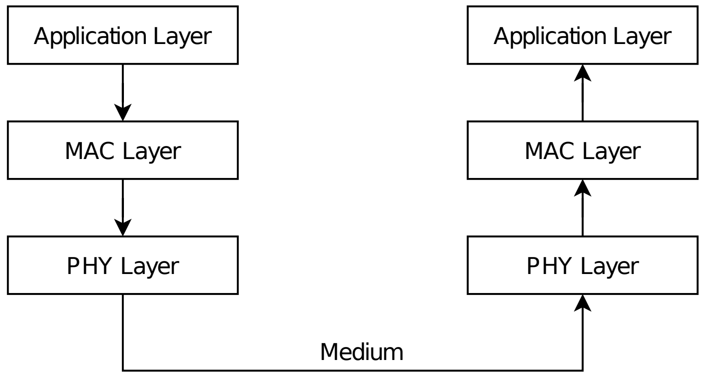

Figure 1: Typical VLC Architect.

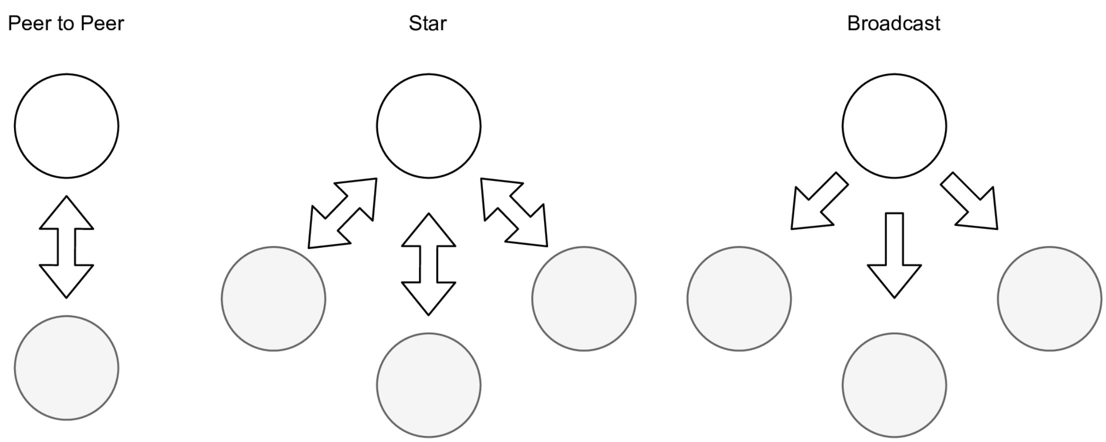

Figure 2: Common MAC Topologies.

- Beacons generation,
- Supporting WPAN disassociation and association,
- Providing a reliable link between peer MAC entities.

The most common topologies supported by the MAC layer are peer-to-peer, broadcast and star, as shown in Fig. 2. Communication in star topology is carried out using a single central controller.

1.4.2 Pyhsical Layer

The physical layer defines the hardware peripheral characteristics of the device. Fig. 3 shows the overall physical layer architecture block diagram of a VLC system. According to

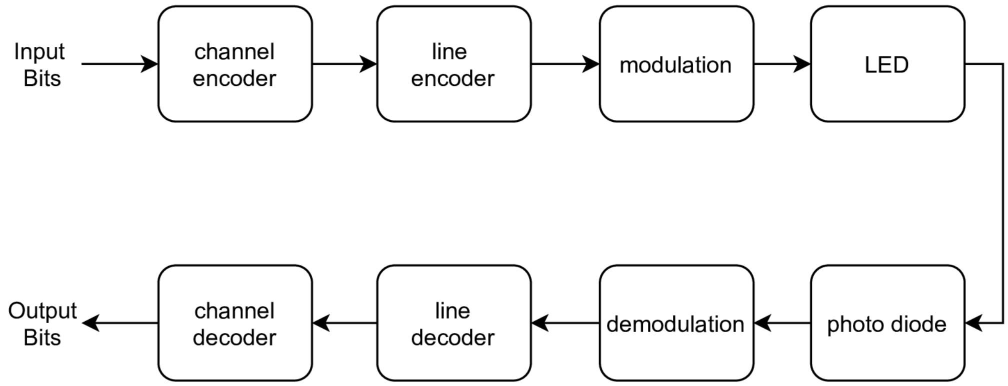

Figure 3: Typical PHY Layer Architecture.

block diagram, the input bit stream is passed through the channel encoder first (optional). To improve the performance of the VLC system, Linear block codes [25], convolutional codes [26] and the state of the art turbo codes [27] can be used. Next, the channel coded bit stream is passed through the line encoder to give the coded bit stream.After line coding, modulation (ON - OFF keying, PPM and PWM, etc.) is performed and finally data is fed to the LED for transmission over the optical channel. In [28], different applications of visible light communication systems are given. In [29], a full-duplex bidirectional VLC system is proposed using RGB LEDs in downlink and uplink respectively and a commercially available phosphor-based LED.

Wavelenght Division Multiplexing (WDM) and Sub-Carrier Multiplexing (SCM) are used for bidirectional communication, Orthogonal frequency division multiplexing (OFDM) and Quadrature Amplitude Modulation (QAM) are used to increase data rate. On the receiver side, the photodiode receives the optical signal (like silicon photodiode and PIN photodiode). After the optical signal is demodulated and line decoded, the bit stream goes through the channel decoder to extract the output bits.

1.4.3 VLC Transmitter

LEDs developments create new field that is solid state lighting [30]. Compared to incandescent light sources, LEDs outperform incandescent light sources in terms of reliability,

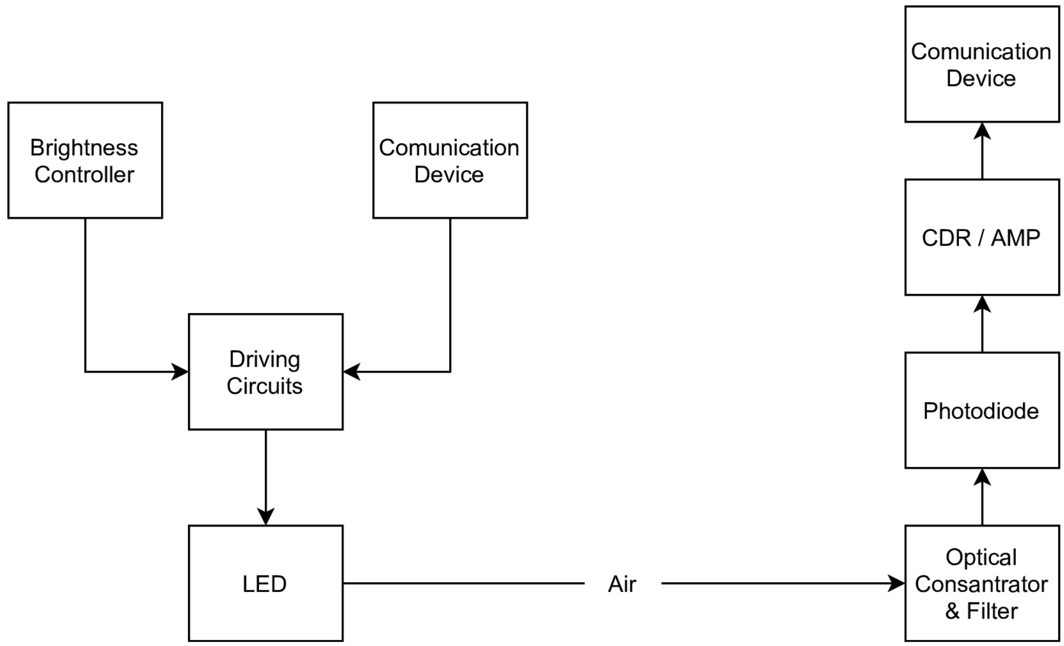

Figure 4: Typical VLC Receiver and Transmitter.

power requirements and luminous efficiency. The efficiency of LEDs is 20 lm/W more than the efficiency of incandescent lamps [31]. LEDs are used for data transmission in VLC. LEDs can provide both lighting and data transmission. For data transmission in VLC, white light LEDs are a good transmitter. There are different possible spectra such as tetra-chromatic, dichromatic and tri-chromatic modes used for white light generation [32]. The most commonly used methods to create white light using LEDs are trichromatic. This method uses red, green and blue spectra. The advantage of using RGB LEDs for white light generation is that it allows high bandwidth and therefore high data rates. The disadvantage of RGB LED is high complexity and modulation difficulties [33].

A sample VLC transmitter hardware described in Fig. 4 [34], [35], [36].

1.4.4 VLC Receiver

In LEDs, the scattering of light over large areas causes the signal to weaken. To compensate for this attenuation, a device called an optical concentrator is used. In VLC, light is detected using a photodiode and then converted into photocurrent. Infrared communication differs from VLC due to different wavelength and other parameter features. Therefore, silicon photodiode, PIN diode and avalanche photodiode are used for VLC [33]. Avalanche photodiode has a higher gain than a PIN photodiode, but at the expense of high cost.

VLC is very susceptible to interference from sunlight and other lighting sources. Therefore, optical filters are designed. Optical filters remove the noise from the received signal by reducing the DC noise components present in the received signal. A photodiode can be used as a receiver in a VLC. If the system is mobile, it would be better to use an imaging sensor instead of a photodiode. Imaging sensors have low energy efficiency and operate more slowly. Therefore, cost, speed, and complexity must be considered when choosing between photodiode and imaging sensors.

A Sample VLC receiver hardware described in Fig. 4 [36].

1.5 Visible Light Communication Standardization

VLC is promising due to the rapid development of LED lighting technology. However, the current challenges for the implementation of the VLC system are as follows:

- Integration of the VLC with the already existing communication standards such as Wi-Fi etc.
- The issue of interference with ambient light sources.
- The mobility issues such as handover should be properly considered in VLC.
- To improve the communication system performance by specifying Forward Error Correction schemes.
- Interference between the different devices using VLC is expected in the future because of an increase in the number of VLC devices.

In order to overcome the above challenges, standardization of VLC is necessary. The standardization of VLC has been carried out by several working groups. Some common VLC standards are as follows:

1.5.1 802.15.7

The Japan Electronics and Information Technology Industries Association (JEITA) CP-1221, JEITA Cp-1222 and JEITA Cp-1223 are published by the VLC [37]. The 802.15.7 is the standard published by the IEEE for physical and MAC layers [38]. This standard has key features such as:

- Providing access to several hundred THz bands.
- Providing immunity against the electromagnetic interference.
- Communication that complements extra services to the existing visible light infrastructure.
- Specifying the FEC schemes, modulation techniques and data rates for VLC communication.
- The channel access mechanisms such as contention access period (CAP), contention-free period (CFP) and visibility support when channel access are also described.
- The PHY layer specifications, such as optical mapping, TX-RX turn around time, RX-TX turn around time and flicker and dimming mitigation, are also explained.

Three different device classes are considered for IEE 802.15.7. These are vehicles, mobiles and infrastructures [39]. The JEITA CP-1221 standard aims to provide the required requirements and level of indication to avoid interference between different VLC devices.

The VLC wavelength range defined by JEITA CP-1221 is between 380 and 750 nm. JEITA uses frequency range 1 to implement the visible light identification system. Since the frequency range of the inverter fluorescent lamp is 2, this range is not suitable for VLC use. Frequency range 3 is used for high speed communication and JEITA CP-1222 used 28.8 kHz subcarrier frequency with 4.8 kbps transmission rate. Also used cyclic redundancy check was used for error correction.

1.5.2 802.15.13

The IEEE 802.15.13 Task Group defines an physical layer (PHY) and medium access control (MAC) layer for light communication systems using light wavelengths ranging from 10,000 nm to 190 nm in an optically transparent area. The standard, unobstructed line-of-sight supports data rates up to 10 Gbit/s at distances up to 200 meters and is designed for point-to-point and point-to-multipoint communication in both coordinated and uncoordinated topologies. For topologies coordinated with more than one co-coordinator, there is a master coordinator. The standard also includes adapting to changing channel conditions and maintaining connectivity while moving within a single coordinator range or between coordinators. The TG13 continued work on High-speed photodiode communications (also called Li-Fi) previously made on the TG7m, which focused on optical camera communications. Work on LiFi continued on 802.15.13 as of March 2017. The first draft of the TG13 was completed at the end of 2019. In 2020, there was an 802.15 working group letter vote. Work on IEEE P802.15.13 is almost complete. The current draft D3.0 has been completed and the final cycle in the 802.15 working group has begun [40]. It is anticipated that the standard will be completed in 2021 [1].

This standard defines use of VLC for Wireless Personal Area Network (WPAN).The features in this standard as follows:

- Star, peer-to-peer, broadcast topologies
- 16 bit short, 64 bit extended addresses for devices
- Scheduled and slotted random access with collision avoidance (CA) transmission
- Acknowledged mechanism for data transfer reliability

The system is designed to meet the constraints of industrial and medical environments and offers a secure, robust, high performance, high data rate communication link in environments where it is difficult to operate traditional wireless systems.

Focusing on private networks rather than mass-market applications provides some flexibility in choosing the physical layer to use, due to lower integration requirements.

IEEE P802.15.13 also defines a minimalist MAC layer that can operate independently of other RF counterparts and integrate some of the key features of industrial wireless applications. The main tools for these features in the 802.15.13 MAC are distributed Multi-User MIMO and the extension of common TDMA-based channel assignment to allow parallel transmissions to multiple devices in areas where fast retransmission mechanism is not available. It also includes custom routines to support the capabilities of existing PHY layers, such as adaptive bit loading supported in HB PHY.

1.6 Organization

The outline of this dissertation is organized as follows.

1. **In Chapter II**, we talk about 802.15.13 standard. Firstly, we introduce the standard scope, components of the 802.15.13 networks and the standard compliant devices. Later on, we describe the IEEE 802.15.13 Optical wireless personal area network (OWPAN) standard applications which has different supported topologies. Then, we schematize the PHY and MAC Layer architecture of 802.15.13 OWPAN that is defined in terms of number of layers and sublayers in order to simplify the standard. In the next section, we talk about 802.15.13 OWPAN MAC functional overview that includes data transfer model, concept of primitives and MAC Frames based on the architecture. This section provides a brief overview of the general functions of an OWPAN MAC sublayer. Finally, depending on previous informations about the standard, We explain the channel access mechanism of the 802,15.13 MAC which is the most important part for this thesis subject. It includes super frame structure design, different time period medium access and synchronization of devices according to standard.

2. **In Chapter III**, Firstly, we discuss the data rates for 802.15.13 standard and important point for the network throughput optimization. We divide data rates into two separate parts, Physical and MAC Layer data rates. This sections provide description of some simulation parameters in terms of mathematical expressions. Depending of these expressions, It describes the relation of the MAC and PHY Layer data rates and throughputs. Then, based on expressed simulation parameters, We analyse the network behaviour by making some series of simulations. Finally, We propose an algorithm to optimize network throughput depending of the analysis. Then, we present series of additional simulation results to support proposed algorithm improvement.

CHAPTER II

802.15.13 OPTICAL WIRELESS PERSONAL AREA NETWORK

2.1 Introduction

802.15.13 defines a PHY and MAC layer which are using light wavelengths ranges between 10 000 nm and 190 nm in optically transparent areas for communications. The standard has capability to deliver data rates up to 10 Gb/s at distances in the range of 200 m clear line of sight. It's design is developed for point to point and point to multi point communications in the non-coordinated and coordinated topologies. There will be a master coordinator for coordinated topologies with more than one peer coordinator. The standard includes adaptation to changing channel conditions and maintaining connectivity when moving within range of a single coordinator or between coordinators. [1].

The standard purpose is defining the specifications of Optical Wireless Communications (OWC) in an optically transparent areas that allow high data rate transfer between endpoints at speeds of up to 10 Gb/s and up to 200 m of optically clear field lines.

2.2 Components of IEEE 802.15.13 Networks

An OWPAN constitutes of standard-compliant devices. Devices carry a 48-bit MAC address for identification and flat addressing in the network. During association with the network, 16-bit short addresses are allocated to devices.

Devices constitute of a standards-compliant MAC implementation and make use of a compliant PHY defined in the standard. Not all devices are required to implement functionality to maintain an OWPAN. Devices, which support that functionality, are also referred to as coordinator-capable devices or coordinators if they actively maintain an OWPAN.

In each OWPAN, a single coordinator-capable device assumes the role of the coordinator. The coordinator is responsible for starting, maintaining and finally stopping the OWPAN. The coordinator is furthermore involved in all data transmissions in the OWPAN.

Non-coordinator devices, hereafter simply referred to as devices, implement less functionality than coordinators. Devices associate with an OWPAN in order to gain layer 2 connectivity with the network.

Each OWPAN needs an identifier. This OWPAN identifier provides communication between devices within a network using short addresses. The mechanism for selecting OWPAN identifiers is beyond the scope of this standard.

2.3 Network Typologies

The IEEE 802.15.13 optical wireless personal area network (OWPAN) standard implements its applications to four topologies: peer-to-peer, star, broadcast, and coordinated, as shown in Fig. 5. Also, as shown in Fig. 6, two advanced networking functions of OWC and Radio Frequency (RF) are supported, transitive and heterogeneous networking. In star topology, communication is established between devices and a single central controller. coordinator. For a peer-to-peer topology, one of the two devices in an association takes on the role of coordinator. One of the two devices in an association takes on the role of coordinator. In coordinated topology, multiple devices communicate each others with multiple coordinators coordinated by a master coordinator. The master coordinator is connected to each coordinator via a backhaul link. Note that the functionality of the master coordinator is not part of this standard. In addition, two advanced network functions can be enabled as relaying and heterogeneous RF-OWC. An intermediate relay node is added between the coordinator and the device with the transfer function. Data transmission over an optical wireless link can be combined with a parallel radio-based wireless link with heterogeneous RF-OWC functionality. Each device, coordinator and relay node have an unique 48-bit MAC address. When a device is associated with a coordinator or relay, it can allocate

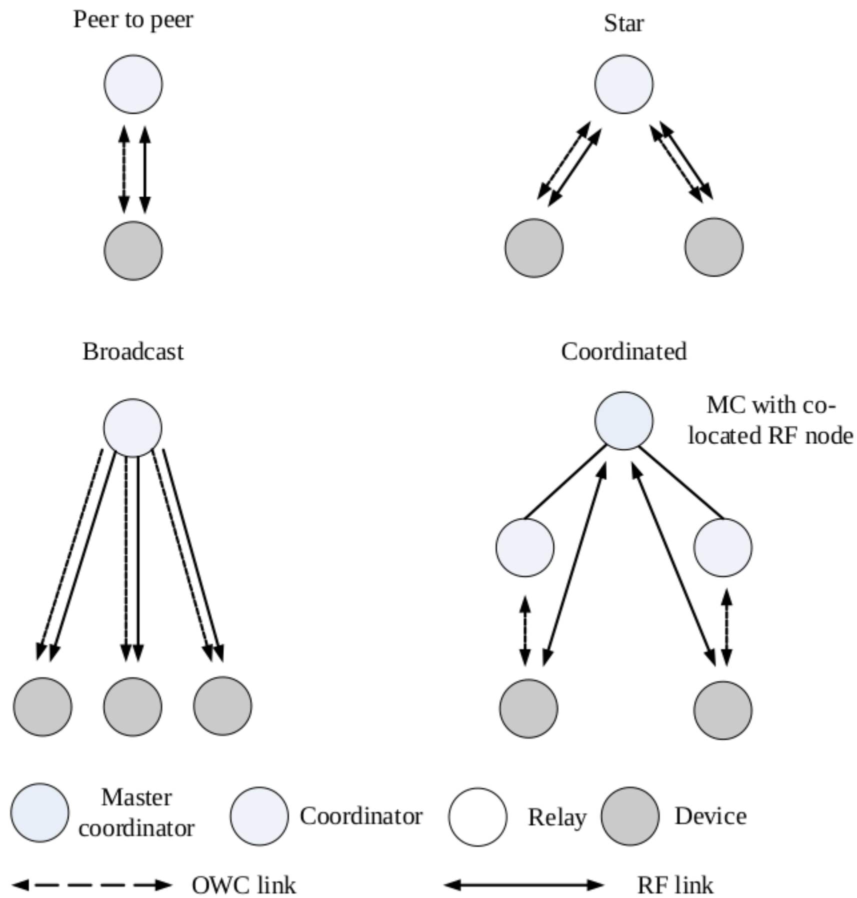

Figure 5: 802.15.13 Supported Topologies.

a short 16-bit address by coordinator. Both short and MAC addresses can be used for communication within the OWPAN. The coordinator, relay node, and master coordinator usually mains powered, while devices usually uses battery power. Star topology is used to realize different physical topologies depending on the application.

2.3.1 Peer-to-peer Topology

Per-to-peer topology is shown in Fig. 5. Each device can communicate with any other device within range in a peer-to-peer topology. One of the peers acts as the coordinator.

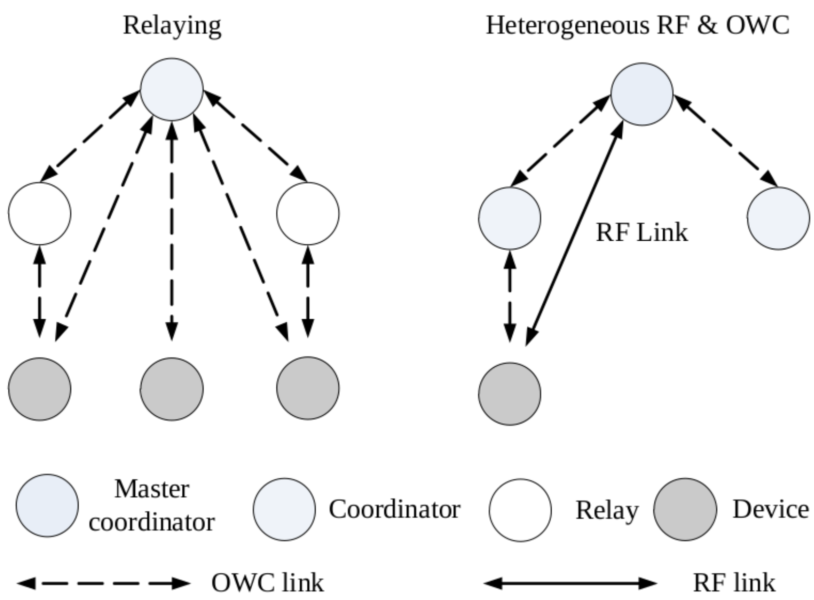

Figure 6: Advanced Functionalities.

2.3.2 Star Topology

Star topology is shown in Fig. 5. All star networks operate independently of any other currently operating star networks. It is achieved by selecting an OWPAN unique identifier that means it is not used by any other network within its coverage area. When the OWPAN identifier is selected, the devices can join to the network.

2.3.3 Broadcast Topology

The broadcast topology is shown in Fig. 5. The device can transmit a signal to other devices without creating a network in broadcast mode. Transmission is in the one-way and there is no destination address.

2.3.4 Coordinated Topology

The coordinated topology is shown in Fig.5. Multiple coordinators are connected to each other and to the master coordinator over the backhaul network in the coordinated topology. Multiple OWPANs are coordinated by a master coordinator. The master coordinator may

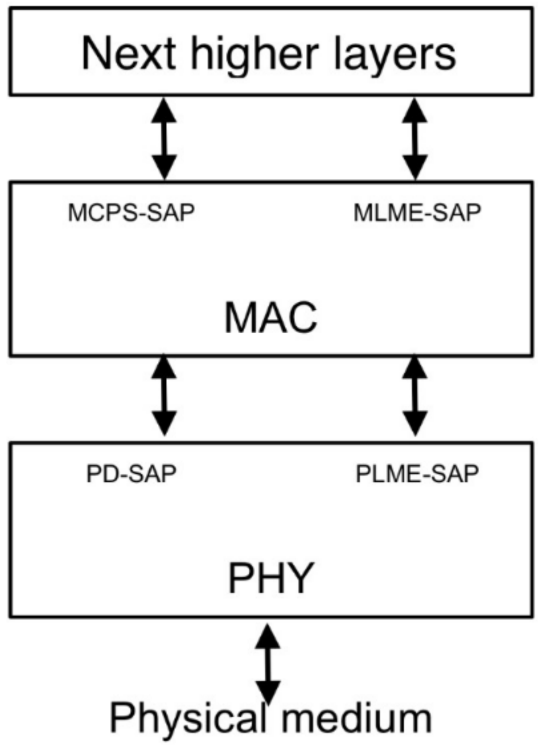

Figure 7: System Architecture.

be responsible for various types of coordination among multiple OWPANs, eg. transmission, enterprise management, OWPAN status monitoring, etc. There may be a need for synchronization between multiple coordinators, which can be provided over the backhaul network via the main coordinator for coordinated operation.

2.4 Architecture

To simplify the standard, The IEEE 802.15.13 architecture is described as a set of layers and sublayers. Each layer is responsible for a section of the standard and provides necessary services to higher layers. The interface between the layers provides to describe the logical connections defined in this standard. An OWPAN device consists of a PHY layer that includes the optical wireless transceiver along with low-level data, control and management mechanisms, and a middle access control (MAC) layer that provides access to the physical channel for all such transmissions. Fig. 7 shows the presentation of these layers.

The higher layers consist of a network layer, which provides network configuration, manipulation, and message routing, and an application layer, which provides the intended function of the device. The definition of these upper layers is outside the scope of this standard.

2.4.1 PHY Layer

The PHY layer supports multiple PHY types.

- Pulsed Modulation (PM-PHY): This PHY type is intended for moderate data rate applications. This mode uses 2-PAM modulation and 8B10B line coding or M-ary Pulse Amplitude Modulation (PAM)in combination with Hadamard-coded modulation (HCM) with data rates from 1 MB/s to several hundrets of Mb/s.
- low bandwidth OFDM PHY (LB-PHY): This PHY is intended for low rate applications with data rates in the tens of Mb/s using bit-interleaved coded OFDM modulation.
- high bandwidth OFDM PHY (HB-PHY): This PHY is intended for high rate applications with data rates data rates from 10 Mb/s up to multiple Gb/s using OFDM modulation with adaptive bitloading.

The PHY layer receives PHY service data unit (PSDU) from the MAC layer and converts them to corresponding physical-layer data unit (PPDU). It subsequently passes the PPDU, consisting of signal samples, to the optical front end (OFE).

After the medium-access-control service-data unit (MSDU) is passed through the service access point (PD-SAP) and becomes the PHY service data unit (PSDU) at the input of the PHY layer. it is processed with the various PHY blocks such as channel coding, line coding and modulation.

The PSDU is beginning with a synchronization header (SHR). It is containing the preamble sequence field; and a physical-layer header (PHR) that also contains the length

Preamble	Channel Estimation	PHY header	HCS	Optional Fields	PSDU
SHR		PHR			PHY Payload

Figure 8: PPDU Format.

of the PSDU in octets. The preamble sequence provides to achieve synchronization for receiver. The SHR, PHR, and PSDU together form the PHY frame or PHY layer data unit (PPDU).

For convenience, The PPDU frame structure is presented in such a way that the leftmost field is transmitted or received first, as written in this standard. The PPDU frame structure is illustrated in Fig 8.

2.4.2 MAC Layer

The MAC sublayer meets two services accessed via two service access point (SAP). MAC data is accessed via the medium-access-control common-part sublayer service access point (MCPS-SAP) supporting the MAC service defined in IEEE Std 802.1AC. The MAC data service enables the transmission and reception of medium-access-control protocol-data unit (MPDU) across the PHY data service. The MAC management is accessed through the medium-access-control link-management entity service access point (MLME-SAP). The features of the MAC sublayer are:

- association
- disassociation
- channel access
- frame validation
- acknowledged frame delivery

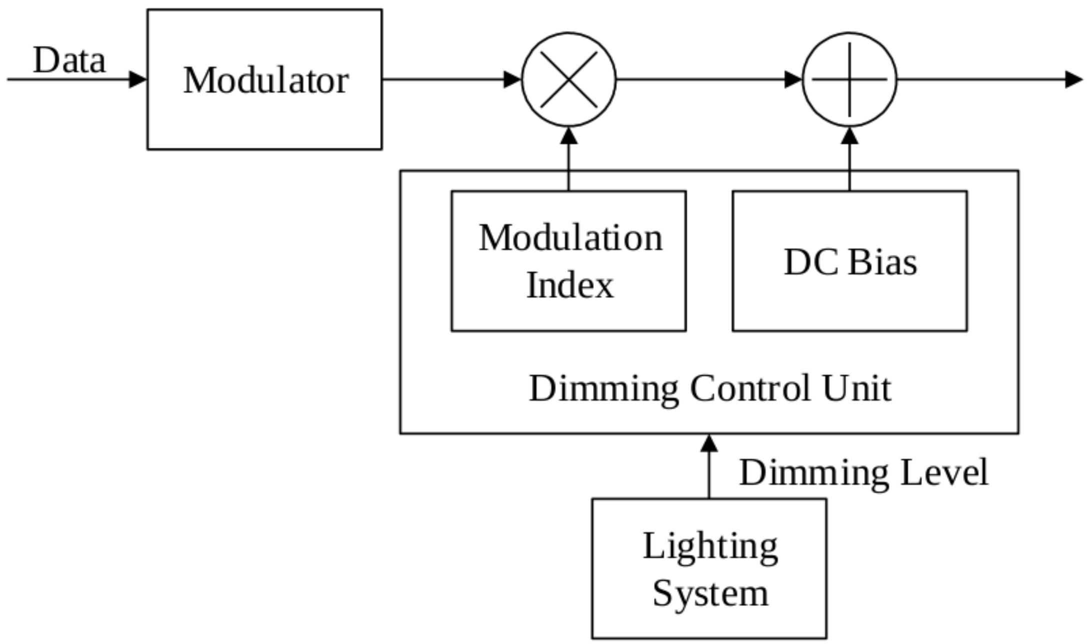

Figure 9: Dimming control through modulation index and DC bias.

Moreover, the 802.15.13 MAC supports the use of advanced MIMO schemes with distributed, networked optical wireless frontends and for multiple mobile devices.

In this standard, dimming is considered independent of the communication functionality. The receiver is not required to know what dimming level is used while communication is ongoing.Dimming can be controlled via a bias current, which is constant over time and orthogonal to the modulator output signal used for the data transmission (denoted as modulation signal). The OWC system is responsible for the modulation while the lighting system provides a dimming level, which is processed in a control unit being independent of the OWC system. The control unit can set both,the bias and the modulation index to achieve the required dimming level and to avoid clipping. Finally, the bias and the modulation are added, as shown in Fig. 9.

In this way, the receiver does not need to know the dimming level for decoding the data from the compound signal received after the PD, and if needed, the transmitter is free to set the dimming level independent of the receiver. Accordingly, there is no need for signaling fields telling the receiver the dimming level used at the transmitter, or an accordingly used parameter setting of the modulation scheme.

2.5 MAC Functional Overview

IEEE 802.15.13 OWPANs have characteristics that are not common in many other wireless networks, due tomdirectionality and visibility when using the visible optical spectrum. Unlike in radio frequency-basedm wireless networks, optical signals do not propagate through solid media such as walls. In addition, signals are significantly weaker outside the line of sight of the transmitter.

Procedures of MAC sublayer may be initiated by the MAC or the consequence of a MLME-SAP primitive invocation. The MAC makes use of the PHY service and is responsible for the following tasks:

- Performing channel access and transmission in correspondence with the OWPAN's configuration
- Starting and maintaining an OWPAN
- Associating with an OWPAN
- Disassociating from an OWPAN
- Fragmenting and reassembly of MSDUs
- Aggregating and de-aggregating MSDUs
- Adapting to alternating channel conditions

2.5.1 Data Transfer Model

Two types of data transfer transactions exist:

- **The data transfer from user to a coordinator;**

The transfer from a device to the coordinator happens in a coordinated way in both channel access mechanisms supported in the standard.In a beacon-enabled OWPAN, each device listens for the beacon before starting data transmission to a coordinator. The device synchronizes to the superframe structure by cathing the beacon. Device transmits its data frame to the coordinator without contention in the guaranteed time slot. The coordinator optionally acknowledges the reliable reception by transmitting an acknowledgment.

- **The data transfer from a coordinator to user;**

  Data transfers from the coordinator to the device may happen at all time. In full-duplex operation, devices are able to receive frames from the coordinator at all time. In half-duplex operation, devices only have to be ready for receptions while they are not transmitting, i.e. outside their guaranteed time slot (GTS) in beacon-enabled channel access mode and outside their polling request in the non-beacon-enabled channel access mode.

Direct communication between non-coordinator devices is not foreseen. The standard supports multiple optical clock rate (OCR). It also supports the use of asymmetric maximum clock rates between two devices since the transmitter and receiver in a device are independent and may support different OCRs. As an example, the coordinator may be able to use higher OCR than a mobile device. Coordinators are required to support all lower OCR besides their maximum supported OCR. In contrast, devices may be able to support only a single OCR or few selected OCRs. The set of optical clock rates for communication is negotiated using the MAC and communicated to the device in each PPDU header.

An OWPAN can operate in beacon-enabled mode. Depending on which mode is used by the coordinator, channel access is performed in different ways. However, the remaining transmit and receive process are the same, regardless of the applied channel access mechanism.

Within the OWC MAC, each device shall be addressable through a 48-bit MAC address compatible with IEEE Std. 802-2014 (EUI-48). In addition, a 16-bit short address is issued to each device as part of the association process. The allocation of short addresses is at the discretion of the coordinator implementation. The short address 0x0000 shall always belong to the coordinator. Furthermore, the address 0xffff shall be regarded as the short broadcast address and hence received by all devices. It shall not be allocated to an associating device.

For each associated device, there is a 1:1 correspondence between short addresses and its MAC addresses. The two types of addresses may be used interchangeably where appropriate. The 48-bit broadcast address 0xffff ffff ffff shall correspond to the short broadcast address 0xffff; Each OWPAN is identified through its OWPAN ID. The OWPAN ID corresponds to the MAC address of the coordinator.OWPANs in broadcast mode shall make use of the OWPAN ID 0xffff ffff ffff.

The transmit process starts when the MAC receives an MSDU through the MCPS-SAP or when the medium-access-control link-management entity (MLME) requests transmission of a management frame. The transmit process is illustrated in Fig. 10.

A device prepares MPDUs for transmission in accordance with the requirements of the channel access mode. This includes generation of the appropriate header fields and limiting the MPDU size to the maximum available transmission time. In addition, a transmitting device shall ensure that the MPDU size does not exceed the maximum supported PSDU size of the PHY.

MPDU generation process involves optional aggregation of multiple MSDUs. The MSDUs may optionally be fragmented. For protected transmission, sequence numbers may be assigned to MPDUs. Finally, the channel access mechanism applied in the OWPAN, regulates when to hand the resulting MPDU to the PHY for transmission over the medium.

After a PSDU was successfully received by the PHY, the corresponding MPDU enters the MAC through the PD-SAP. The receive process is illustrated in Fig 11.

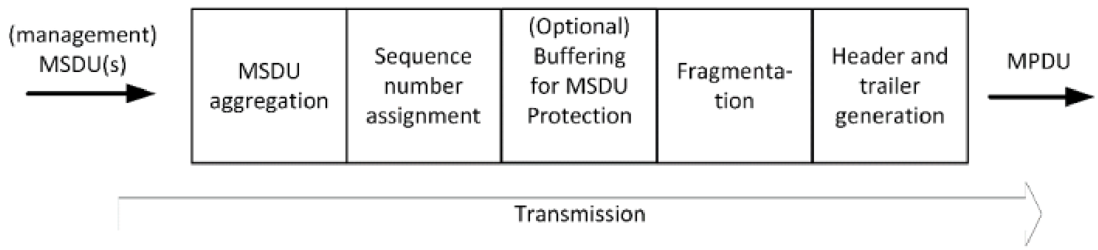

Figure 10: The MAC Transmit Process.

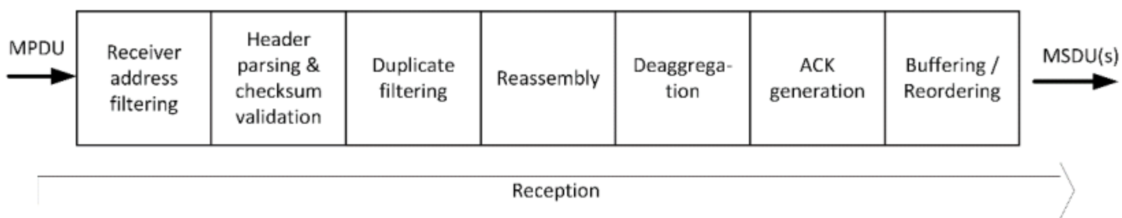

Figure 11: The MAC Receive Process.

The MAC shall filter frames based on the included receiver address. It shall discard all frames that have a receiver address that does not belong to the device or the broadcast receiver address. The MAC shall also discard data and management frames that do not belong to its associated OWPAN. Each device shall receive MPDUs with the OWPAN ID and destination address set to the broadcast address.

The MAC then shall check the integrity of the frame based on the frame check sequence (FCS) field included in the frame. If the frame contains errors, the MAC shall discard the frame. The MAC shall discard frames that have an unsupported Frame Version in their Frame Control element.If the frame indicates that it contains a fragment, the MAC shall buffer the frame and perform reassembly according to 5.5. Subsequently, it shall perform deaggregation, if the frame contains aggregated MSDUs.

The MSDUs of protected frames from a single transmitter shall be passed to the upper layers in order. The MAC shall discard duplicate protected MPDUs. Finally, the MAC shall generate an acknowledgment for each successfully received protected MPDU.

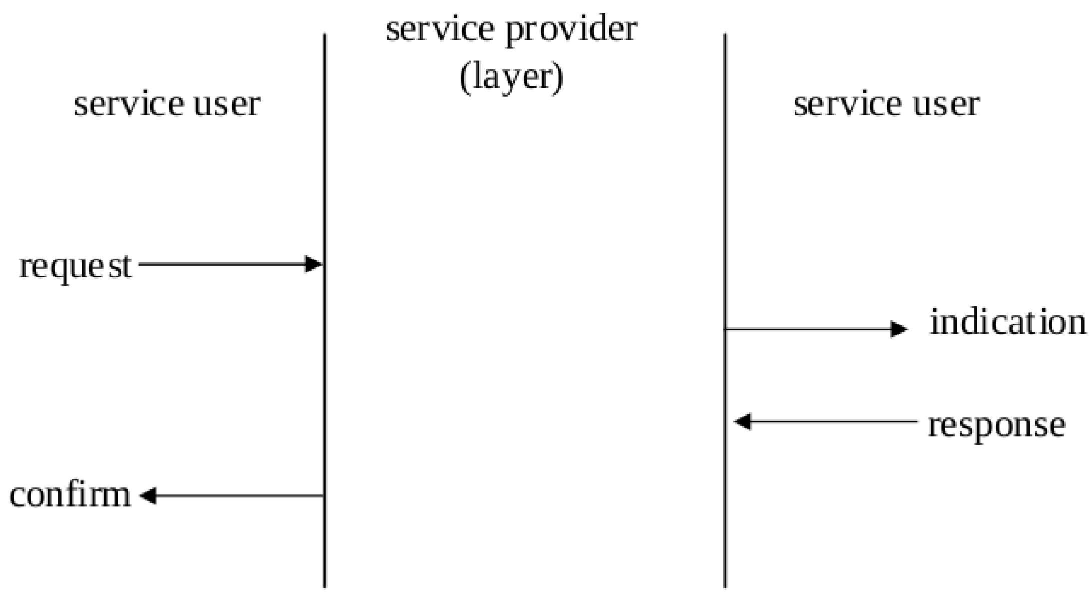

Figure 12: Service Primitives.

2.5.2 Concept of Primitives

This concept is shown in Fig 12. The services are specified by describing the information flow between the user and the layer. This flow of information is modeled by discrete, instantaneous events. Each event consists of passing a service primitive from one layer to another via a layer service access point (SAP) associated with a user. Service primitives convey the necessary information by maintaining a particular service. These service primitives are an abstraction because, they just describe the service, rather than the means delivery. The definition is independent from interface implementation.

Each service primitive may have zero or more parameters that convey the information required to provide the service. A primitive can be one of the following types;

- Request: is used to request a service to do a job.
- Confirm: is used to convey the results of requests.
- Indication: is used to indicate an event the next higher layer

- Response: is used to complete a procedure previously invoked by an indication primitive.

2.5.3 MAC Frames

The frame structures is designed to keep the complexity to a minimum. It is also providing the error protection for transmission over a noisy channel. The MAC frames are seperated into three types. These are follows;

- data frame: is used for all data transfers.
- management frame: is used for all data transfers which are about OWPAN management of the network.
- control frame: is used for all data transfers which are about controlling the delivery of data.

802.15.13 standard defines a single general MAC frame format, occurring in multiple variants depending on what information is carried in the frame. For discrimination and subsequent interpretation, each MAC frame starts with a Frame Control element, indicating a Type and Subtype of frame. Currently, three basic frame Types for the transmission of data, management and control information are supported. 3 Data, management and control frames have distinct MAC headers.

The payload in turn differs for different Subtypes of data, management or control frames. It contains the actual information to be conveyed via the MAC frame. For data frames, this may be one or multiple MSDUs received via the MCPS-SAP for transmission. For management frames, the payload constitutes of management information. Analogously, the payload of control frame comprises control information, aiding the MAC in its operation. Each MAC frame shall end with the FCS field, containing a 32-bit cyclic redundancy check (CRC) sum over all preceding information bits of the MAC frame. The general MAC frame structure is depicted in Fig. 10.

Octets: 2	**0/2**	**2/6**	**2/6**	**0/2/6**	**0/2**	**variable**	**4**
Frame Control	Poll ACK	Receiver Address	Transmitter Address	Auxiliary Address	Sequence Control	**Payload**	**FCS**
MAC frame header (MHR)							

Figure 13: 802.15.13 MAC Frame Format.

2.6 Channel Access Mechanism

IEEE 802.15.13 OWPANs use different types of channel access mechanism, depending on the network configuration. Beacon-enabled OWPANs use a beacon, a slotted random channel access mechanism in the contention access period (CAP) and a deterministic channel access mechanism in the contention-free period (CFP). Note that the CAP is only used for association purposes. Acknowledgment frames are always sent during the CFP. Non-beacon-enabled OWPANs use unslotted channel access mechanism in general, starting with a control period normally followed by data period. Association is done during the control period. In the data period, the device is polled for transmission by the coordinator. Acknowledgment frames are sent in the next available frame for which a particular device has been polled.

If an OWPAN operates in beacon-enabled channel access mode, channel time is divided into superframes. Each superframe is composed of three major parts: a beacon transmission, a Contention Access Period (CAP) and the Contention Free Period (CFP). Transmission of the beacon by the OWPAN coordinator. In the CAP, devices may access the channel randomly by means of slotted ALOHA. Random channel access in the CAP is only allowed for specific procedures and frame types. All other frame transmissions happen in the CFP. The CFP consists of reserved resources, called GTSs, which are assigned to each device for a given superframe. The coordinator schedules and announces GTS allocations.

2.6.1 Superframe Structures

A superframe consists in total of macNumSuperframeSlots superframe slots. macNumSuperframeSlots is a variable determined by the OWPAN coordinator and announced to the devices in the beacon frame. The maximum number of superframe slots within a superframe is 65535. Each superframe slot has a duration of aSuperframeSlotDuration. The number of superframe slots and their respective duration determine the total duration of each superframe.

The standard makes use of integer numbers of superframe slots to specify durations within the superframe. That can be durations of the CAP, CAP slots, GTS and other subparts of the superframe. Each OWPAN coordinator defines the superframe structure for its coordinated OWPAN. Consecutive superframes of an OWPAN do not necessarily have to be adjacent but may have channel time between them that is not used by the OWPAN. In the coordinated topology, the master coordinator determines when the superframe of each OWPAN starts and how long it is. The details of the coordinated topology are outside the scope of this standard. Of the macNumSuperframeSlots superframe slots in a superframe, three consecutive slot groups are used for the beacon transmission, the CAP and CFP respectively as shown in Fig. 14. The number of superframe slots reserved for the beacon transmission depends on the length of the beacon frame. The length of the CAP is determined by the OWPAN coordinator and may change from superframe to superframe. The remaining slots in the superframe are used for the CFP and can be used for frame transmissions between the devices and the coordinator.

2.6.2 Beacon Transmission

In the beacon-enabled channel access mode, the coordinator shall transmit a beacon at the beginning of the superframe. Beacons should be transmitted with a constant periodicity when possible.

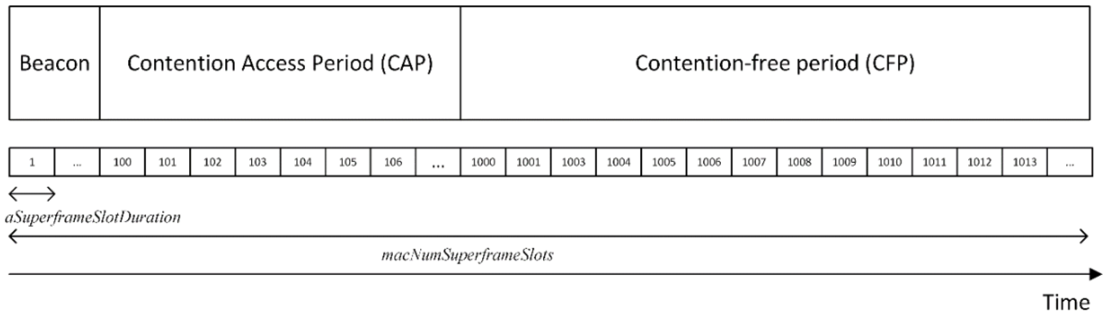

Figure 14: Super Frame Structure.

The beacon frame is a control frame having the Superframe Descriptor element as payload. The Superframe Descriptor element may include additional elements in the embedded Variable Element Container element.

The coordinator shall maintain the macBeaconNumber physical-layer personal-area-network information base (PIB) attribute and increment it by one for every started superframe and corresponding beacon transmission. The macBeaconNumber value wraps to 0 after reaching the maximum value given in the standard.

The coordinator shall embed the current macBeaconNumber into the Superframe Descriptor element of each beacon. Upon reception of a beacon frame, each associated device shall set their value of the macBeaconNumber attribute to the value in the received beacon frame.

Upon reception of a beacon frame, devices shall synchronize their clocks to the received beacon frame. Moreover, devices which are either associated with the corresponding OWPAN or attempt to associate with the given OWPAN shall set their macNumSuperframeSlots, macCapSlotLength attributes of the MAC to the values contained in the received Superframe Descriptor element.

When multiple OFEs are used by the coordinator, the beacon frame shall be transmitted over all OFEs simultaneously. If the coordinator supports the capMultiOfeEstimation capability, it shall embed multi-OFE pilots in the beacon frame.

Devices shall expect the next beacon reception directly after the superframe. If no beacon frame is detected, devices shall keep listening for the next beacon frame in order to synchronize before attempting further transmissions.

2.6.3 Medium Access in the CAP

The CAP shall start with the superframe slot following the beacon and end before the beginning of the CFP on a superframe slot boundary. The length of the CAP macNumCapSlots is advertised in the CAP Slots field of the Superframe Descriptor element contained in each Beacon frame. Both CAP and CFP periods may shrink or grow dynamically on a superframe-by-superframe basis in order to allow more random access transmissions in the CAP or more scheduled ones in the CFP.

The slotted Aloha scheme is used for contention-based access in the CAP. The superframe slots in the CAP are grouped in so-called CAP slots, which comprise macCapSlotLength superframe slots each. The number of superframe slots per CAP slot determines the slot size for the slotted Aloha scheme and hence the effectiveness of collision prevention. macCapSlotLength is advertised in each beacon frame.

A device willing to transmit a frame in the CAP shall choose a random number of CAP slots RS ("Random Slots") uniformly distributed from [0, max(CW, CAP slots in current superframe - 1))], where CW ("Contention Window") is equal to aInitialCapCw for the first attempted transmission. Random number generators of all devices shall be statistically uncorrelated. Subsequently, the device shall wait for RS CAP slots before attempting transmission. The waiting process may extend over multiple superframes, until a total of RS CAP slots have passed. The transmission shall then be performed at the starting boundary of the next CAP slot.

Transmissions in the CAP may not be acknowledged like other frames. If a device implicitly detects that a CAP transmission was not successful, e.g. by the fact that the expected response is never received, the device shall increment the variable rety count (RC) one. RC shall initially be 0. How to detect an unsuccessful CAP transmission depends on the specific procedure. The CAP transmission shall ultimately be given up, once RC exceeds macCapMaxRetries.

For every failed transmission, the device shall double CW before attempting retransmission of the frame in the CAP. However, CW should not exceed aMaximumCapCw. For the retransmission, the device shall then wait again for a random slot (RS) of CAP slots , drawn from [0, max(contantion window (CW), CAP slots in current superframe - 1))] and pursue retransmission at the start of the following CAP slot.

Following a CAP transmission, a device shall be continuously listening in the CFP in order to receive a potential response to the frame transmitted in the CAP.

The process of CAP transmission is visualized for the association and resource request procedure in Fig.15 and Fig. 16 respectively.

The CAP shall only be used for frame transmissions in the:

- **Association Procedure:** As a device does not have GTS assigned prior to association, the association request frame must be transmitted in the CAP. Hence, the requesting device begins the CAP transmission procedure after preparing a frame containing the Association Request element. If the device supports the capMultiOfeEstimation capability, it shall include a Multi-OFE Feedback element, containing the CSI obtained from the latest beacon frame reception in the same frame. If the beacon does not contain additional multi-OFE channel estimation pilots, the device shall not include the Multi-OFE Feedback element. A flow chart of the association request procedure is given in Fig. 15. After transmitting the Association Request element, the device shall continue to listen for an Association Response element from the coordinator for at least macAssociationTimeout. If no Association Response element is received within this time, the device may reattempt association through sending the Association Request element again. A device shall not attempt association more than macCapMaxRetries automatically.

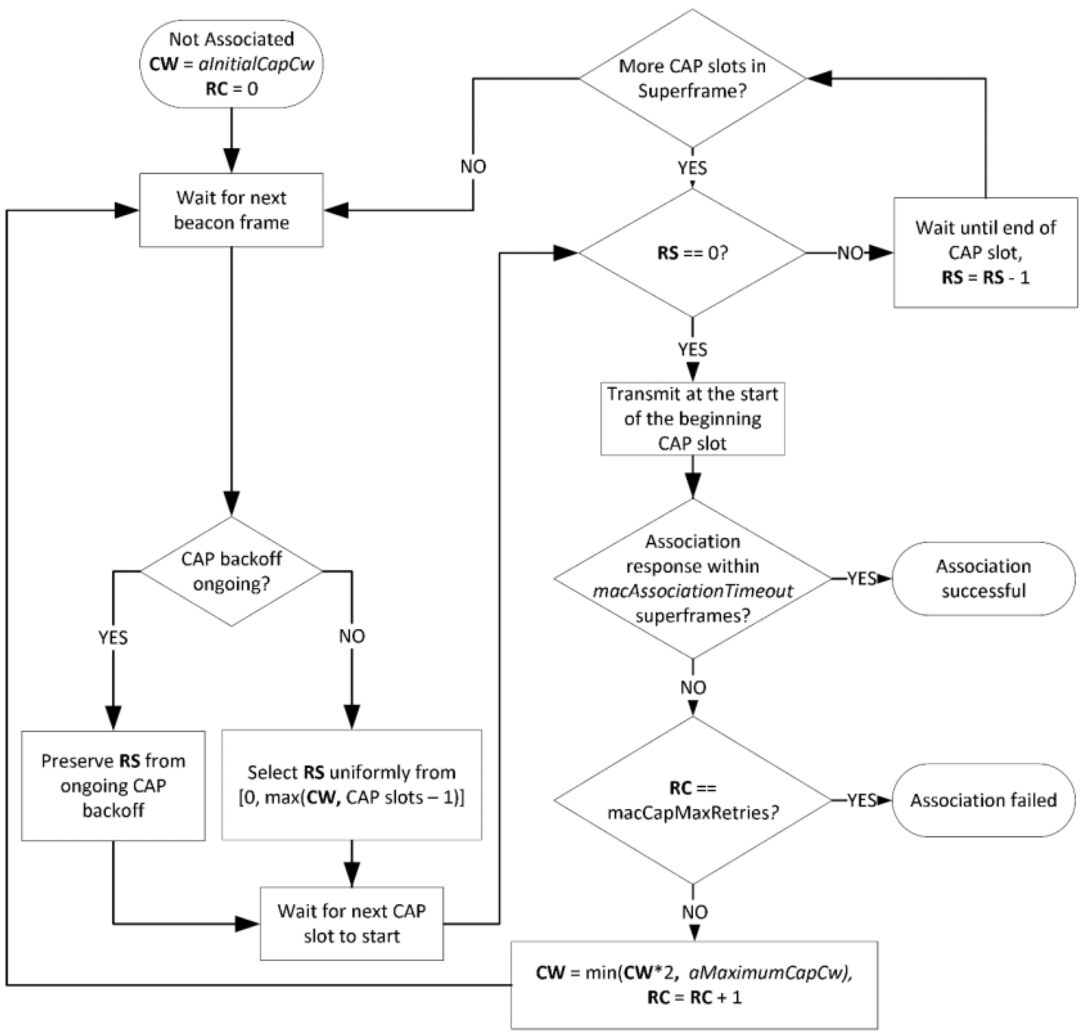

Figure 15: Association Procedure Flowchart.

- **Resource Request Procedure:** Typically, devices shall request additional resources in the CFP. However, when a device does not have any or only insufficient GTS time allocated for to perform a resource request, it may make use of the CAP to transmit a resource request to the coordinator. For example, this may be the case after the connectivity from coordinator was interrupted and the coordinator stopped allocating GTSs for the device. In that case, the device may transmit a control frame containing the GTS Request element in the CAP to signal the requirement for GTS time to the coordinator. If the capMultiOfeEstimation capability was negotiated during association, the control frame shall include the Multi-OFE Feedback element, containing the multi-OFE CSI obtained from the latest beacon frame reception. After transmitting the resource request, the device shall await updated GTS allocations from the coordinator. If the device does not receive sufficient GTS resources after superframes, it shall consider the resource request failed. In that case, it may transmit a new resource request. The flow chart for the resource request procedure is depicted in Fig 16.

2.6.4 Medium Access in the CFP

Channel access in the CFP is based on a dynamic Time Division Multiplexing Access (TDMA) principle. Superframe slots can be reserved on a per-device basis in order to allow contention-free medium access. A group of adjacent superframe slots that is reserved for a specific device is called guaranteed time slot (GTS). The first superframe slot and a duration, given in an integer number of superframe slots, define the position of a GTS in the superframe as described in 6.6.7. GTS shall only reside within the CFP. A device shall keep a list of all its upcoming GTS after it received the corresponding GTS Descriptor element. A device shall only transmit in GTS that were assigned to it.

Devices should ensure that transmitted signals do not interfere with transmissions in other GTS at any other device. This includes, for example, regarding for the total transmit delay introduced by the used PHY and the assumed propagation delay and range. A device

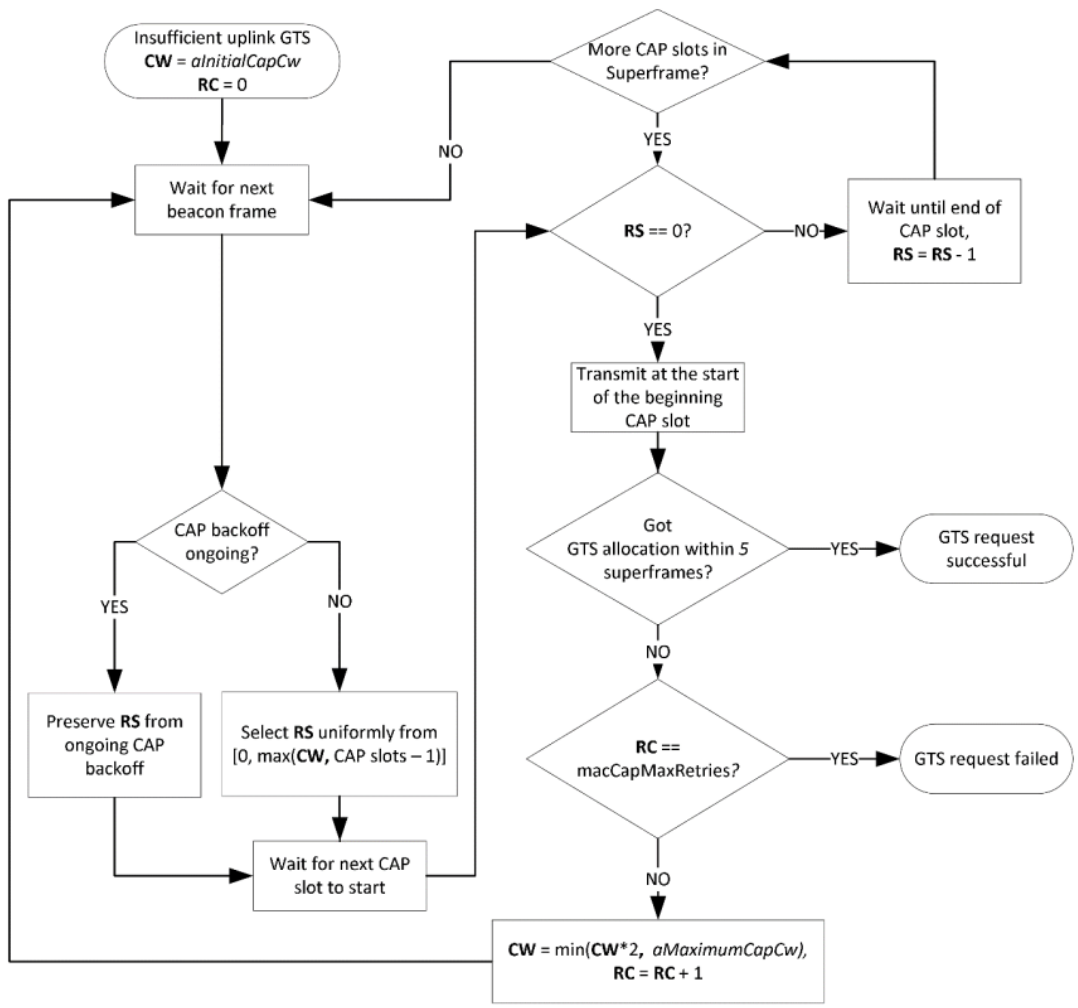

Figure 16: Resource Request Procedure Flowchart.

shall ensure that its transmissions adhere to the rules for interframe spaces. A device with a GTS may or may not make use of all the allocated time duration within the GTS. The selection of an MPDU for transmission is determined locally by the device depending on the number of pending frames in its queue and the value of their user priority fields and potentially other criteria. The coordinator may perform transmissions to a device at any point in the CFP. If the capFullDuplex was negotiated during association, devices shall enable the receiver within the whole superframe. Otherwise, the connection is assumed to be half-duplex. In that case, devices shall enable their receiver outside their own GTSs.

2.6.5 GTS Allocation and Signalling

Only the OWPAN coordinator is entitled to allocate GTSs. Any allocated GTSs shall be located within the CFP. If the coordinator has control over multiple spatially distributed OFEs, it may allocate the same superframe slots in different GTS for multiple spatially distant devices in order to facilitate spatial reuse of resources throughout the OWPAN's coverage area. However, the coordinator must ensure that transmissions from and to devices that share the same superframe slots do not interfere and the interference does not lead to packet losses.

Devices aid the coordinator in the GTS allocation process through providing information about their queue states. For that purpose, devices may transmit GTS Request elements to the coordinator. Devices aid the coordinator at allocating GTSs in an interference-free manner through providing information about the signal strengths by which they receive the nearest OFE. For this purpose, devices shall transmit Multi-OFE Feedback elements to the coordinator if the capMultiOfeEstimation capability was negotiated during association.

The coordinator may move GTSs within the superframe on a superframe-by-superframe basis. This allows the coordinator the flexibility to rearrange GTS assignments, optimize the utilization of resources and prevent collisions of GTSs if visibility and signal strength varies among OFEs and devices due to mobility.

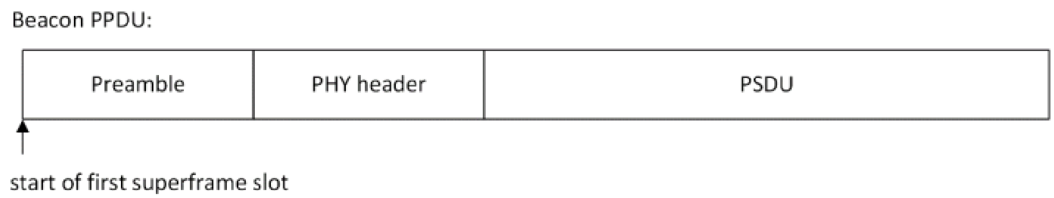

Figure 17: Timing Relative to the Beacon Frame Reception at Every Device.

GTS allocations shall be signalled from the coordinator to the corresponding devices via control frames including GTS Descriptor elements or GTS Descriptor List element. These control frames shall be unicasts and only be received by the devices for which the GTS allocations are designated. Devices shall infer that a GTS allocation belongs to themselves based on that receiver address. A GTS allocation is only valid for one superframe

2.6.6 Synchronization

All devices, whether they are associated with a beacon-enabled OWPAN or attempting association, shall be synchronized to the coordinator's clock before they start transmission or reception. The beacon sent at the beginning of every superframe enables synchronization of the devices in the beacon-enabled OWPAN through time of arrival synchronization.

Each device in the OWPAN, including the coordinator, shall begin counting the first superframe slot at the beginning of the PHY preamble of the beacon, as shown in Fig. 17. All superframe slots and hence timings within the superframe are thus relative to the start of the beacon preamble.

A compliant device implementation shall maintain the accuracy of the local time to be at least as accurate as aClockAccuracy.

2.6.7 Interframe Spaces

The only inter frame space (IFS) defined by this standard is the Turn Around Interframe Space (TAIFS). The TAIFS is required to ensure sufficient turnaround time between transmissions. The turnaround time is defined as the maximum time a transceiver requires to switch from transmitting to being ready to receive or from receiving to starting a subsequent transmission. A transmitter has to ensure that its transmissions end at least a TAIFS before the end of the GTS in order to enable all receiving devices to utilize fully their GTSs from the beginning. The TAIFS shall be at least the maximum expected turn-around time as defined for each PHY.

If a device is able to ensure that all other devices are able to transmit and receive orderly in their GTSs, for example because they implement the capFullDuplex capability and full-duplex operation was negotiated during association, it may disregard the requirement to finish transmissions at least a TAIFS before the end of its GTS. In that case, TAIFS may be set to 0.

Spaces between successive transmissions of a single transmitter are not strictly required. Receivers are expected to be able to process incoming frames fast enough to handle subsequent transmissions without interruption.

In a TDMA system, guard times are required to keep transmissions in adjacent GTS from colliding when local clocks of devices are imperfectly synchronized, e.g. through drift caused by frequency inaccuracy of local oscillators in devices. A GTS is defined by the start time and the duration, as specified in the GTS Descriptor element. Guard time is the time between the end of one GTS and the start of the next GTS. Guard time is counted in superframe slots. For that purpose, the guard time shall be rounded up to the next integer number of superframe slots.

Fig. 18 depicts an illustration of the guard time such that consecutive transmissions are always separated by at least a TAIFS if the owners of adjacent GTS have drift towards the other GTSs.

The required guard time depends on the $T_M D$ denotes maximum drift between a device's local time and the ideal time. This drift is a function of the time elapsed since a synchronizing reference event, i.e. the beacon reception, and the precision of local oscillators in OFEs and devices defining the local sampling clock. In an IEEE 802.15.13 OWPAN,

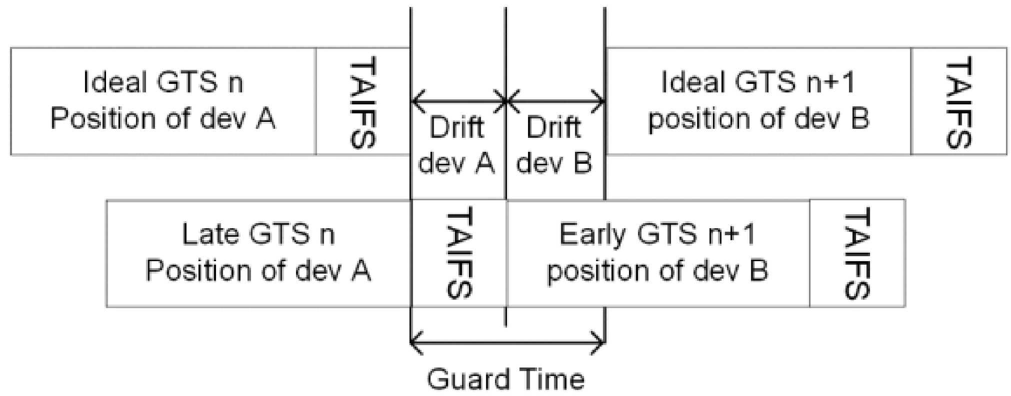

Figure 18: Application of the Guard Time and TAIFS Between Adjacent GTSs.

the synchronizing event is the start of the preamble of a beacon. The maximum drift can be calculated as $T_{MD} = C/T_{Sup}$ where T_{Sup} denotes suoerframe duration and C denotes the clock accuracy.

The clock accuracy depends on the device implementation but shall not be worse than the value given by the aClockAccuracy PIB attribute. The superframe duration is the current duration of the superframe and hence periodicity of the synchronizing event.

The synchronization accuracy describes how accurately the devices can be synchronized to the coordinator's clock. This value depends on the coordinator implementation and shall be determined by the vendor. The value shall also include the uncertainty introduced through the varying propagation time of the beacon frame, based on which the synchronization is performed. The coordinator shall ensure that a guard time of at least $2\,(T_{MD} + S_A)$ lies between two subsequent GTS that are not orthogonal in space, where S_A is synchronization accuracy

CHAPTER III

THROUGHPUT ANALYSIS AND OPTIMIZATION

3.1 Introduction

802.15.13 MAC protocol uses ”slotted Aloha” and ”reserved dynamic time slots” protocols simultaneously to provide the required quality-of-service (QoS) by resource reservation and achieve high resource utilization with multiplexing gain during the contention periods. However, reservation operation can significantly affect the behavior of the network. How to split time between reservation periods with reserved time slots and how to determine the number of reservation slots are crucial tasks of 802.15.13 MAC Network Coordinator.

The IEEE 802.15.13 MAC superframe consists of a contention access period (CAP) and a contention free period (CFP). In the CAP, each node transmits its packets to the coordinator using slotted Aloha protocol through contention with the other nodes. On the other hand, in the CFP, each node transmits its packets to any device in the network by using the guaranteed time slots (GTSs) dedicated to itself. In order to transmit packets in the CFP, a node transmits a request packet to the coordinator during the CAP. If the coordinator successfully receives the request packet, it allocates the GTS to the node according to its buffer or queue. Therefore, the performance of the CAP and that of the CFP are related to each other.

For the network coordinator, defining CAP duration is vital for the network data rate optimization. The CAP duration affects packet drop rate and total throughput. The coordinator has to define the total number of CAP slots according to user numbers in the network. And then, it can decide the maximum CFP slots which can be assigned for each user according to the queue length of devices. High CFP slot numbers also cause more buffer and latency but more throughput. Thus, CFP duration is also vital for overall performance. In this work, we investigate how those period lengths and time slot numbers should be determined and optimized by the coordinator. According to a series of simulations, we further propose a heuristic algorithm to improve total network throughput efficiency.

3.2 IEEE 802.15.13 Data Rates

In this section, we present the 802.15.13 MAC and physical (PHY) layer data rates and underlying modulation and coding schemes. In all simulation scenarios, the Physical Layer configuration parameters affect the MAC Layer throughput. The MAC Layer throughput changes according to the environmental factors, network data traffic, and Physical Layer configuration.

MAC and PHY data rates are related, but different from each other. In this section, we examine PHY and MAC data rate relations.

3.2.1 Physical Layer Data Rate

To calculate the data rates at MAC layer, we need to start our analysis from the PHY layer. In 802.15.13 standard, Physical Layer data rates depends on the OCR (Optical Clock Rate), and modulation order according to the suitable SNR value of the user. Optical Clock Rate is the frequency at which the data is clocked out to the optical source. The standard supports multiple Optical Clock Rates (OCRs) to accommodate a wide variety of optical sources and receivers. In Table 1, OCR20 (20 MHz Optical Clock Rate) data rates are shown. Modulations of BPSK, QPSK, 16-QAM and 64-QAM are supported along with 1/2 and 3/4-rate convolutional coding.

Let N_{OFDM_i} denote the number of OFDM symbols for the user i^{th}, with I denoting the total number of users. Furthermore, let N denote the number of sub carrier in each OFDM symbol, and N_{cp} denote the length of cyclic prefix. The length of overall packet excluding both synchronization header (SHR) and Physical Layer header (PHR) for the i^{th} user is given as $N_{DOWN_i} = N_{OFDM_i}(N_{cp} + N)$. After pulse shaping, the total number of samples for the user in the frame is given by $N_{UP_i} = N_{DOWN_i}U$ where N_{UP_i} denotes the up-sampling factor.

Table 1: Supported OCR20 Physical Layer Data Rate and Throughput in Mb/s.

Mod.	Symbol	OCR20	Bits	Throughput
BPSK CC(1/2)	2046	6 Mb/s	24480	4,34 Mb/s
BPSK CC(3/4)	2046	9 Mb/s	36756	6,66 Mb/s
QPSK CC(1/2)	2046	12 Mb/s	49032	8,89 Mb/s
QPSK CC(3/4)	2046	18 Mb/s	73584	13,34 Mb/s
16-QAM CC(1/2)	2046	24 Mb/s	98136	17,78 Mb/s
16-QAM CC(3/4)	2046	36 Mb/s	147240	26,68 Mb/s
64-QAM CC(1/2)	2046	48 Mb/s	196344	35,58 Mb/s
64-QAM CC(3/4)	2046	54 Mb/s	220896	40,02 Mb/s

Out of N sub carriers, N_D data sub carriers are loaded with data. Each data sub carrier for the i^{th} user is loaded with $k_i = \log_2(M_i)$ with M_i denoting the selected modulation order for the i^{th} user. Let B_{Ti} denote the total number of transmitted data bits in a frame for the i^{th} user. The number of actual transmitted bits due to the punctured convolutional coding for the i^{th} user is then given as $B_i = B_{Ti}CC_i$ where CC_i is the code rate. The required number of OFDM symbols for the i^{th} user is therefore obtained as $N_{OFDM_i} = \lceil B_i/N_D \log_2(M_i) \rceil$.

Devices may require different number of symbols (N_{UP_i}) which depends on the selected modulation order of the i^{th} user and the selected code rate. This in fact requires assigning different time slots for different users. Let T_S denote the sampling time. Then the required time for transmitting one frame for the i^{th} user is given as

$$T_i = \left(\lceil B_i/(N_D \log_2(M_i)) \rceil\right)(N + N_{cp})U\ T_S. \tag{3.1}$$

Let D_{R_i} and F_{S_i} denote, respectively, the number of data bits per second (i.e., data rate) and number of frames per second for the i^{th} user. Noting $D_R = B_T F_S$, the required number of frames per second for the i^{th} user can be calculated as

$$F_{S_i} = D_{R_i}/B_{Ti}. \tag{3.2}$$

Further noting $F_{S_i} = 1/T_i$ and utilizing (3.1) and (3.2), we have $T_S = \min(\mathrm{T_{S_1}}, \mathrm{T_{S_2}}, ...\mathrm{T_{S_i}})$ where T_{S_i}, $i = 1,2,3...I$.

$$T_{S_i} = \frac{1}{F_{S_i} \lceil B_i \left(N_D \log_2 M_i\right) \rceil \left(N + N_{cp}\right) U}. \tag{3.3}$$

3.2.2 MAC Layer Data Rates

The MAC Layer will receive samples each T_S second. Based on quantization level of L (i.e., fixed point conversion), MAC layer will handle each T_s second, $\log_2(L)$ bits. The resulting MAC layer data rates depend on channel access mechanism and software implementation. There are three time periods as Beacon Period, CAP and CFP. The users only can send data in the assigned part of CFP for them. The total superframe duration is given by $T_{Total} = T_B + T_{CAP} + T_{CFP}$ where T_B denotes beacon period duration, T_{CAP} denotes CAP duration and T_{CFP} stands for CFP duration.

Every superframe is divided into time periods and also time periods are divided into slots. Every period duration can be therefore described in terms of time slots. Let S_B, S_{CAP}, S_{CFP} denote the slot numbers and $T_{S_B}, T_{S_{CAP}}, T_{S_{CFP}}$ denote the slot lengths. Beacon period duration, CAP duration and CFP duration are respectively given by

$$T_B = S_B \, T_{S_B}, \tag{3.4}$$

$$T_{CAP} = S_{CAP} \, T_{S_{CAP}}, \tag{3.5}$$

$$T_{CFP} = \sum_{1}^{N} S_{CFP} \, T_{S_{CFP_i}}. \tag{3.6}$$

The slot lengths are defined by the network coordinator and it may be redefined in every superframe. The Beacon Period, CFP and CAP slot lengths are calculated according to transmission delay of the users. At least one frame must be able to send in the one slot length by any user in the network. Therefore, coordinator should choose the unit slot length of periods, according to the user's Physical Layer data rate and throughput in the network. Slot Length of the periods depend on the transmission delays . Total delay of Beacon Period, CAP and CFP slots are the sum of MAC and PHY Layer delay. MAC Layer delay is caused by software implementation delay and PHY Layer delay is caused by the configuration and channel. Beacon Period, CAP and CFP delays are defined as follows: $T_{S_B} = T_{M_B} + T_{P_B}$ where T_{M_B}, T_{P_B} are the MAC and PHY Beacon packet Transmission Delays, $T_{S_{CAP}} = T_{M_{CAP}} + T_{P_{CAP}}$ where $T_{M_{CAP}}, T_{P_{CAP}}$ are the MAC and PHY CAP packet Transmission Delays. $T_{S_{CFP}} = T_{M_{CFP}} + T_{P_{CFP}}$ where $T_{M_{CFP}}, T_{P_{CFP}}$ are the MAC and PHY CFP Data packet Transmission Delays.

The MAC protocol data unit (MPDU) becomes the PHY service data unit (PSDU) at the output of the PHY Layer when it passed through the PHY Layer. The PSDU is beginning with a synchronization header (SHR). It contains the preamble sequence field and a PHY header (PHR), which are also containing the length of the PSDU in octets. The preamble sequence provides to achieve synchronization for the receiver. As a result, PHY Layer data unit (PPDU) is consist of SHR, PHR, and PSDU. PHY Layer delay includes data transmission PPDU header delay which includes SHR and PHR parts, data transmission delay (PSDU) and short inter frame space time duration, because of different packet size and supported data rates. The Beacon Period, CAP and CFP have different transmission delays. These transmission delays can be described as $T_{Delay} = M_i / D_{R_i}$ where M_i is frame size and D_{R_i} is the throughput of supported PHY Data Rate of the i^{th} user. The Physical Layer throughputs are presented in Table 1.

The CFP Physical Layer delay includes T_H, T_{SIFS}, T_{MD}, which respectively denote header transmission delay, short inter frame space duration and guard time. Guard time can be described by $T_G = 2\,(T_{MD})$ where T_{MD} is the max drift time. Max drift time should be defined as $T_{MD} = C / T_{Sup}$ where C is clock accuracy and T_{Sup} is superframe duration. Max Drift time must be always greater than short inter frame space duration. Thus, physical layer delays of beacon period, CAP and CFP are denoted as respectively T_{P_B}, $T_{P_{CAP}}$ and $T_{P_{CFP}}$ are can be defined as

$$T_{P_B} = T_H + T_T + T_{SIFS}, \tag{3.7}$$

$$T_{P_{CAP}} = 2\ (T_H + T_R + T_{SIFS}), \tag{3.8}$$

$$T_{P_{CFP}} = T_H + T_D + T_G, \tag{3.9}$$

T_R, T_D, T_T are respectively CAP Response-Request packet Delay, CFP Data packet Delay, Beacon transmission delay.

Beacon Period, CAP and CFP delays could be different for users in the network, because of different supported Physical Layer data rates and throughput. Coordinator should consider the Beacon Period, CAP and CFP delays of users for defining the slot lengths. Any user in the network can send at least one data packet within one period slot. Therefore, Beacon Period and CAP slot lengths should be defined according to the worst transmission environment of any user in the network. Because, every user which has the lowest supported physical data rate must be able to use these periods for any operation in the network. Also in CFP, every user has different transmission delay. So, coordinator defines different CFP slot length for every user. Every user can send data packet which has maximum MAC frame length in one superframe as much as frames in the total assigned CFP slot. $A = (T_{Total})\ D_i$ is the total bits that is generated until one superframe duration by the device. So, device buffer B should be always greater than data bits that generated until one superframe as $B \geq A$. T_{CFP} denotes the CFP duration and is the total of all active user's CFP slot lenght. So, It can be define as;

$$T_{CFP} = \sum_{1}^{N} S_{CFP}\ T_{S_{CFP_i}}. \tag{3.10}$$

The ideal MAC Data Rate D_i for the i^{th} user is the total bits that sent to the network in one super frame duration. So, It can define as;

$$D_i = \frac{S_{CFP}M_i}{T_B + T_{CAP} + T_{CFP}}. \tag{3.11}$$

where M_i is the maximum packet size for the user. D_i describes also theoretically maximum througput. througput is the number of successfully sent and received packets in the network, ignoring packet collisions and physical layer errors at the MAC layer. However, in real practice and software implementation, the increase in the number of users causes more collisions and thus packet drops by overflowing the device's memory. Errors and packet drops in the physical layer are neglected.

3.3 Simulation Scenarios and Numerical Results

In this section, we describe the simulation scenarios and present the simulation results. The data rate in (3.15) is the ideal MAC data rate, which means there are no collisions in the CAP period for CFP slot allocation. Therefore, it is the maximum data rate, which will be reached by the user. If collisions are considered, the data rate decreases and latency increases.

Each user in the network tries to send data on the network according to the default and calculated data rate in previous section. However, due to collisions in the CAP, the memory of the devices overflow over time. For this reason, the device has to drop some packets from its memory. Network load is the network traffic that occurs when each device tries to reach the data rate that we calculated theoretically without collisions. Network performance decreases as the network load increases. Naturally, less throughput is observed in the network while network load is increasing.

Each simulation consists of a simulation sequence. Each simulation sequence creates another simulation sequence. For example, the graph showing the parameter changes according to the total number of active users and the total number of CAP slot consists of two nested series of simulations in total. These series are as follows;

2 CAP Slot Number for 2 User, 3 CAP Slot Number for 2 User... 20 CAP Slot Number

for 2 User 2 CAP Slot Number for 3 User, 3 CAP Slot Number for 3 User... 20 CAP Slot Number for 3 User .... 2 CAP Slot Number for 15 User, 3 CAP Slot Number for 15 User... 20 CAP Slot Number for 15 User

The smallest simulation in these simulation series takes 20 minutes in total.

The latency in this work is caused by the MAC layer when no problem is encountered in the physical layer. At the MAC Layer side, the main reasons for latency is the collisions and mac layer software implementation. Software implementations can be done using many different algorithms. Physical Layer has fixed delays according to throughput of the physical layer as described in Table 1. In the real application, the physical layer throughput can be changed according to some conditions like SNR value, frame size etc. We can also expect physical layer implementation and usage latency issues in real applications. But, In this work, we aim to increase MAC Layer protocol performance and efficiency. MAC protocols are mostly related to software implementations. The MAC can be implemented with many different algorithms causing many different network throughput behaviour. So, The improvements of this work is done from the perspective of MAC software implementation. In real application MAC layer calculates and assumes the Physical Layer delay according to some reference like Table 1. So, The MAC software defines a slot length according to physical layer delay reference values of the physical layer in the 802.15.13.

Problems occurring in the physical layer have been ignored. If physical layer problems are added, of course, it could be better to describe the network mathematically. However, in such a case, it becomes very difficult to analyze and simple improvements on the MAC layer side could be overlooked. Also, there is no need for analysing physical layers to improve MAC software algorithms. This study aims to solve the algorithmic problems that occur only on the MAC layer side by fabricating most of the physical layer problems rather than mathematically modeling the behavior of the network.

3.3.1 Scenario I

In Scenario I, we select users which have different supported physical data rates as 9, 12, 18 Mbit/s with OCR20 in Table 1. The ideal data rate and transmission delays according to Section III are used as simulation inputs. In the simulation, every user generates data to send in the network as much as ideal data rate input. But, they can not send all generated data. This is due to the fact that the ideal data rate is calculated based on the assumption of no collision. Therefore, collisions cause extra latency, much packet drop and less user data rate. Scenario I simulation constants are shown in Table 2. The purpose of the scenario is to see the effect of the CAP Slot length actually.

Table 2: Simulation I Input Constants

Active User Number	3
1.User PHY throughput	9 mb/s
1.User CFP Slot lenght	1.880 ms
2.User PHY throughput	12 mb/s
2.User CFP Slot lenght	1.425 ms
3.User PHY throughput	18 mb/s
3.User CFP Slot lenght	0,970 ms
Beacon Period lenght	0.1 ms
CFP Slot number for per user	8

Fig. 19, Fig. 20 and Fig. 21 demonstrate respectively how the CAP slot lengths and CAP slot numbers affect collision ratio, network data rate and latency, when the maximum 8 number of CFP slot (i.e., the length of 1.8 ms) can be assigned per user, while beacon slot length is 0.11 ms. Results quantify the performance in data rate and latency associated with choosing the suitable CAP slot number. For example, in order to achieve a highest data rate and lowest latency for this scenario, 4 CAP slot is required and collision ratio is 0.38 at that point as shown in Fig. 19. While the CAP slot length is increasing from 0.11 ms to 1.9 ms, the network gains more stable values in the latency and data rate. With increasing of CAP slot number, the collision ratio decreases exponentially and the extremum points becomes flatter in the data rate and latency.

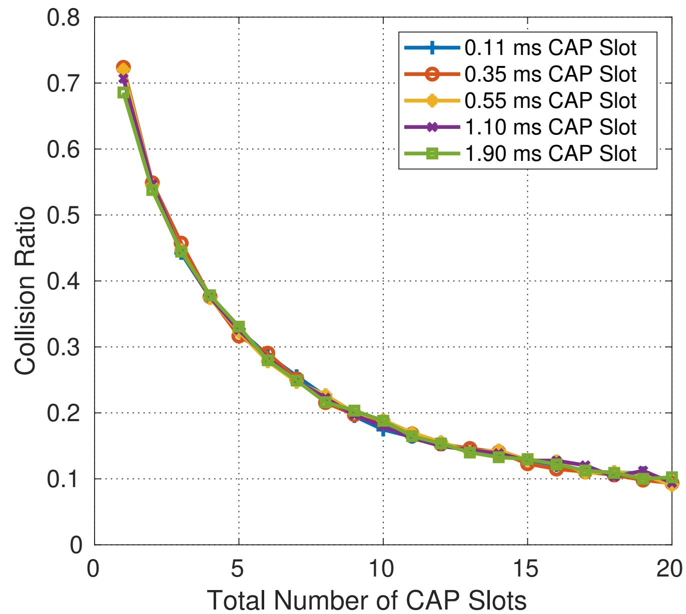

Figure 19: Simulation Results of Scenario I. Collision Graph

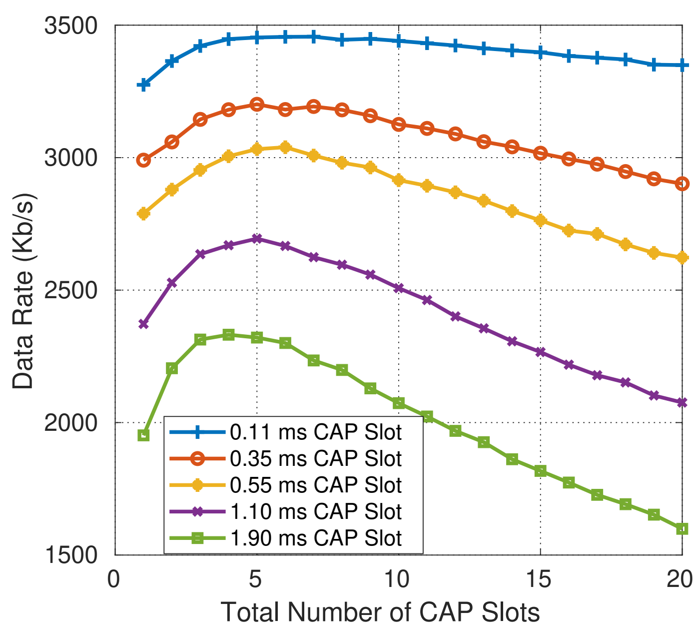

Figure 20: Simulation Results of Scenario I. Data Rate Graph

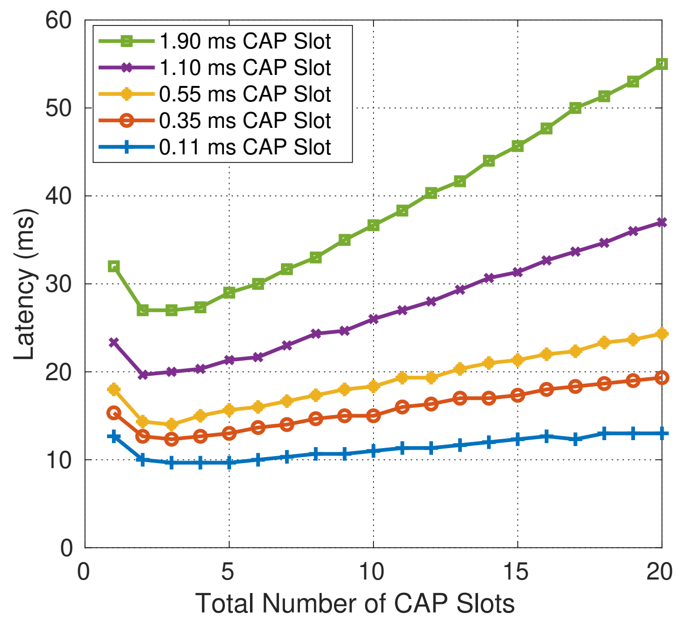

Figure 21: Simulation Results of Scenario I. Latency Graph

3.3.2 Scenario II

In this scenario, same users in Scenario I are selected. The maximum CFP slot numbers which can be assigned per user increases while the total CAP slot number and CAP slot width are constant. Scenario II simulation constants are shown in Table 3.

Fig. 22, Fig. 23, and Fig. 24 respectively show how the CFP slot numbers affect the packet drop, data rate and latency and ratio in the network, when the maximum CFP slot length is 1.8 ms and beacon slot length is 0.11 ms. Increasing the number of CFP slots increases the latency linearly, but also increases the data rate exponentially. For example, the data rate climbs to 2768.78 kb/s, 3292.63 kb/s, 3406.86 kb/s, 3472.08 kb/s, while latency increases as 6.3 ms, 11.3 ms, 16 ms, 20.3 ms for 2, 8, 14, 20 number of CFP slots respectively. Thus, the packet drop decreases with increasing CFP slot number. For example, the packet drops are the 0.15, 0.074, 0.054, 0.041 for the 2, 8, 14, 20 number of CFP slots respectively. Due to the increase in CFP duration compared to CAP duration, the network begins to saturate in data rate and packet drop as shown in Fig. 22. The purpose is the scenario is to see the effect of the CFP slot number.

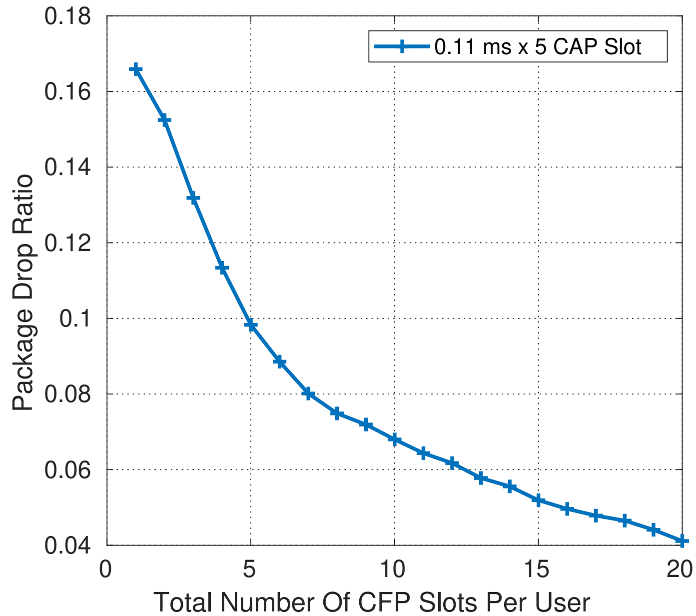

Figure 22: Simulation Results of Scenario II. packet Drop Graph

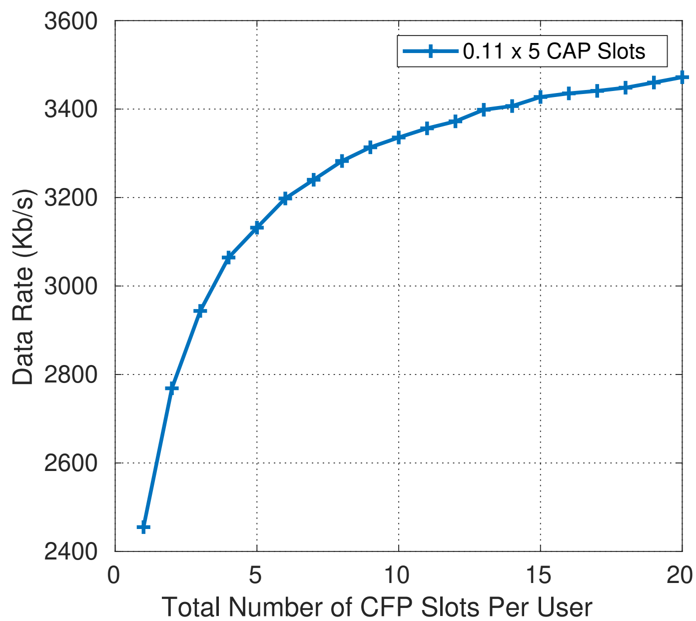

Figure 23: Simulation Results of Scenario II. Data Rate Graph

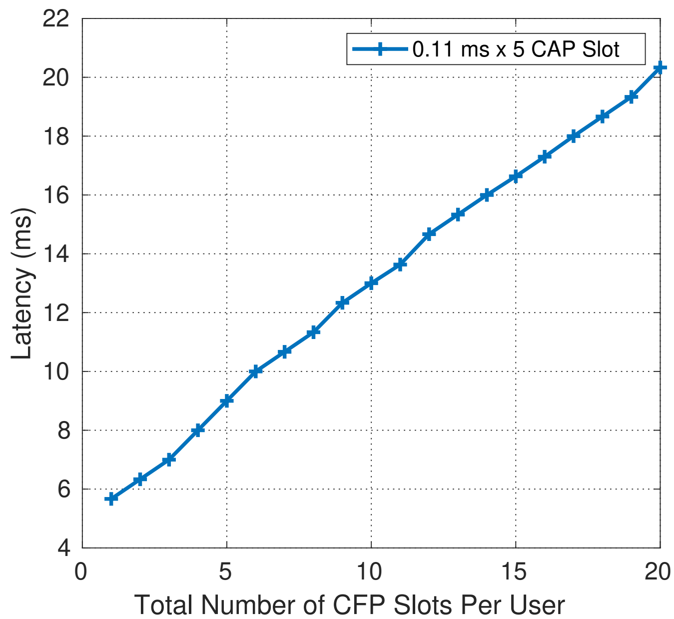

Figure 24: Simulation Results of Scenario II. Latency Graph

Table 3: Simulation II Input Constants

Active User Number	3
1.User PHY throughput	9 mb/s
1.User CFP Slot lenght	1.880 ms
2.User PHY throughput	12 mb/s
2.User CFP Slot lenght	1.425 ms
3.User PHY throughput	18 mb/s
3.User CFP Slot lenght	0,970 ms
Beacon Period lenght	0.1 ms
CAP Slot Number	4
CAP Slot Lenght	1.1 ms

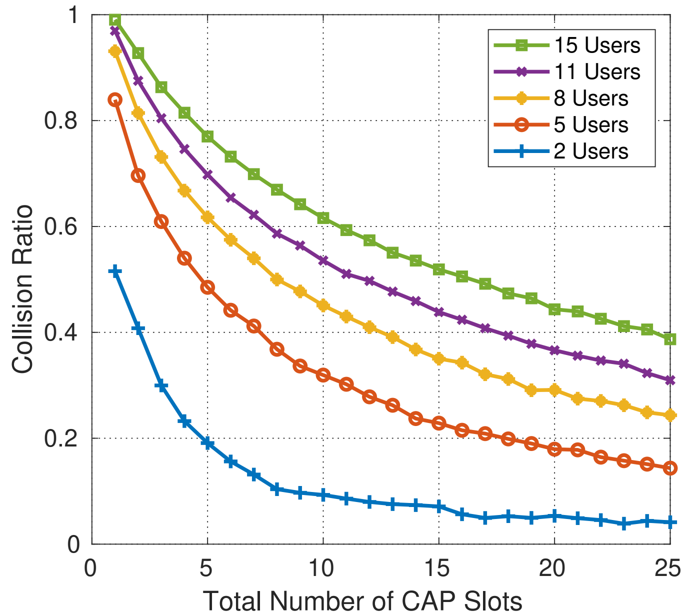

Figure 25: Simulation Results of Scenario II. Collision Graph

3.3.3 Scenario III

In scenario III, the total number of CAP slot increases, CAP Slot length is constant as 1.1 ms, and users have the same supported Physical Layer data rate as 24 Mb/s. Longer CAP slot lengths are selected to investigate the effect of CAP. In this case, the beacon period is 0.11 ms length and CFP slots are 0.742 ms length while the maximum number of CFP slot is 8 for per user. Scenario III simulation constants are shown in Table 4.T he purpose of this scenario is the seeing the effect of the active user changing according to CAP Slot number.

Fig. 25, Fig. 26 and Fig 27 respectively show how the CAP slot numbers affect the collision ratio, data rate and latency with different total active users in the network. Increasing the number of users also increases the CFP duration compared to the CAP duration. Therefore, the network is more stable with a large number of active users. As the number of active users decreases, the extreme points in data rate and latency become clear. And, the slope of the parabolic drop in the collision ratio increases.

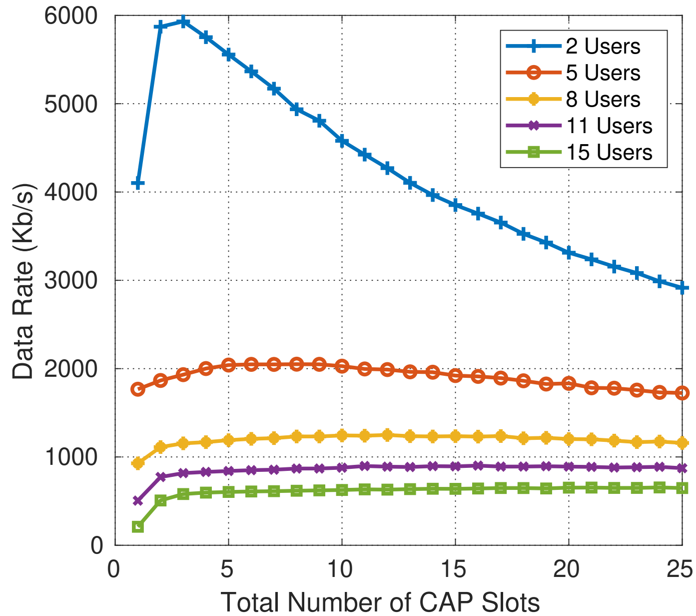

Figure 26: Simulation Results of Scenario II. Data Rate Graph

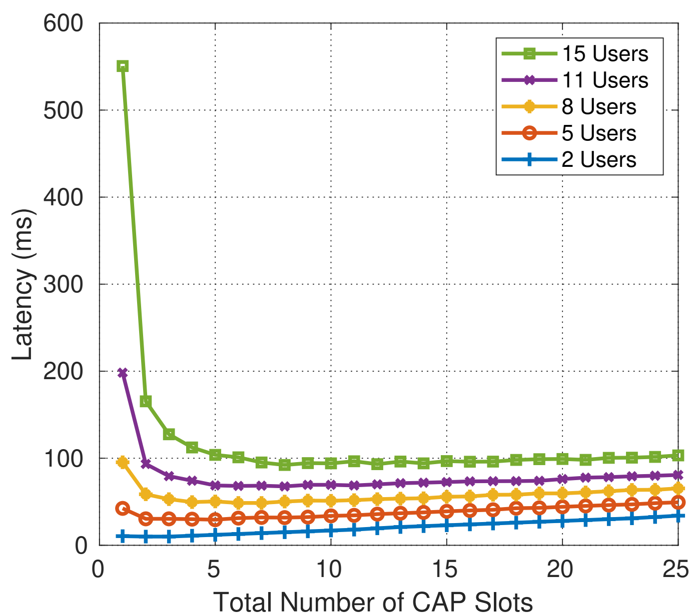

Figure 27: Simulation Results of Scenario II. Latency Graph

Table 4: Simulation III Input Constants

All Users PHY throughput	24 mb/s
Users CFP Slot lenght	0,742 ms
Beacon Period lenght	0.1 ms
CFP Slot number for per user	8

3.4 Proposed Algorithm

Slotted Aloha algorithm has no closed loop control mechanism to arrange the number of slots. If the network load demand changes with time, the coordinator needs to estimate the network demand for network optimization by changing total slot length and number. To estimate the demand, the commonly used statistical approach is the Markov Chain. However, this approach includes many calculation iterations which might be hard to implement on embedded systems.

To address this, we propose a simple yet computationally efficient algorithm (see Fig.28) that enables the coordinator to optimize the network according to load demand with a slotted Aloha mechanism. In the proposed method, the coordinator observes the user's feedback in the CAP. It sets an observation time and declares the length and beginning of the time in the Beacon Frame. It collects all feedback of users until observation time ends. The user requests GTS and sends also the amount of total request and retry number that occurred in the observation time. In this way, the coordinator calculates the collision ratio, estimates the load demand according to collision ratio and arranges a suitable total number of CAP slot for the network.

To evaluate the performance of proposed algorithm, simulations are carried out following Scenario III. Fig. 29 shows the maximum throughput according to specific collision probability range. The collision ratio is controlled by arranging total CAP slot number according to the user's collision ratio feedback in the proposed algorithm. The maximum throughput is observed at the specific collision ratio. Considering the simulations, the suitable collision ratio is between 0.4 and 0.6 to obtain maximum throughput. If the collision ratio remains at the suitable values, the network reaches the maximum throughput. The performance and time responsiveness of the algorithm can be changed according to the applied control approach. The PID Control also can be implemented for more efficient time responsivity performance.

Fig. 29 and Fig. 30 shows the maximum total throughput that a network can reach in

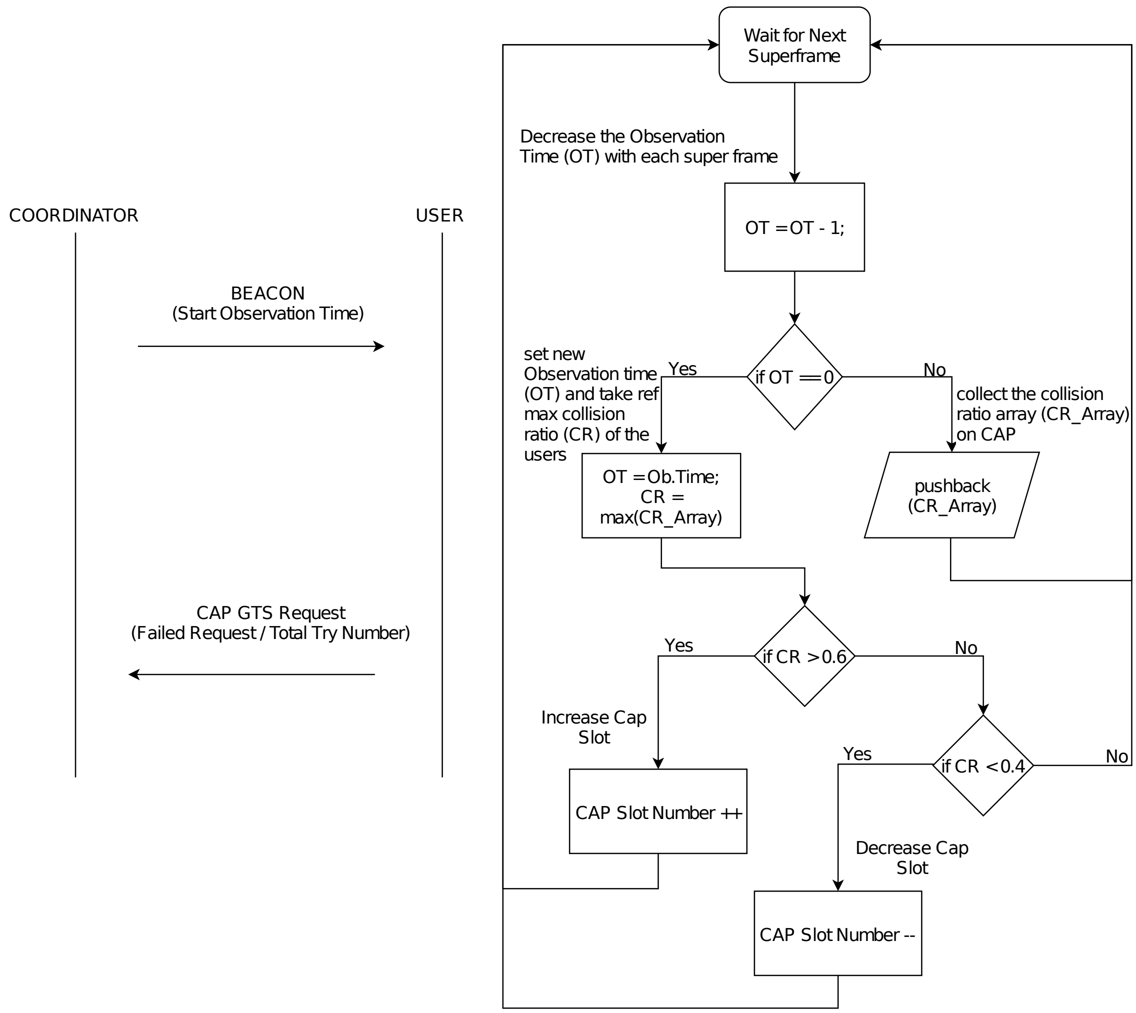

Figure 28: Proposed Algorithm.

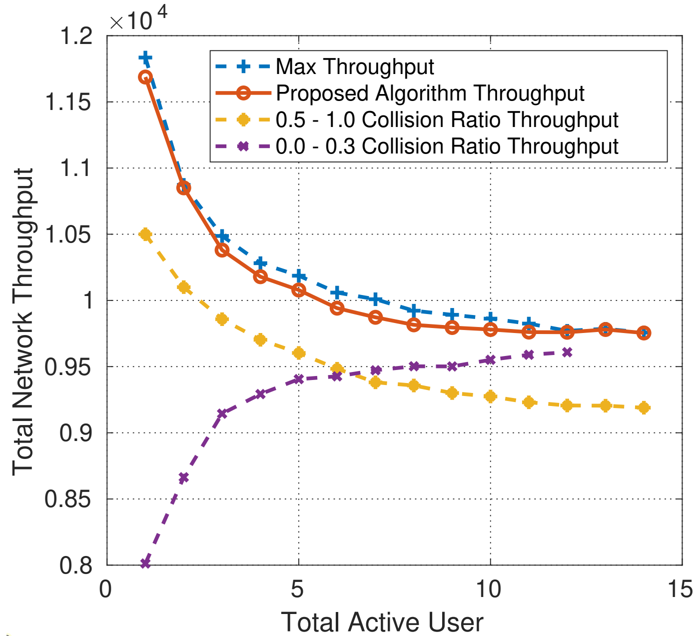

Figure 29: Total Network Throughput Comparison.

total. That means the total number of packets that can be sent and received for every device in different situations in the network. The maximum throughput here is obtained through simulations and we cannot produce these graphs with the theoretically calculated data rate in the previous section. Values such as the data rate calculated in the previous sections are only mathematical expressions of simulation input values for programmatic network users. The maximum throughput here is the result of simulations directly and exhibits the behavior of a network which is based 802.15.13 standard in specified situations.

Similar to this study, the performance improvements of previous studies that performed ”mean value analysis” like [5], [6], [7], [8] cannot be compared with the predictive improvement for this study.The first reason for this is that previous studies have different standards and are based on different protocols. The other reason is that the different input parameters which are described with a mathematical expression for the simulation cause too many changes in the simulation numerical results. The numerical values of the studies cannot be compared. However, the efficiency of any algorithm that uses the same standard structure outside of the proposed algorithm and works with the same input parameters is

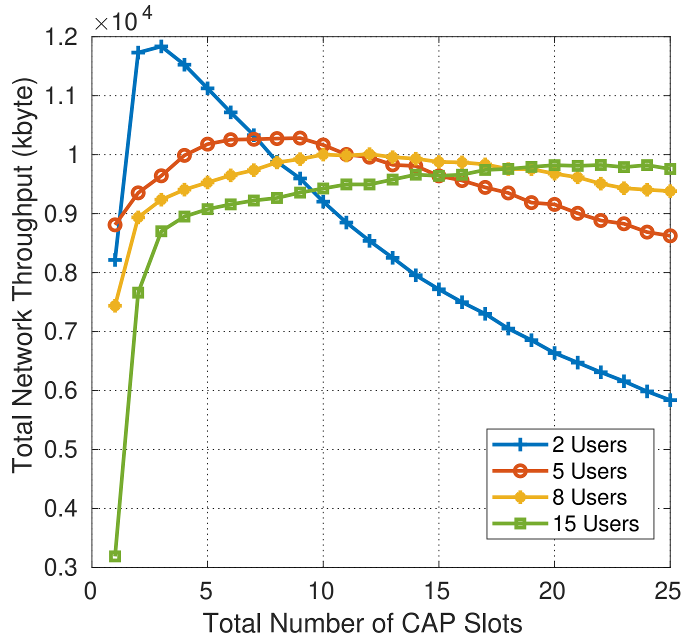

Figure 30: Total Network Throughput.

comparable. For this reason, the values of the total maximum throughput reached by the proposed algorithm for the network are compared with other algorithms that can be operating in the other probability distribution of the collision. Fig. 29 shows the comparison of the maximum throughput value reached by other algorithms that can be found in another possible probability range and total throughput of the proposed algorithm. This gives us an idea about improvement.

Fig. 30 shows the total throughput of the network according to total CAP slot and total active user number. While total active user number change with time in the network, total throughput and suitable total CAP slot number change accordingly. When the total network throughput in different collision probabilities are compared; total network throughput with probability range between 0.4 and 0.6 is at least 5% higher than the other probability ranges as shown in Fig. 29. This indicates at least 5% improvement. This value changes according to individual conditions. In cases wheres the difference between the number of active users changes is high, further improvement can be obtained.

CHAPTER IV

CONCLUSIONS AND FUTURE WORK

In this chapter, we review the entire dissertation objectives and results. We emphasize on the contributions that this research made. At the end, we give some prospective points for future work.

4.1 Conclusions

In this work, we analyzed the effect of superframe design on the throughput of IEEE 802.15.13-based VLC networks. Through simulations, we analyzed the effect of the total number of CAP slots and active user number. It is shown that for a specific CAP slot duration and collision ratio, there is an optimum number of CAP slots either to increase the data rate or to reduce latency. For short CAP duration or long CFP duration, the number of CAP slots has a limited effect. If the CAP duration is the same or larger than CFP duration, the coordinator should select the number of CAP slots carefully. Our simulations show that the effect of collision ratio to data rate and latency is high only if the number of active users is low. If the number of active users and total number of CAP Slots is higher, both latency and data rate are stable. We further investigate the effect of the number of CFP slots. The data rate increases logarithmically, whereas latency increases linearly with the increase of the total number of CFP slots.

To optimize the network throughput, we suggested a system which determines the number of CAP slot according to the obtained collision ratio information. Our simulation results show that our algorithm is very close the maximum throughput.

4.2 Future Work

In this study, total network efficiency is improved by applying a closed loop control system to the slotted Aloha channel access mechanism. The applied algorithm has been evaluated only in terms of total efficiency, but the timing performance of the improvement achieved has not been studied yet. Because the length of the observation time determined for the algorithm will affect the efficiency of the algorithm. To increase this performance, an approach such as PID control can be applied. The timing performance of the algorithm can be topic for the future studies.

PUBLICATIONS

The research leading to this dissertation has appeared previously in the following publication.

Conference Papers

- Yusuf Bülbül, Mohammed Elemassi, Tuncer Baykaş, Murat Uysal: **Analysis and Optimization of the Network Throughput in IEEE 802.15.13 based Visible Light Communication Networks**.– *Blackseacom*, May 2021, Bucharest, Romania.

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