Università degli Studi di Firenze
Facoltà di Ingegneria

Corso di Laurea in
Ingegneria delle Telecomunicazioni

Analysis and feasibility study of communication architectures for sensor networks operating in IEEE 802.15.4/IEEE 802.15.4a technology

Tesi di Laurea di

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Acronyms and Abbreviations

ACK Acknowledgment

AP Access Point

BAN Body Area Network

CA Collision Avoidance

CAP Contention Access Period

CCA Clear Channel Assessment

CD Collision Detection

CDMA Code Division Multiple Access

CFP Contention Free Period

CSMA Carrier Sensing Multiple Access

DCF Distributed Coordinator Function

DS Direct Sequence

DSSS Direct Sequence Spread Spectrum

ED Energy Detection

EIRP	Effective Isotropically Radiated Power
FCC	Federal Communications Commission
FDM	Frequency-Division Multiplexing
FDMA	Frequency-Division Multiple Access
FFD	Full Function Device
FIFO	First In, First Out
GTS	Guaranteed Time Slot
HDR	High Data Rate
IEEE	Institute of Electrical and Electronics Engineers
IP	Inactive Period
IR-UWB	Impulse Radio UWB
ISO	International Standard Organization
LDR	Low Data Rate
LDR-LT	LDR with Location/Tracking
LLC	Logical Link Control
MAC	Medium Access Control
MFR	MAC Footer
MHR	MAC Header
MLME	MAC Layer Management Entity

MB-OFDM MultiBand OFDM

MC-UWB Multi-Carrier UWB

MPDU MAC Protocol Data Units

MSDU MAC Service Data Unit

OFDM Orthogonal Frequency-Division Multiplexing

OSI Open System Interconnection

OWR One Way Ranging

PAN Personal Area Network

PAM Pulse Amplitude Modulation

PDA Personal Digital Assistant

PHY Physical Layer

PHR PHY Header

PLME Physical Layer Management Entity

PN Pseudo-Noise

POS Personal Operating Space

PPDU PHY Protocol Data Unit

PPM Pulse Position Modulation

PSDU PHY Service Data Unit

PULSERS Pervasive Ultra-wideband Low Spectral Energy Radio System

QoS Quality of Service

RF Radio Frequency

RFD Reduced Function Device

RNG Ranging

RTS Request To Send

SAP Service Access Point

SHR Synchronization Header

SS Spread Spectrum

SSCS Service Specific Convergence Sublayer

TDMA Time Division Multiple Access

TDOA Time Difference Of Arrival

TOA Time Of Arrival

TWR Two Way Ranging

TH Time Hopping

UWB Ultra-WideBand

UWEN UWB Wireless Embedded Systems

VHDR Very High Data Rate

WPAN Wireless Personal Area Network

Chapter 1

Introduction

1.1 What is UWB?

Historically, Ultra-WideBand (UWB) refers to a radio communications technique that spreads a signal on a very large spectrum of frequency with an extremely low power spectral density (can work at noise level).
According to Federal Communications Commission (FCC)'s wording [1] an UWB radio device is defined as any device with a fractional bandwidth (ratio between the signal's absolute bandwidth and its center frequency) greater than 0.20 or with a bandwidth occupation of 500 MHz or more of spectrum. Translating the above definitions in mathematical formulas

$$B_F = B/f_C = 2(f_H - f_L)/(f_H + f_L) > 0.2 \tag{1.1}$$

where f_H is the upper frequency of the -10 dB emission point and f_L is the lower frequency of the -10 dB emission point. The center frequency is defined as

$$f_C = (f_H - f_L)/2 \tag{1.2}$$

and, according to the FCC, the minimum bandwidth required is

$$B = f_H - f_L > 500MHz. \tag{1.3}$$

These conditions mean that UWB systems with a center frequency greater than 2.5 GHz need to have a -10 dB bandwidth of at least 500 MHz while systems working with a center frequency lower than 2.5 GHz need to have a fractional bandwidth of at least 0.20.

The FCC on 14th February 2002 approved a spectral mask for operation of UWB devices [1]. It is evident that the major part of the allowed spectrum lies between 3.1 and 10.6 GHz with allowed effective Effective Isotropically Radiated Power (EIRP) of -41.3 dBm/MHz.
These constraints can be satisfied with IR-UWB systems or with Orthogonal Frequency-Division Multiplexing (OFDM) systems. Also MultiBand OFDM (MB-OFDM) systems are suitable to fit into FCC's regulations. These systems will be described with major details in Section 2.1.
Thus, with appropriate technical standards, UWB devices can operate using spectrum occupied by existing radio services without causing interference. Additionally, the large instantaneous bandwidth and potential for low-cost digital design make systems based on UWB technology suitable for a wide range of applications, such as high-speed networking devices as well as low-speed sensor and Wireless Personal Area Network (WPAN) devices.

In sensors and WPAN devices the battery is a relatively high-cost component, so the whole system must be developed with particular care about the power consumption. The Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard describes a very low-cost and extremely low-power

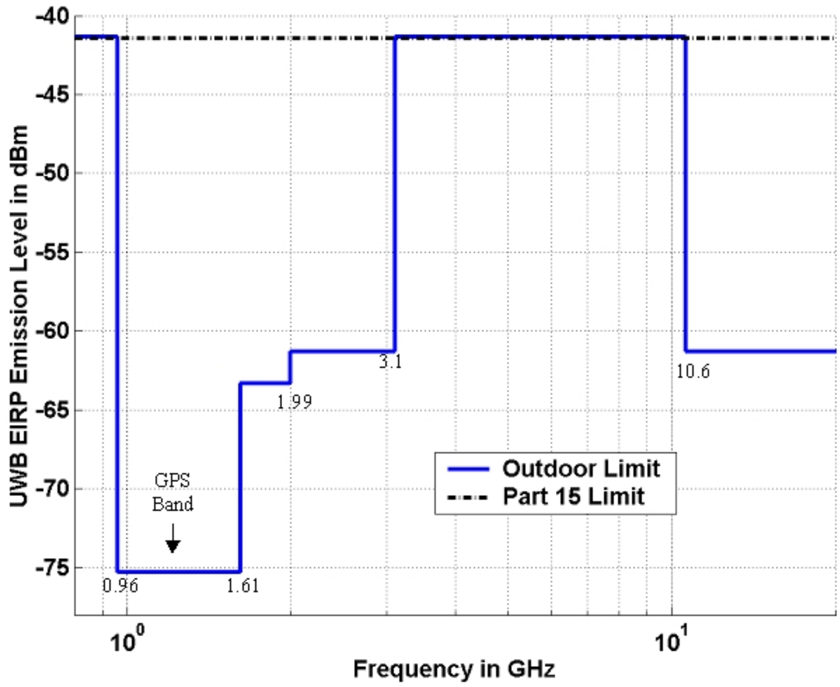


Figure 1.1: FCC Allocated Spectral Mask

Low Data Rate (LDR) system [2].

1.2 Research Purpose

Purpose of this research is to analyze three different UWB Medium Access Control (MAC) protocols used in LDR devices from the point of view of the energy consumption. The work will be done using an energy analysis model for multi-hop MAC [3]. With this energy model will be also possible to analyze the delays introduced.

Simulations and results will be produced using the NS-2 simulator to analyze the performance of the Directed Diffusion routing algorithm over IEEE 802.15.4 and IEEE 802.15.4a devices.

1.3 Overview of the thesis

The thesis is organized as follows.

Chapter 1 is this chapter, it includes a brief description of UWB and the purpose of the research.

Chapter 2 will describe some common Physical Layer (PHY) used in UWB devices, will introduce the reader to the most common MAC and will describe the energy analysis model.

Chapter 3 will show the three MAC under examination giving a brief description of the capability of each.

Chapter 4 will show the analysis work and the simulator set-up.

Chapter 5 will show the result of the analysis and of the simulations.

Appendix and *Bibliography* will end the document giving some additional information.

Chapter 2

UWB Overview

At the end of ’70s the International Standard Organization (ISO), trying to unify the communication between network projected by different manufacturers, developed a standardized model called Open System Interconnection (OSI) [4, pp.425-432].
The model divide the function of a protocol into a series of layers. Each layer has the property that it only uses the functions of the layer below, and only exports functionality to the layer above. A system that implements protocol behavior consisting of a series of these layers is known as a ’protocol stack’ or ’stack’. Protocol stacks can be implemented either in hardware or software, or a mixture of both. Typically, only the lower layers are implemented in hardware, with the higher layers being implemented in software.
Additionally, there are also interface standards for different layers to talk to the ones above or below. The commands and answers that the layers use to communicate through the interface are called *primitive*. There are four primitive:

- Request,

- Indication,
- Answer and
- Confirm.

All the layers use this four primitives to control every their interaction through the interface that divides them. With these rules this model allows the design of complex but highly reliable protocol stacks.
The IEEE 802 communication standards define only the two bottom layer of the OSI reference model: the Physical Layer (PHY) and the data link layer.
Nowadays all the communications devices follow the OSI model or with slightly difference (*i.e.*,the simplified 5 layer protocol stack).
Figure 2.1 shows the OSI 7 layer model.

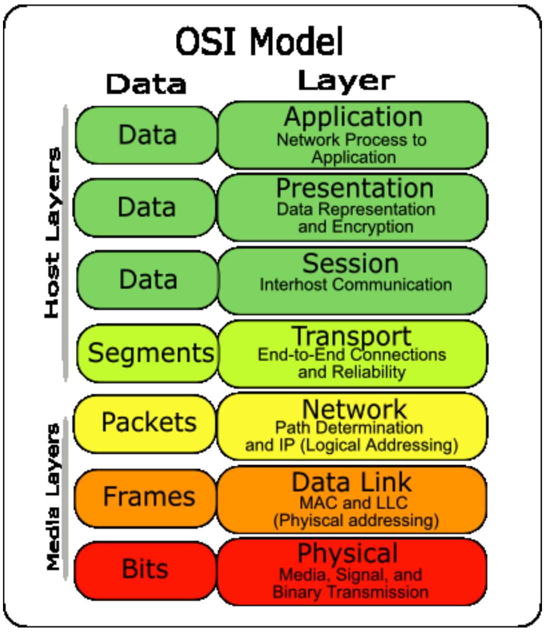


Figure 2.1: The ISO-OSI Reference Model

2.1 The UWB Physical Layer

The PHY layer manages the interaction between the higher layer and the medium and is in charge of providing control of the radio transceiver, energy detection, link quality, modulation and transmitting/receiving message packets through the physical medium.

Actually, there are two main methods to create an UWB signal. The first method works sending a very short duration pulses to convey information. This method is called Impulse Radio UWB (IR-UWB).
The second method uses multiple simultaneous carriers for data transmission and it's called Multi-Carrier UWB (MC-UWB).
Both methods are suitable for UWB communications and the choice of one of them for devices development is essentially application-oriented.

2.1.1 IR-UWB System

An IR-UWB device works sending very short duration pulse, generally Gaussian based pulse, to convey information.

The basic model for an unmodulated IR-UWB train of pulses is

$$s(t) = \sum_{i=-\infty}^{\infty} A_i p(t - iT_F) \tag{2.1}$$

where $A_i(t)$ is the amplitude of the pulse, $p(t)$ is the pulse shape with normalized energy and T_F is the frame duration.
A Gaussian pulse is described analytically as

$$p(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{(t-\mu)^2/(2\sigma^2)} \tag{2.2}$$

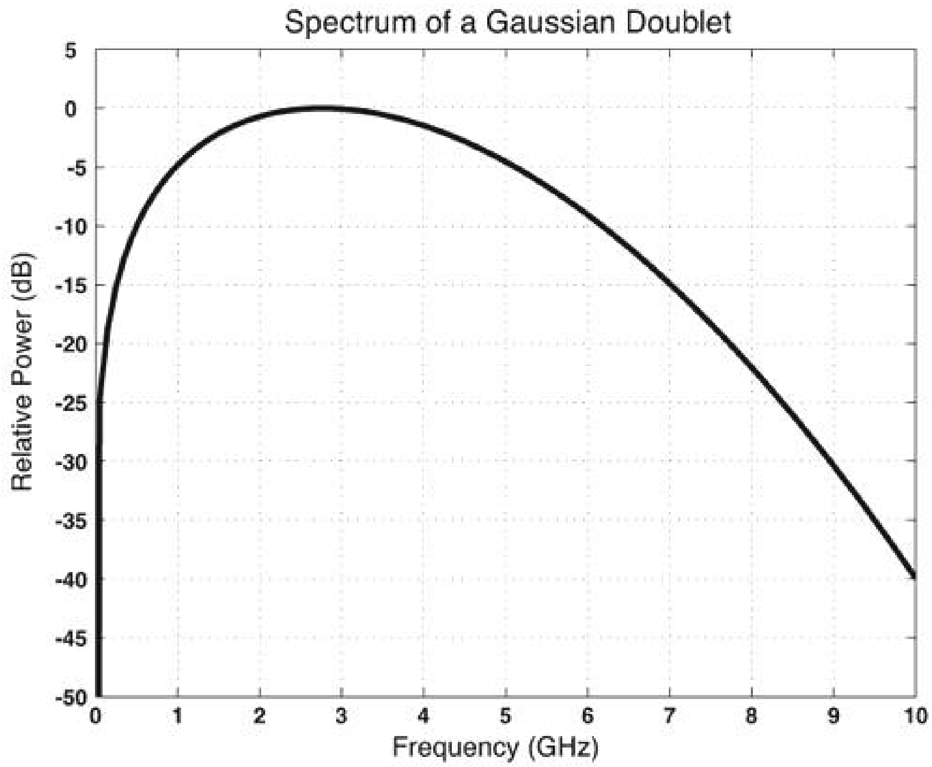


Figure 2.2: Spectrum of a Gaussian Monocycle-Based Impulse UWB Signal

where σ is the standard deviation of Gaussian pulse in seconds and μ is the location in time for the midpoint of the Gaussian pulse in seconds.

Another useful shape is the first derivative of the Gaussian pulse, due the fact the a UWB antenna may differentiate the generated Gaussian pulse with respect to time, leading the following pulse shape (assuming $\mu = 0$)

$$p(t) = \left(\frac{32k^6}{\pi}\right) te^{-(kt)^2} \tag{2.3}$$

where k is a constant that determines the pulse width.

Unfortunately these two shapes don't fit into the FCC spectrum mask (3.1-10.6 GHz band), so the preceding pulse shape may be not used for commercial systems.

A more useful pulse shape is the Gaussian modulated sinusoidal pulse

$$p(t) = \left(\frac{8k}{\pi}\right)^{\frac{1}{4}} \frac{1}{\sqrt{1 + e^{\frac{2\pi^2 f_C^2}{k}}}} e^{-(kt)^2 \cos(2\pi f_C t)} \tag{2.4}$$

where f_C is the desired center frequency for the pulse.
Figure 2.3 shows the shape of the obtained pulse.

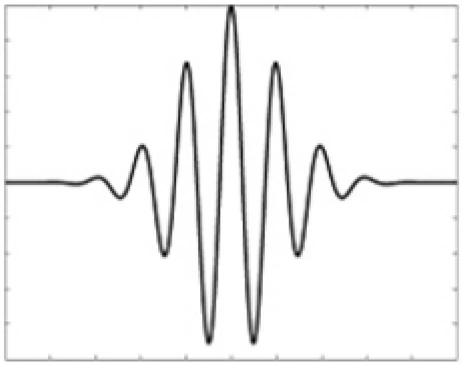


Figure 2.3: Gaussian modulated sinusoidal pulse

The IR-UWB allows several modulation schemes, including Pulse Amplitude Modulation (PAM) and Pulse Position Modulation (PPM).
The first modifies the amplitude of the pulse according to the data flow, analytically

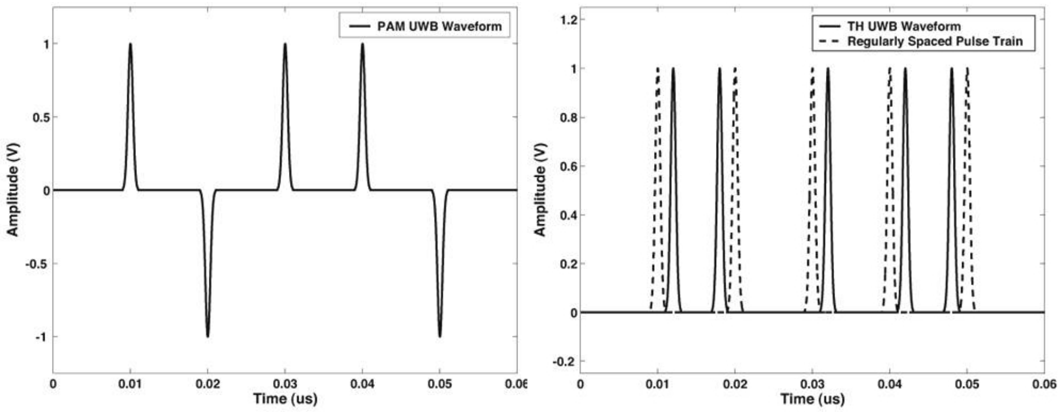
$$s(t) = \sum_{i=-\infty}^{\infty} A_i(t) p(t - iT_F) \tag{2.5}$$

where $A_i(t)$ represents the amplitude of the i^{th} pulse, which is dependent on the data $d_i(t)$ and the specific modulation scheme.
The latter shifts the pulses slightly before or slightly after their ideal positions in a regularly spaced pulse train. Analytically

$$s(t) = \sum_{i=-\infty}^{\infty} A_(t) p(t - iT_F - \delta d_i(t)) \tag{2.6}$$

where $d_i(t)$ is the time modulation based on the information and d is the base time increment.

Figure 2.4 shows the effect of both modulation schemes.



(a) Antipodal Pulse Amplitude Modulation: Positive Pulses Represent a +1 and Negative Pulses Represent a −1.

(b) Time Hop Modulation: Pulses Transmitted After Their Ideal Position Represent a +1 and Pulses Transmitted Prior to Their Ideal Position Represent a −1.

Figure 2.4: Modulation schemes for IR-UWB

As the signal energy is spread over a band of frequencies up to a few GHz, these signals would overlay many existing narrowband spectrum users or other UWB piconet devices. To avoid this occurrence it's possible to use in addition Spread Spectrum (SS) technique as Direct Sequence (DS) and Time Hopping (TH) spreading codes. This, as well as provide some immunity to interference from existing narrowband users overlaid by the UWB system, also provide a multiple access means for many users to share the available bandwidth.

In DS-SS the modulated information-bearing signal is directly modulated by a digital, discrete time, discrete valued code signal.

Figure 2.5 shows a block diagram of a DS-SS transmitter.

In TH-SS the data signal is transmitted in rapid bursts at time intervals

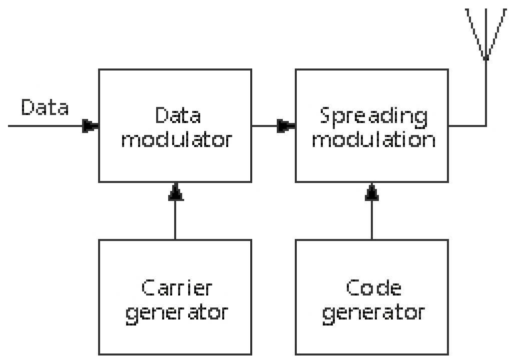


Figure 2.5: Block diagram for a DS-SS transmitter

determined by the code assigned to the user. The time axis is divided into frames, and each frame is divided into M time slots. During each frame the user will transmit in one of the M time slots. Which of the M time slots is transmitted depends on the code signal assigned to the user. Since a user transmits all of its data in one, instead of M time slots, the frequency it needs for its transmission has increased by a factor M.

In Figure 2.6 a block diagram of a TH-SS in given.

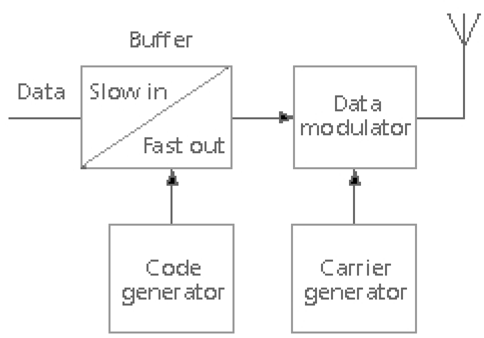


Figure 2.6: Block diagram for a TH-SS transmitter

2.1.2 MC-UWB System

MC-UWB systems use OFDM techniques to transmit the information. OFDM is a transmission technique based upon the idea of Frequency-Division Multiplexing (FDM) where multiple signals are sent out at different frequencies. Here the data flow is sent over simultaneous multiple orthogonal overlapping carriers independently modulated. OFDM has several properties, including high spectral efficiency, inherent resilience to RF interference, robustness to multi-path, and the ability to efficiently capture multi-path energy. The transmitted OFDM signal $s(t)$ has the following complex baseband form

$$s(t) = A \sum_{r} \sum_{n=1}^{N} b_n^r p(t - rT_p) e^{j2\pi n f_0 (t - rT_{p}))} \tag{2.7}$$

where N is the number of subcarriers, b_n^r is the symbol that is transmitted in the r^{th} transmission interval over the n^{th} subcarrier, and A is a constant that controls the transmitted power spectral density and determines the energy per bit. The fundamental frequency is

$$f_0 = \frac{1}{T_p}. \tag{2.8}$$

Figure 2.7 shows the spectrum of an OFDM-based signal.
Unlike narrowband OFDM, the OFDM-UWB spectrum can have gaps between subcarriers.
OFDM-UWB uses a frequency coded pulse train as a shaping signal. The frequency coded pulse train is defined by

$$p(t) = \sum_{n=1}^{N} s(t - nT) e^{(-j2\pi c(n) \frac{1}{T_c}} \tag{2.9}$$

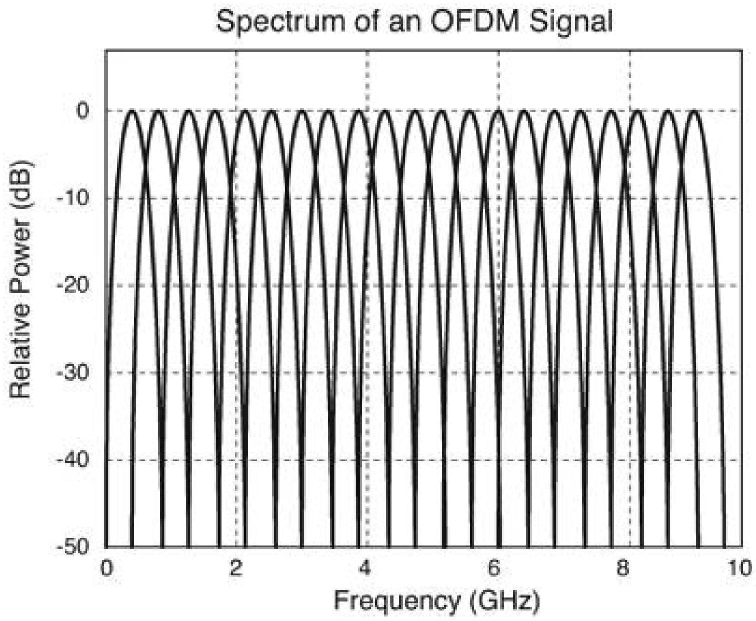


Figure 2.7: Spectrum of an OFDM-based MC-UWB signal

where $s(t)$ is an elementary pulse with unit energy and duration $T_s < T$, and $p(t)$ has duration $T_p = NT$. Each pulse is modulated with a frequency

$$f_n = \frac{c(n)}{T_c} \tag{2.10}$$

where c (n) is a permutation of the integers $1, 2, ..., N$.

As the FCC states that a UWB signal must occupy a minimum -10 dB bandwidth of 500 MHz, a UWB systems can be obtained also dividing the entire spectrum into several sub-bands, whose bandwidth is approximately 500 MHz, instead of having to use the entire band to transmit information. By interleaving the symbols across sub-bands, UWB systems can still maintain the same transmit power as if they were using the entire bandwidth. Information on each of the sub-bands can be transmitted using either IR-

UWB or MC-UWB techniques. If the latter techniques is chosen than the whole system is called MB-OFDM.
Figure 2.8 shows the sub-bands allocation for the 3.1-4.8 GHz frequency band.

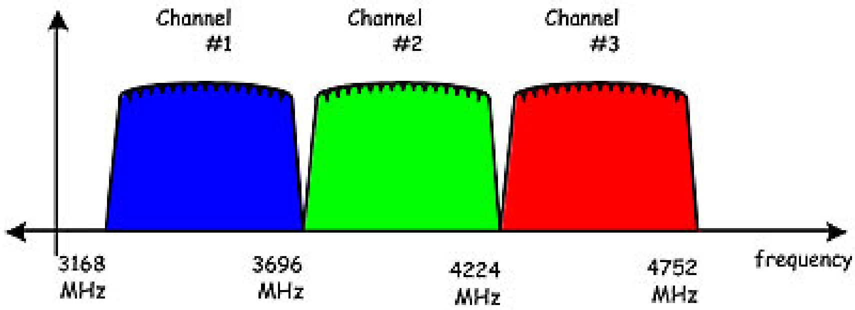


Figure 2.8: Sub-bands allocation for the 3.1-4.8 GHz frequency band

2.2 Medium Access Control

The MAC sublayer, together with the Logical Link Control (LLC) sublayer, comprises the data link layer in the ISO/OSI model. The MAC layer provides access control to a shared channel and reliable data delivery.
For a wireless network there are two main topologies: star topology and peer-to-peer mesh. In the first each node is connected with an unique coordinator that operates as a network master, sending beacons for device synchronization and maintaining association management. Instead, a peer-to-peer topology allows any node to communicate with any other node within its range, and to have messages relayed to nodes outside its range, via multi-hop routing of messages.
As an optimal use of the wireless media is desirable, particular attention is

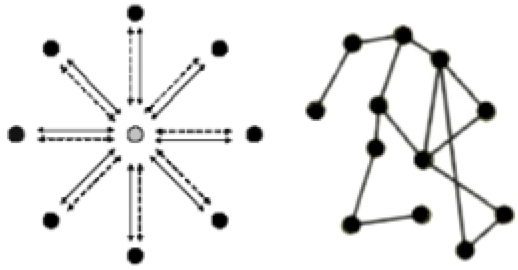


Figure 2.9: Star and Peer-to-Peer topology

needed for choosing the protocol for media sharing because many devices can operate in restricted unlicensed bands shared by other wireless technologies. There are two main categories of medium sharing protocol, the contention-free and the contention protocols. The former divides the channel into smaller "pieces" (*e.g.*,time slots, frequency, code) and allocates each piece to an assigned node, the latter doesn't divide the channel, works without *a priori* coordination among nodes and allows collisions but the protocol know how to detect and recover from them. There are also slotted ad-hoc protocols employed for specific applications, such sensor networks and Body Area Network (BAN)s.

2.2.1 Contention-free Protocols

TDMA - Time Division Multiple Access

Time Division Multiple Access (TDMA) is a digital transmission technology that allows a number of users to access a single Radio Frequency (RF) channel without interference by allocating unique time slots to each user within each channel. The users transmit in rapid succession, one after the other, each using their own time slot. This allows multiple users to share the same transmission medium (e.g. radio frequency) whilst using only the part of its bandwidth they are allocated. Figure 2.10 shows the TDMA frame structure.

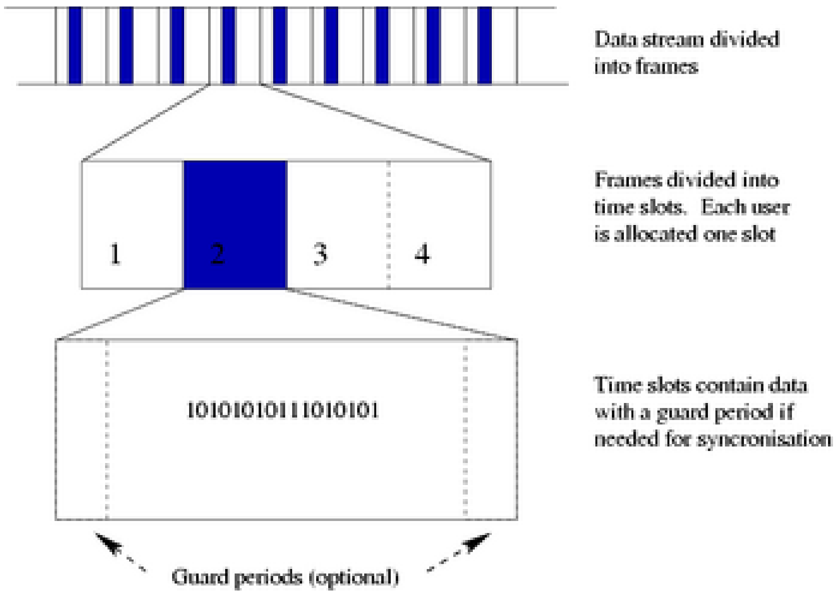


Figure 2.10: TDMA frame structure

The data stream is divided into frames, each frame contains a number of time slots equal to the numbers of transmitting devices.

One of the main points of strength of TDMA is that the transceiver needs only to listen or transmit during its own time slot as well as the beacon at the beginning of the superframe, for the rest of time it can perform other activities like channel measurement or going to sleep.

On the other hand, a disadvantage is that in each time slot may be a guard time to allow synchronization that limit the potential bandwidth of a TDMA channel. It's possible also to create interference at a frequency which is directly connected to the time slot length. TDMA cannot prevent the potential waste of channel resource when many devices don't transmit during their tome slot.

FDMA - Frequency Division Multiple Access

Frequency-Division Multiple Access (FDMA) is the division of the frequency band allocated for communication into several channels, each of them can carry analog or digital data. Each user can transmit data using its own channel. Since the user has his portion of the bandwidth all the time, FDMA does not require synchronization or timing control, which makes it algorithmically simple. Even though no two users use the same frequency band at the same time, guard bands are introduced between frequency bands to minimize adjacent channel interference. Figure 2.11 shows the FDMA structure.

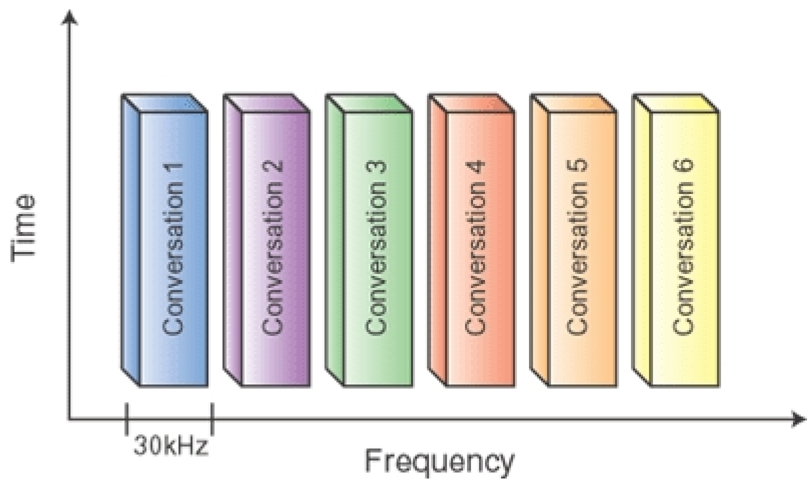


Figure 2.11: FDMA structure

CDMA - Code Division Multiple Access

In Code Division Multiple Access (CDMA) each user has its own pseudo-random code (also called Pseudo-Noise (PN) code) used to spread the spectrum of its data over the all channel bandwidth. In this way is possible that several devices transmit using the same frequency channel at the same time without harmful interference. Signals with the desired spreading code and timing are received, while signals with different spreading codes (or the same spreading code but a different timing offset) appear as wideband noise reduced by the process gain. Figure 2.12 shows the CDMA structure.

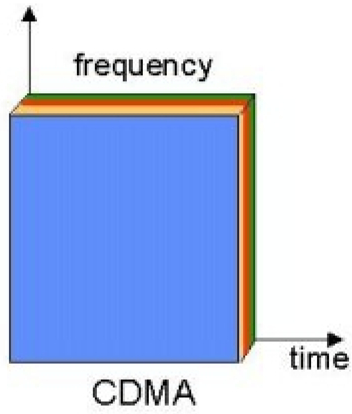


Figure 2.12: CDMA structure

The main advantage of CDMA over TDMA and FDMA is that, as the pseudo-random codes are essentially infinite, it allows a very large number of simultaneous communications.
In the other hand, CDMA cannot completely reject unwanted signals as the TDMA and FDMA do.

2.2.2 Random Access Protocols

Pure ALOHA

Pure ALOHA [5], refers to a simple communications scheme in which each source in a network sends data whenever there is a frame to send and then listen for the Acknowledgment (ACK) that ensure that the data is successfully received. If the frame successfully reaches the destination, the next frame is sent. If the frame fails to be received at the destination, and thus no ACK is received by the source during a timeout period, it is sent again after waiting for a random time. This protocol was originally developed at the University of Hawaii for use with satellite communication systems in the Pacific.

In a wireless broadcast system or a half-duplex two-way link, Pure ALOHA works perfectly. But as networks become more complex, for example in systems involving multiple sources and destinations in which data travels many paths at once, trouble occurs because data frames collide. The heavier the communications volume, the worse the collision problems become. The result is degradation of system efficiency, because when two frames collide, the data contained in both frames is lost. Under this assumption the vulnerable period is, if T is the transmission time for a packet, is $2T$. As depicted in figure 2.13 the three first attempt to send data by some nodes in the networks are all failed. Only node B after waiting for a random time send successfully his data.

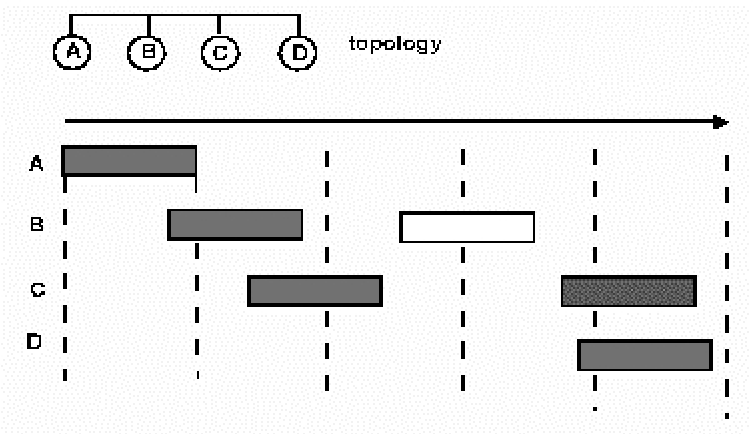


Figure 2.13: Pure ALOHA protocol

The formula to estimate the throughput S for a Pure ALOHA is

$$S = Ge^{-2G} \tag{2.11}$$

where G is the number of transmissions attempted per unit time. So, the maximum throughput achievable is 0.184 obtained when $G = 0.5$.

Slotted ALOHA

By making a small restriction in the transmission freedom of the individual stations, the throughput of the ALOHA protocol can be doubled [6]. Assuming constant length packets, transmission time is broken into slots equivalent to the transmission time of a single packet. Stations are only allowed to transmit at slot boundaries. When packets collide they will overlap completely instead of partially. So, now, if T is the transmission time for a packet, the vulnerable period is only T. Figure 2.14 shows how Slotted ALOHA works.

Figure 2.14: Slotted ALOHA protocol

This method, known as Slotted ALOHA, has the effect of doubling the efficiency of the Pure ALOHA protocol

$$S = Ge^{-G} \tag{2.12}$$

Figure 2.15 shows the graphics for the throughput for a Pure ALOHA system and for a Slotted ALOHA system.

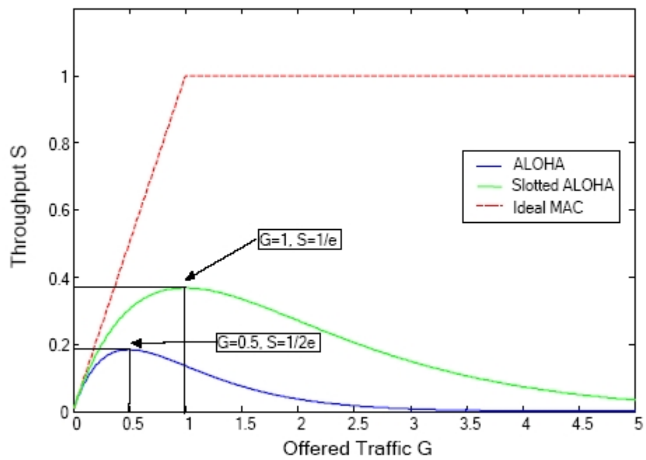


Figure 2.15: Pure and Slotted ALOHA throughput

CSMA - Carrier Sense Multiple Access

As in networks with high load the use of ALOHA protocols is not effective due to collisions, another protocol is introduced to achieve better performance. The main idea is to listen the channel before transmitting to avoid the collisions. This method is know as Carrier Sensing Multiple Access (CSMA) [7] and it is currently employed with the Collision Avoidance (CA) mechanism [8] in IEEE Std 802.11 Distributed Coordinator Function (DCF) networks [9].

When a terminal **A** has packets to transmit, it senses the channel before starting transmission. If another terminal **B** is already transmitting, terminal

A will detect its transmission will postpone its own transmission after a random time. When **A** senses the channel as idle for a predefined amount of time, it assumes the channel as available and starts transmission.
Unfortunately, collisions are always possible due the propagation time. If the packet emitted by **B** propagates to **A** after the channel sensing phase is concluded then **A**, assuming the channel free, will begin its transmission creating a collision. This method will lead to a throughput S equal to

$$S = \frac{Ge^{-aG}}{G(1+2a)+e^{-aG}} \tag{2.13}$$

where a is the propagation time between **A** and **B**. Because the propagation delay is different for every pair of terminals, throughput is evaluated with parameter a being set to the largest possible delay in the network (normalized by packet duration), leading to a lower bound for system performance. Figure 2.16 shows the throughput for a CSMA system in relation with different propagation time value.
To improve the throughput in wired systems a variation of standard CSMA, called CSMA/CD, is employed. In this case sending nodes are able to detect when a collision occurs and stop transmitting immediately, backing off for a random amount of time before trying again. This results in much more efficient use of the media since the bandwidth of transmitting the entire frame is not wasted.

The performance of CSMA can significantly be reduced in presence of two phenomena, the hidden terminal and the exposed terminal.
The former happens when a node **S** is transmitting to another node **D** and a third node **H** which cannot detect the transmission by node **S** (*i.e.*,due to limited radio coverage) and begins its own transmission creating collision in node **D**.

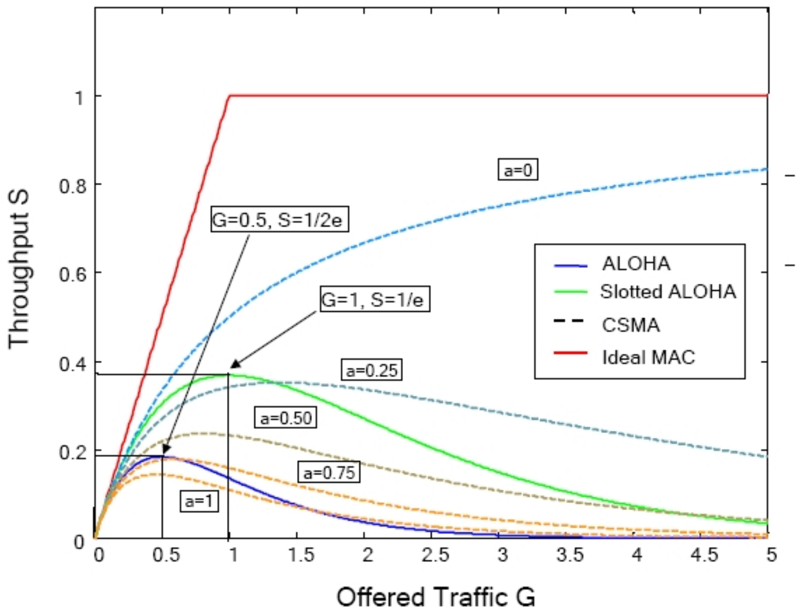


Figure 2.16: CSMA throughput

The latter happens when a node S1 transmission overlap another node S2 that, sensing the channel busy, postpones its transmission even if wants to transmit to a third node D2 not reachable from the first node, thus the transmission could be activated without causing any collision.

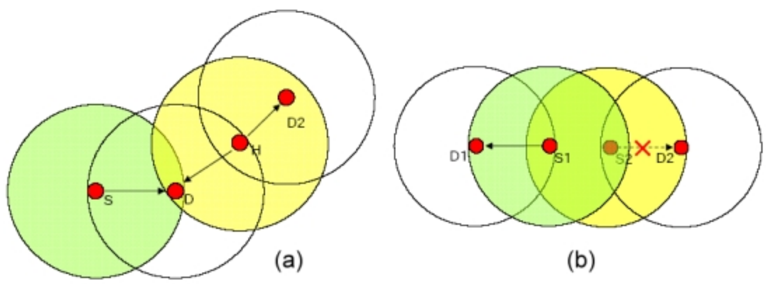


Figure 2.17: Hidden node (a) and Exposed node (b) problems

Figure 2.17 shows the hidden node and exposed node problems.

A mechanism to solve the hidden terminal is employed in CSMA/CA protocols where a sending node tries to avoid collisions by transmitting a short signal (Request To Send (RTS)) to indicate its intent to transmit and then wait to receive the answer signal (**CTS)!** (**CTS)!**) from the receiver device. When other nodes see the RTS signal, they wait long enough for this transmission before attempting to send any frames. Collisions are still possible, and are not detected so have the same consequences as in pure CSMA.

Chapter 3

UWB MAC

3.1 IEEE Std 802.15.4 LDR

3.1.1 General Overview

The IEEE 802.15 Working Group has defined three classes of WPANs that are differentiated by data rate, battery drain and QoS. The high-data rate WPAN (IEEE Std 802.15.3™) is suitable for multimedia applications that require very high QoS. Medium-rate WPANs (IEEE Std 802.15.1™/Bluetooth®) are designed as cable replacement for mobile phones and PDAs with a Quality of Service (QoS) suitable for voice applications. The last class of WPANs (IEEE Std 802.15.4™) [10] is intended to serve applications enabled only by the low power and low cost requirements not targeted in the above WPANs with also relaxed need for data rate and QoS.

The IEEE Std 802.15.4 architecture follows the ISO-OSI reference model, so an LDR-WPAN device comprises a PHY, which contain the RF transceiver along with its low-level control mechanism, and a MAC sublayer that provides access to the physical channel for all types of transfer. The standard doesn't provide specifications for the upper layers as the network layer, which provides network configuration and message routing, and application layer, which provides the intended function of the device.

PHY Layer

The PHY provides two services: the PHY data service and the PHY management service interfacing to the Physical Layer Management Entity (PLME). The PHY data service enables the transmission and reception of PHY Protocol Data Unit (PPDU)s across the physical radio channel.
The radio shall operate at one of the following license-free bands according to the regulatory requirements:

- 868-868.6 MHz for a 20kb/s DSSS service (*e.g.*,Europe),
- 902-928 MHz for a 40kb/s DSSS service (*e.g.*,North America) or
- 2400-2482.5 MHz for the faster 250kb/s DSSS service(worldwide).

The 2400-2482.5 MHz may be the first choice for many IEEE 802.15.4 applications, due the worldwide availability, especially those involving travel between different regulatory regions. The other bands can be used as an alternative when the use of the 2.4 GHz band is deprecated, due the presence of many others services operating in that band.

The IEEE Std 802.15.4 specifies also a total of 27 channels across the three frequency bands. The channels are number from 0 to 26, a channel is assigned in the 860 MHz band, 10 channels in the 915 MHz band and 16 channels in the 2.4 GHz band.

Currently the IEEE 802.15 Low Rate Alternative PHY Task Group (TG4a) for WPANs has defined a project to develop an alternative UWB PHY for IEEE Std 802.15.4. The principle interest is in providing communications and high precision ranging/location capability (1 meter accuracy and better), high aggregate throughput, and ultra low power; as well as adding scalability to data rates, longer range, and lower power consumption and cost.

MAC Layer

The MAC layer provides two service: the MAC data service and the MAC management service interfacing to the MAC Layer Management Entity (MLME) Service Access Point (SAP) (known as MLME-SAP). The MAC data service enables the transmission and reception of MAC Protocol Data Units (MPDU) across the PHY data service.

The features of the MAC sublayer are beacon management, channel access, Guaranteed Time Slot (GTS) management, frame validation, acknowledged frame delivery, association, and disassociation. In addition, the MAC sublayer provides hooks for implementing application appropriate security mechanisms.

To allow the implementation of extremely simple devices that require very low-cost and minimal hardware resources the IEEE 802.15.4 defines two types of devices, the Full Function Device (FFD) and the Reduced Function Device (RFD). The FFD contains the complete set of MAC services and allows it to operate as a network coordinator or network device. The RFD contains a reduced set of the MAC services, and it can only operate as a network device talking only to FFD devices and cannot relay messages.

An IEEE 802.15.4 network may be one of the two basic topologies. The first is the star topology (see §2.2) and it is formed around a FFD device that works as PAN coordinator and that acts as hub with a collection of additional FFD or RFD devices as data terminal locations. A star topology can be or not beacon enabled, according to the specific needs of the Personal Area Network (PAN). The second topology enables peer-to-peer communication without the direct involvement of a designated network coordinator that is still needed to create and maintain the network. As the RFD devices cannot relay messages, and thus they can create only a single connection to an FFD device, an RFD device in a peer-to-peer must be placed only as peripheral device.

Regardless of the type of the network employed, each network device employs a CSMA-CA protocol to access the channel. Exceptions to this are beacon transmission, transmission in GTSs, and acknowledgments, each of which is transmitted without the CSMA-CA process.

3.1.2 Functional Overview

This section provides a brief overview of the general function of a LDR-WPAN and include information about the superframe structure, the data transfer model and the frame structure of IEEE Std 802.15.4.

Superframe Structure

The IEEE Std 802.15.4 allows the optional use of a superframe structure. The format of the superframe is defined by the network coordinator and is bounded by beacon messages sent by coordinator at programmable regular intervals. The superframe is divided into 16 equally sized slot and the beacon is transmitted in the first slot of each superframe. The beacons are used to synchronize the attached devices, to identify the PAN, and to describe the structure of the superframes. Any device wishing to communicate during the Contention Access Period (CAP) between two beacons shall compete with other devices using a slotted CSMA-CA mechanism. All transactions shall be completed by the time of the next network beacon. Figure 3.1 shows the basic superframe structure.

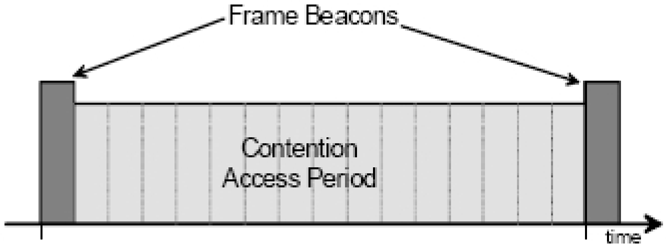


Figure 3.1: Superframe structure

Additionally, for low-latency applications or applications requiring specific data bandwidth, the PAN coordinator may dedicate portions of the active superframe to that application. These portions are called Guaranteed Time Slot (GTS)s. The GTS form the Contention Free Period (CFP), which always appears at the end of the active superframe starting at a slot boundary immediately following the CAP, as shown in 3.2. The PAN coordinator may allocate up to seven of these GTSs, and a GTS may occupy more than one slot period. However, a sufficient portion of the CAP shall remain for contention-based access of other networked devices or new devices wishing to join the network. All contention-based transactions shall be complete before the CFP begins. Also each device transmitting in a GTS shall ensure that its transaction is complete before the time of the next GTS or the end of the

CFP.

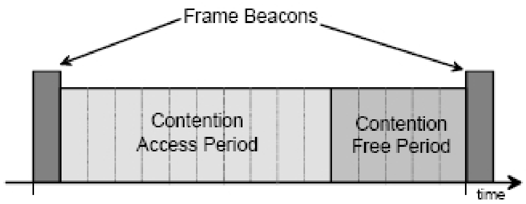


Figure 3.2: Superframe structure with GTSs

Data Transfers Model

The data transfer model of IEEE Std 802.15.4 depends on the network topology in use. In star networks the communication exchange always occur between a PAN coordinator and a network device while in the peer-to-peer mode, a device communicate with any other in its vicinity.

In star topology can have two types of data transfer model depending if the network is beacon-enabled or not.

For a beacon-enabled network, if a device wants to transmit some data to the coordinator, it will first listen for the network beacon to synchronize itself with the superframe structure. At the appropriate point, the device transmits its data frame, using slotted CSMA-CA, to the coordinator. Then the coordinator acknowledges the successful reception of the data by transmitting an optional acknowledgment frame.
If the coordinator wants to transfer data to a device in a beacon-enabled network, it indicates in the network beacon that the data message is pending. The device periodically listens to the network beacon and, if a message is pending, transmits a MAC command requesting the data, using slotted

CSMA-CA. The coordinator acknowledges the successful reception of the data request by transmitting an optional acknowledgment frame. The pending data frame is then sent using slotted CSMA-CA. The device acknowledges the successful reception of the data by transmitting an acknowledgment frame. Figure 3.3 summarizes the transmission models for a beacon-enabled networks.

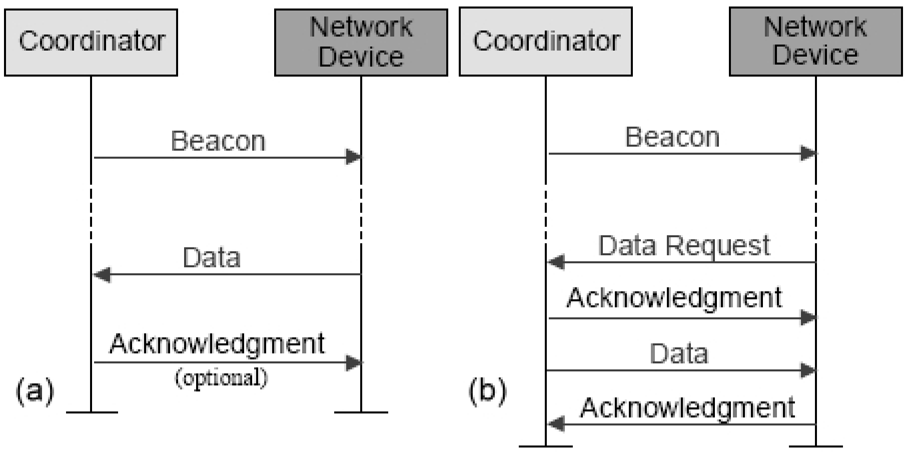


Figure 3.3: Communication (a) to (b) from a coordinator, beacon-enabled network

For a nonbeacon-enabled network, if a device wants to transmit some data to the coordinator, it simply transmits its data frame, using unslotted CSMA-CA, to the coordinator. The coordinator acknowledges the successful reception of the data by transmitting an optional acknowledgment frame.
If the coordinator wants to transfer data to a device in a nonbeacon-enabled network, network, it stores the data for the appropriate device to make contact and request the data. A device may make contact by transmitting a MAC command requesting the data, using unslotted CSMA-CA, to its coordinator at an application-defined rate. The coordinator acknowledges the successful reception of the data request by transmitting an acknowledgment

frame. If data is pending, the coordinator transmits the data frame, using unslotted CSMA-CA, to the device. If data is not pending, the coordinator transmits a data frame with a zero-length payload to indicate that no data was pending. The device acknowledges the successful reception of the data by transmitting an acknowledgment frame. Figure 3.4 summarizes the transmission models for a beacon-enabled networks.

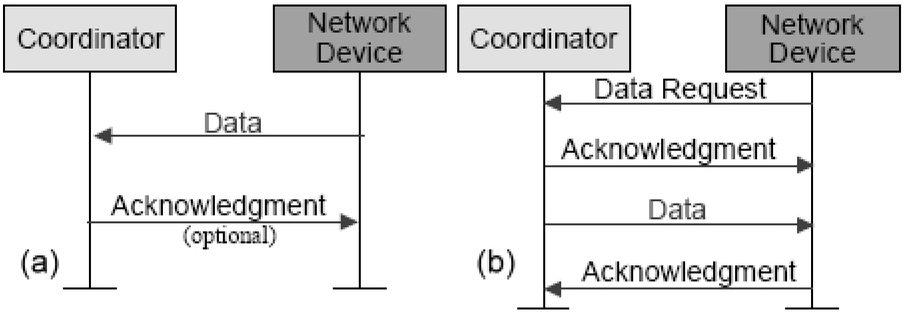


Figure 3.4: Communication (a) to (b) from a coordinator, nonbeacon-enabled network

For peer-to-peer topologies data transfer strategy is governed by the specific network layer managing the wireless network. In order to do this effectively, the devices wishing to communicate will need to either receive constantly or synchronize with each other. In the former case, the device can simply transmit its data using unslotted CSMA-CA. In the latter case, other measures need to be taken in order to achieve synchronization. Such measures are beyond the scope of IEEE Std 802.15.4.

Frame Structure

The IEEE Std 802.15.4 defines four frame structure, each designed as PPDU:

- A beacon frame, used by a coordinator to transmit beacons

- A data frame, used for all transfers of data
- An acknowledgment frame, used for confirming successful frame reception
- A MAC command frame, used for handling all MAC peer entity control transfers

Each PPDU is constructed with a Synchronization Header (SHR), a PHY Header (PHR), and a PHY Service Data Unit (PSDU), composed of the MAC Protocol Data Units (MPDU) as a data structure that services the MAC protocol layer. The MPDU is constructed with a MAC Header (MHR), a MAC Footer (MFR), and a MAC Service Data Unit (MSDU) excepting for the acknowledgement frame which doesn't contain an MSDU.

The beacon frame originates from the MAC sublayer and interfaced to the PHY protocol layer. Only the PAN coordinator can transmit beacon frames in a beacon-enabled network. It has a number of uses, including superframe boundary marker, frame synchronization signal, and association supervision, all as a service to the higher protocol layers. Figure 3.5 shows the composition of the beacon frame.

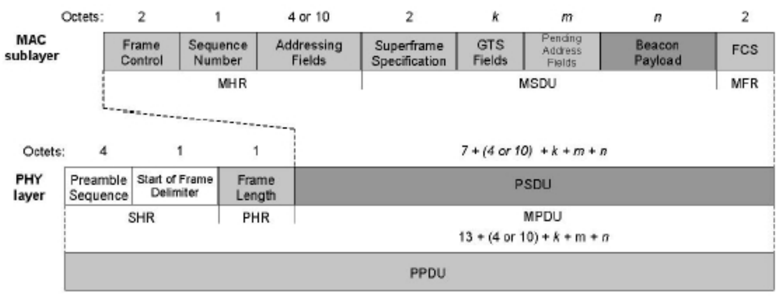


Figure 3.5: Beacon frame structure

The data frame is available to all device in any network, independently of the network topology. It provides the primary data payload as a service to the higher protocol layers. Figure 3.6 shows the composition of the data frame.

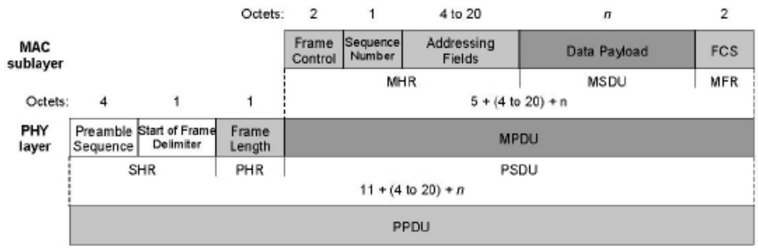


Figure 3.6: Data frame structure

The acknowledgment frame is also available to all device in any network, independently of the network topology. It doesn't contain a MAC payload and provides only the acknowledgement for receipt of data as a service to the higher-lever protocol layers for end-to-end message control. Figure 3.7 shows the composition of the acknowledgement frame.

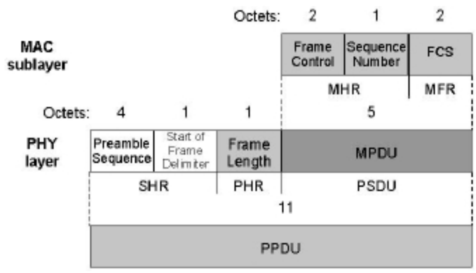


Figure 3.7: Acknowledgement frame structure

The MAC command frame is also available to all device in any network, independently of the network topology. It provides the primary supervisory payload as a service to the MAC protocol layer. Figure 3.8 shows the composition of the MAC command frame.

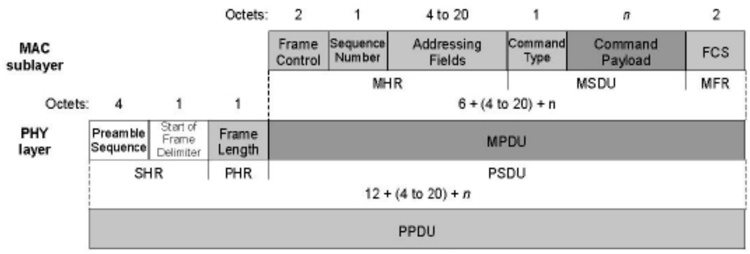


Figure 3.8: MAC command frame structure

3.1.3 Functional Description

This section provides a description of the MAC functionality. It describes the mechanisms to allow devices to join or leave a PAN, the association procedure, the synchronization with the coordinator and the use of GTSs.

Starting and maintaining PANs

There are four types of channel scans. All devices shall be capable of performing passive and orphan scans across a specified list of channels. In addition, an FFD shall be able to perform Energy Detection (ED) and active scans. They are as follows:

Energy Detection Scan Allows an FFD to obtain a measure of the peak energy in each requested channel. This could be used by a prospective

PAN coordinator to select a channel in which to operate prior to starting a new PAN. During an ED scan, the MAC sublayer shall discard all frames received over the PHY data service.

Active Channel Scan Allows an FFD to locate any coordinator transmitting beacon frames within its POS. This could be used by a prospective PAN coordinator to select a PAN identifier prior to starting a new PAN, or it could be used by a device prior to association. During an active scan, the MAC sublayer shall discard all frames received over the PHY data service that are not beacon frames.

Passive Channel Scan A passive scan, like an active scan, allows a device to locate any coordinator transmitting beacon frames within its Personal Operating Space (POS). The beacon request command, however, is not transmitted. This type of scan could be used by a device prior to association. During a passive scan, the MAC sublayer shall discard all frames received over the PHY data service that are not beacon frames.

Orphan Channel Scan An orphan scan allows a device to attempt to relocate its coordinator following a loss of synchronization. During an orphan scan, the MAC sublayer shall discard all frames received over the PHY data service that are not coordinator realignment MAC command frames.

A PAN shall be started by an FFD only after an active channel scan has been performed and a suitable PAN identifier selection has been made. In some instances a situation could occur in which two PANs exist in the same POS with the same PAN identifier. If this conflict happens, the coordinator and its devices shall perform PAN identifier conflict resolution procedure. In that case the coordinator shall perform an active scan and choose a valid PAN

ID, then it shall broadcast the coordinator realignment command containing the new PAN identifier with the source PAN identifier.

On the detection of a PAN identifier conflict by a device, it shall generate the PAN ID conflict notification command and send it to the PAN coordinator. If the PAN ID conflict notification command is received correctly, the PAN coordinator shall send an acknowledgment frame, thus confirming receipt. The PAN coordinator shall then resolve the conflict as described above.

After a valid PAN ID has been selected the coordinator is allowed to send beacon frames to allow the other devices to perform device discovery.

Association and disassociation

Following a successful active or passive channel scan, a network device can issue an association request to the coordinator found, that can accept or reject the request depending on the capabilities and the requirements of the application controlling the PAN coordinator. If the association request command is received correctly, the coordinator shall send an acknowledgment frame, thus confirming receipt. The acknowledgment to an association request command does not mean that the device has associated, the association response will be sent inside the beacon or in a command frame depending on the type of the network. On receiving the association response command, the device requesting association shall send an acknowledgment frame, thus confirming receipt. If the association status field of the command indicates that the association was successful, the device shall store the addresses of the coordinator with which it has associated.

When a coordinator wants one of its associated devices to leave the PAN, it shall send the disassociation notification command to the device using indirect transmission, adding the command to the list of pending transactions and extracted at the discretion of the device concerned using the request data command. If the device requests and correctly receives the disassociation notification command, it shall confirm its receipt by sending an acknowledgment frame. Even if the acknowledgment is not received, the coordinator shall consider the device disassociated.

If an associated device wants to leave the PAN, it shall send a disassociation notification command to its coordinator. If the disassociation notification command is received correctly by the coordinator, it shall confirm its receipt by sending an acknowledgment frame. Even if the acknowledgment is not received, the device shall consider itself disassociated.

An associated device shall disassociate itself by removing all references to the PAN. A coordinator shall disassociate a device by removing all references to that device.

Synchronization

For PANs supporting beacons, synchronization is performed by receiving and decoding the beacon frames, otherwise synchronization is performed by polling the coordinator for data. All devices operating on a beacon-enabled PAN shall be able to acquire beacon synchronization in order to detect any pending messages or to track the beacon. If a beacon frame is received, the device shall verify that the beacon frame came from the coordinator with which it associated, otherwise the device must discard it.

In nonbeacon-enabled PANs any device shall be able to poll the coordinator for pending data.

If the next higher layer receives repeated communications failures following its requests to transmit data, it may conclude that it has been orphaned. If the next higher layer concludes that it has been orphaned, it may perform the orphaned device realignment procedure sending an orphan notification to the coordinator that will search for the orphan devices in its devices list and, if the search is successful, send a realignment command to the orphan devices. Otherwise the orphan device may reset the MAC sublayer and then perform the association procedure.

GTS management

A GTS allows a device to operate on the channel within a portion of the superframe that is dedicated exclusively to that device. A GTS shall be allocated only by the PAN coordinator, and it shall be used only for communications between the PAN coordinator and a device. A single GTS may extend over one or more superframe slots. The PAN coordinator may allocate up to seven GTSs at the same time, provided there is sufficient capacity in the superframe. GTSs shall be allocated on a first-come-first-served basis, and all GTSs shall be placed contiguously at the end of the superframe and after the CAP. Each GTS shall be deallocated when the GTS is no longer required (*i.e.*,due the inactivity of the device during its GTS), and a GTS can be deallocated at any time at the discretion of the PAN coordinator or by the device that originally requested the GTS. A device that has been allocated a GTS may also operate in the CAP.

A device to request the allocation of a new GTS shall send the GTS request command to the PAN coordinator and shall continue to track beacons for a GTS descriptor that must be received until a timeout time, if the descriptor is not received before reaching the timeout the higher layer will be notified of the failure. If the GTS request command is received correctly, the PAN coordinator shall send an acknowledgment frame, thus confirming receipt. On receipt of a GTS request command indicating a GTS allocation request, the PAN coordinator shall first check if there is available capacity in the current superframe, based on the remaining length of the CAP and the desired length of the requested GTS, and after shall set the appropriate GTS descriptor in the beacon.

When a device receive a valid GTS descriptor indicating the successful allocation of the GTS that device can transmit inside its GTS without using CSMA-CA protocol.

If a GTS deallocation is initiated by a device, it shall send a GTS request command to the PAN coordinator indicating a request for GTS deallocation. From that point onward the device will not use anymore the previous allocated GTS. If the GTS request command is received correctly, the PAN coordinator shall attempt to deallocate the GTS and shall send an acknowledgment frame, thus confirming receipt. If the GTS request command is not received correctly by the PAN coordinator, it shall determine that the device has stopped using its GTS due inactivity.

If a GTS deallocation is initiated by the PAN coordinator, it shall deallocate the GTS and add a GTS descriptor into its beacon frame corresponding to the deallocated GTS. On receipt of a beacon frame containing a GTS descriptor corresponding to a GTS deallocation, the device shall immediately stop using the GTS.

The deallocation of a GTS may result in the superframe becoming fragmented. In that case the PAN coordinator shall ensure that any gaps occurring in the CFP, appearing due to the deallocation of a GTS, are removed to maximize the length of the CAP.

3.2 Low Data Rate MAC with Location and Tracking for Ultra-WideBand Technology

3.2.1 General Overview

PULSERS is the acronym for Pervasive Ultra-wideband Low Spectral Energy Radio System (PULSERS) project and its main objective is to study, design and develop new communication systems based on UWB [11]. A PANs working with PULSERS technology can work at Very High Data Rate (VHDR), High Data Rate (HDR), LDR and LDR with Location/Tracking (LDR-LT), thus systems based on PULSERS technology can cover a wide range of applications from high-quality video streaming devices to very low cost and low power consumption devices for sensor networks.

The PULSERS architecture follows the ISO-OSI reference model and its approach is to reuse as much as possible from the IEEE Std 802.15.4 in order to reduce the unproductive design of a completely new protocol, and to focus on the key issues described above [12]. The main deviations from the standard are following:

- Support for peer-to-peer communication, whereas 802.15.4 requires mediation from the coordinator to allow this.
- Dedicated time slots for ranging and allocation request.
- Simplification of association, transaction to allow very low complexity implementations.

PHY Layer

The key feature of the PULSERS LDR-LT physical layer is to support ranging, combined with minimal support to relaying.

Framing format and definitions are taken from IEEE Std 802.15.4 with some alterations in the field sizes to optimize the throughput and end-to-end delay.

The radio operates in a single frequency channel at 3.6 GHz as geometric center frequency with 1 GHz bandwidth. The data rate range for LDR devices is from 1 kbps to 1 Mbps, with a mean value of 100 kbps. For LDR-LT devices is from 1 kbps to 100 kbps, with a mean value of 10 kbps.

The PHY is not able/asked to deliver any RSSI, energy detection or link quality indication to the upper layer. Therefore Clear Channel Assessment (CCA) to check if the channel is busy or not is not supported.

In the case multiple access in simultaneously operating piconets is supported, the modulator would support the use of PN code spreading, *e.g.*,polarity or/and TH code. This PN codes are different among piconets for interference mitigation and better performance and a procedure to recognize/share/get the PN is required.

MAC Layer

As the PULSERS follows strictly the IEEE Std 802.15.4, to achieve low-complexity and low-cost devices, also the features of the PULSERS MAC sublayer are beacon management, channel access, GTS management, frame validation, acknowledged frame delivery, association, and disassociation. In addition, the PULSERS MAC sublayer provides an improved mechanism for location and positioning system. Support for FFD and RFD devices is also provided.

In a LDR scenarios [13], the huge bandwidth adopted for transmission translates in very short, rare pulses, and thus in a low probability of collisions between pulses emitted by different terminal. Under this hypothesis, all the devices can use a slotted ALOHA protocol to access the channel. This is translated in terms of lower complexity, and thus cost, and permits adaption between different PHY layers without particular issue, due the absence of specific PHY functions as the Carrier Sensing.

3.2.2 Functional Overview

This section provides a brief overview about the superframe structure, the data transfer model and the frame structure of PULSERS.

Superframe Structure

The coordinator of a PAN bounds its channel time using a superframe structure, itself bounded by transmission of beacons. Active and inactive periods are kept, the last one enabling the coordinator to enter sleep mode.

To improve the QoS for real time service and the performance of ranging some modification are introduced in the superframe structure of IEEE Std 802.15.4. As shown in Figure 3.9, two slot at end of the CFP are now reserved for GTS request and ranging purpose.

The first slot of the superframe is dedicated to the beacon. Only the coordinator can send beacon and it's received by all piconet devices. Then follows the CAP with the primary purpose to enable association. Any device wishing to communicate during the CAP between two beacons shall use a slotted ALOHA mechanism. In case of collision each sender will delay after a colli-

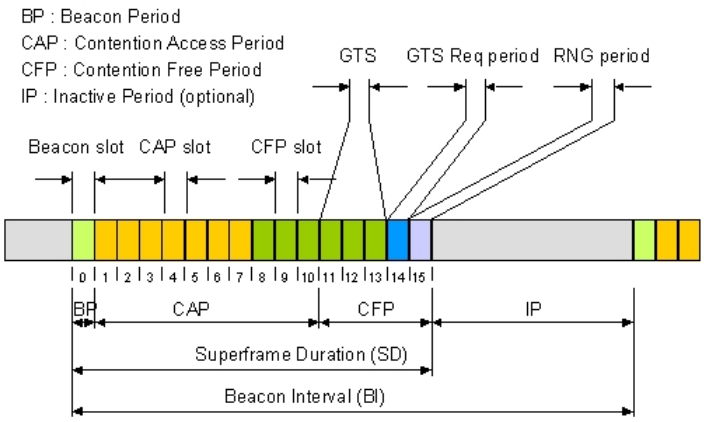


Figure 3.9: PULSERS superframe structure

sion before attempting to retransmit. CFP starts immediately after the last slot of the CAP. A device will be allowed to transmit during a CFP slot according to the slot allocation table transmitted by the coordinator during the previous beacon. Only one frame is allowed per slot. In the optional Inactive Period (IP) the MAC sublayer requests the PHY to disable its receiver. The MAC sublayer may request the PHY to re-enable the receiver shortly before the end of the same period or at any time afterwards. When the device disables its receiver during more than one GTS, it is of its responsibility to determine if its previous GTS grant is still valid or not.

Data Transfer

In PULSERS the indirect transactions, based on the usage of pending messages, are not supported. Thus, if a non-coordinator device wants to send data to the coordinator or to another peer device, it shall wait an indication by the coordinator, in the beacon frame, indicating that a GTS is granted to the device. The receiver shall acknowledge the received message if in the received frame the acknowledge subfield is set.

Frame Structure

The frame structure of PULSERS follows the baseline of IEEE Std 802.15.4 with the addition of the ranging frame. Figure 3.10 show its frame structure.

Octets	2	1	4 or 20	n > TBD	2
Ranging MPDU	Frame Control	Sequence Number	Address Info	Ranging Payload	FCS
	MHR			MSDU	MFR

Figure 3.10: PULSERS ranging frame structure

3.2.3 Functional Description

This section provides a description of the MAC functionality. It describes the mechanisms to allow devices to join or leave a PAN, the association procedure, the synchronization with the coordinator, the ranging procedure and the use of GTSs.

Starting and maintaining PANs

At the actual stage of the project only one channel is supported, thus devices are not required to perform passive and orphan scans. Piconet identifier conflict cannot occur since only one piconet is supported, thus every node uses the same piconet identifier.
A FFD, which is defined as a coordinator by the higher layer, starts the piconet, once it is activated and begins to transmit beacon frames.

Association and disassociation

When activated, a device may begin tracking beacons of the coordinator, when this is requested by the higher layer. When the MAC sublayer of an unassociated device receives a beacon frame it sends a confirm primitive to the higher layer. At the same time, it shall set the PAN ID and the coordinator address according to the beacon frame. When the higher layer replies with a request primitive, the MAC layer shall begin the association procedure sending the association request command to the coordinator with its long address in the appropriate field. If the association request command frame is received correctly, the coordinator must accept the association and assign a short address to the device according to the long address that it has received. The coordinator keeps the links between the short and the long address in a dedicated table. Then an association response command frame shall be sent to the device so as to confirm the association and to provide the assigned short address. After that, the MAC layer of the device will send a confirm primitive to the higher layer in order to indicate that the association procedure has succeeded.

At the actual stage of the project the disassociation procedure is not supported.

Synchronization

A device can synchronize by receiving and decoding beacon frames sent by a coordinator device. Any device that is turned on would seek for a beacon and try to get associated to an existing piconet.
To acquire beacon synchronization, a device shall search for a defined number of symbols. If no beacon frame is received during this time, the number of missed beacons shall be increased by one and the MAC layer repeats this

search. The synchronization is lost if the number of missed beacons reaches a predefined constant. Then the MAC layer notifies the higher layer that the synchronization procedure is failed by sending an indication primitive.
If a valid beacon frame is received, the device shall decode the beacon frame and extract pertinent information. At this time, it is considered as synchronized with the coordinator. Then the MAC sublayer sends a beacon notification primitive, with the information contained in the beacon frame, to the next higher layer. The primitive also transfer a measure of the link quality and the time the beacon frame was received.

Ranging and Positioning

In PULSERS at the end of the superframe structure there are few GTS reserved for ranging purpose, these slots are forming the so called Ranging (RNG) Period. The number of this slot depends on the adopted algorithm for ranging mechanism. There are two main algorithms:

- Time Of Arrival/Two Way Ranging (TOA/TWR), which a priori necessitates two (respectively, three) adjacent GTS in the RNG Period for a peer-to-peer ranging between two distinct asynchronous nodes (fixed or mobile) without (respectively, with) drift correction.
- Time Difference Of Arrival/One Way Ranging (TDOA/OWR), which a priori necessitates only one GTS in the RNG Period for positioning a mobile node relative to at least three isochronous reference nodes.

PULSERS adopts the TOA algorithm which is obviously the preferable protocol in distributed networks and alleviates the constraints on synchronization. The TOA/TWR Mode involves two distinct nodes performing a classical peer-to-peer ranging transaction. A particular node assigned to the initiation of the ranging transaction transmits a request packet to another node, which estimates the TOA of the request, and then sends a response in the form of an ACK to the initiator, after a pre-convinced (theoretical) time defined by the protocol and measured on its own real clock. Then, the initiator measures on its own clock the time elapsed between the reception of the response and the instant when the request was sent. Finally, relying on this measurement and on the theoretical response delay, the initiator computes the relative distance from the responder. An enhancement for this basic scheme consists in sending additional packets (typically, in the next adjacent slot) so as to estimate the relative clock drift between entities.

GTS management

A device has to transmit data frames using guaranteed allocation, which is called GTS for Guaranteed Time Slot. It is requested by a device to the coordinator that can accept or refuse to grant the allocation.
The coordinator shall keep a minimum CAP length, at least two slots, to permit the association process. The first slot of the CAP is used to transmit an association request command frame by a device which intends to associate with the coordinator. Within the remaining CAP slots, the coordinator sends an acknowledgement to confirm the receipt of the frame.

When a device needs an allocation to transmit packets using GTS, it sends a GTS request frame to the coordinator. These requests are processed following a First In, First Out (FIFO) scheme. In this way, when the coordinator receives one of these frames, it shall first check if the number of slots requested is available in the current superframe, according to the remaining length of the CFP. Then it checks if the maximum number of GTS has not

been reached. If these conditions are valid, then the coordinator decides to allocate the GTS. If the node being allocated require the use of acknowledgement delivery, then the coordinator shall double every allocated slot, since every data sent in a slot requires an acknowledgement transmission in the next slot of the same GTS.
When a GTS is allocated successfully, the coordinator shall include the GTS descriptor in the beacon and update the GTS specification field accordingly. For each allocated GTS, a device shall be able to store its starting slot, its length and the destination device address if the device is the transmitter or the source address if the device shall receive this traffic flow.

When a valid GTS is allocated to a node for transmission, then a counter is used to evaluate the expiration of this GTS. If this transmitter doesn't send frames in the specified GTS this counter is increased by one, while when a frame is sent the counter in initialized to zero. Once the counter reaches the maximum value, the GTS is deallocated.
To request the deallocation of the GTS, a device shall send a GTS request command to the coordinator with the appropriate field set to 0 (GTS deallocation). If this frame is received correctly, the coordinator shall send an acknowledgement frame, so as to confirm the receipt. Then the coordinator deallocates the specified GTS.

3.3 MAC Protocol for Location and Tracking with Ultra-WideBand Technology

3.3.1 General Overview

The UWB Wireless Embedded Systems (UWEN) project [14] aims to develop a system capable of offering low rate communications with location and tracking for outdoor applications. The system concept is target for outdoor recreational activities such as cross country skiing, athletics and running. The concept includes the development of small, low power devices which are worn by the user. In a low infrastructure environment, the user is able to relay positioning and performance information via peer-to-peer connections to fixes nodes in the network. Devices which are not within range of the fixed node, called Access Point (AP), send their information using multi-hop techniques via intermediate nodes which act as relays.

PHY Layer

The UWEN transceiver utilizes the IR-UWB to produce a very wideband signal of up to several gigahertz [15]. To allow user separation the data is also spread using a Direct Sequence Spread Spectrum (DSSS) technique.
The -10 dB bandwidth is 4.16 GHz and goes from a minimum of 1.03 GHz to a maximum of 5.19 GHz. As the transmitted power is limited by FCC rules, to achieve enough signal energy the transmitted pulse needs to be repeated several times. So each transmitted bit is defined by a train of pulses.

MAC Layer

The MAC protocol for the UWEN project is TDMA based to give to the mobile devices a guaranteed access to fixed points in the network.
The fixed network is organized in clusters, each cluster contains a predefined number of AP. The purpose of this division is to provide the moving sensor tags an area that is much larger than the span of a single access point. This provide a notable reduction of association requests and channel time allocations. Additionally, the APs have a variable transmission power in such a way that the area to be covered has a minimal amount of overlap and gaps, as shown in figure 3.11. In the figure is also evident that an alternately transmission of beacons inside a cluster permits to cover a bigger area.

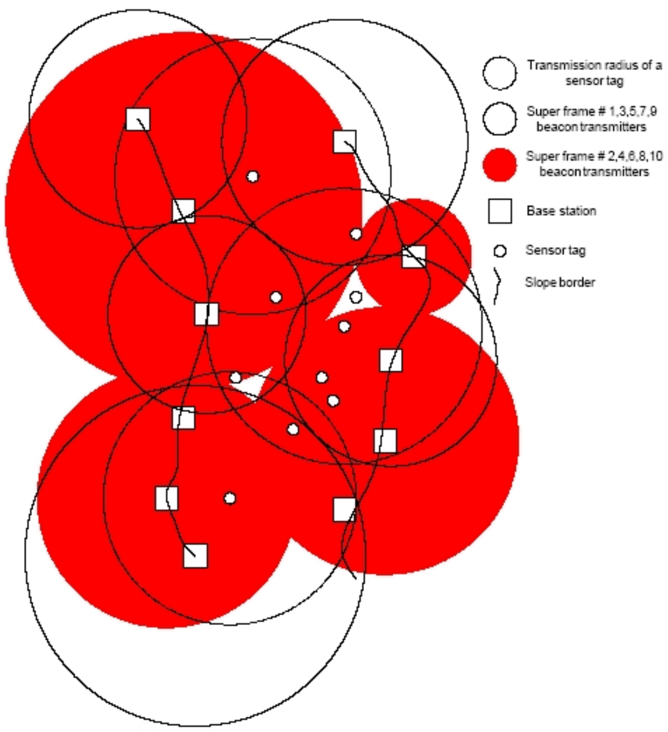


Figure 3.11: UWEN cluster structure

Even though the physical layer is the same, there are two fundamentally different MAC protocols to be defined; the sensor tag MAC and the AP cluster MAC. This is due to the necessity to have a very low cost and very simple MAC protocol in the sensor tags.

All the APs are connected to a positioning server which has the task of handle the data incoming from the AP, calculate the location, tracking the devices and presenting the results.

3.3.2 Functional Overview

This section provides a brief overview about the superframe structure, the data transfer model and the frame structure of UWEN.

Superframe Structure

The system is based on TDMA. The format of the superframe is defined by the network coordinator and is bounded by beacon messages sent by coordinator at programmable regular intervals. There are two main periods inside the superframe, a random access period and a reserved access period. Both the periods are divided in slots. There are two kind of consecutive slots, the uplink slots and the downlink slots. The former are used by the devices to send data to the master device while it is listening, the latter are used by the master device to send data to the other devices while they are listening. So, every device uses this pair of slots to communicate with the master. When a device gets inside the network a registration process starts. The device detects the beginning of the frame tracking the beacon and selects randomly a time slot inside the registration window in its talking time. This slot is selected randomly between n possible choices to try to avoid collision with other new devices. In the master talking time, the master replays in the same slot position of the registration window. The corresponding reply to a sensor tag registration announcement occurs in the next super frame following the current one. The information brought by this replay is the new slot position and the number of uplink/downlink slots for the device communication time. The device will have these time slots for as long as it stays within the cluster network. The bits composing one time slot can be used both for positioning and for data communication. By default, if the sensor tag does not have any data to transmit it transmits a special positioning frame in the beginning of its uplink slots.

To manage the cluster structure a *cluster frame* period is defined as a sequence of ten identical superframe. Figure 3.12 shows the structure of the cluster frame and of one superframe.

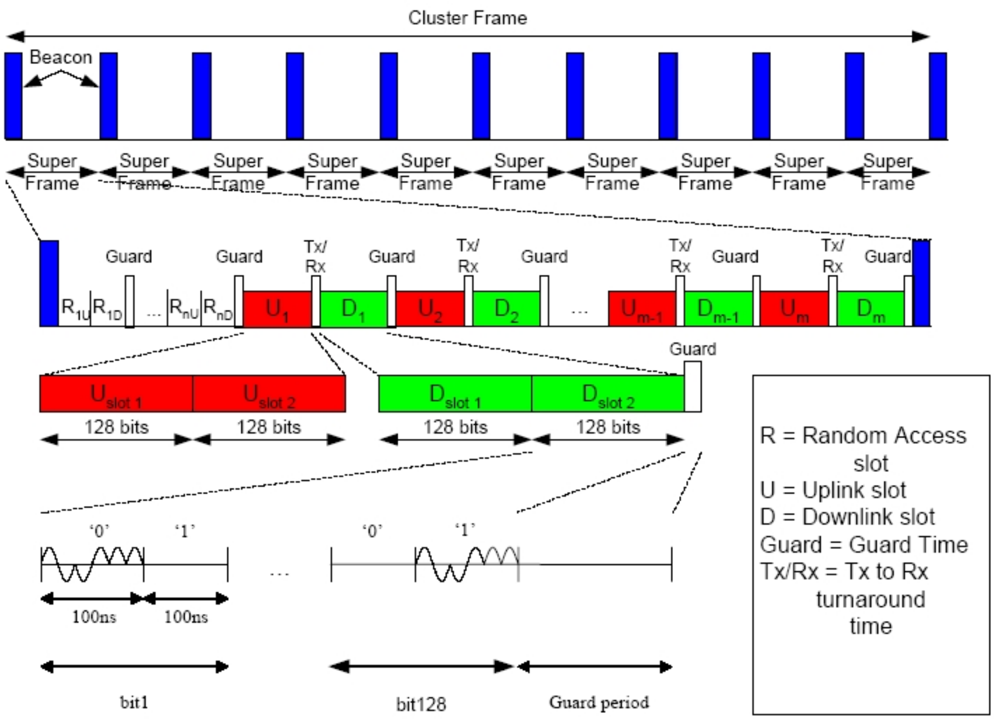


Figure 3.12: UWEN superframe structure

Data transfers

A device that is entering a network, as the network is a beacon-enabled network, first will synchronize listening at the beacon, then shall initiate an association process using the random access slot in the superframe to obtain at least one pair of uplink/downlink slots in the reserved slot period. These reserved slots shall be associated to the device during all the permanence of the device in the network. When the device wants to communicate with the master it shall use its own reserved uplink slots to send data, the master shall also use the corresponding downlink slots to send data to the devices. By default, when a device has no data to transmit a special positioning frame shall be sent.

Frame Structure

There are three types of frames, the sensor tag frame, the beacon frame and the AP.

The sensor tag frame originate from the sensor tag and its structure is shown in figure 3.13. The most important field for this kind of frame is the Type field as it is used to indicate the AP if the frame is a positioning frame, a data frame, a forwarding frame or command frame. A data frame automatically includes a positioning frame which is a frame with no data.
The beacon frame is periodically sent by the coordinator according to the superframe structure. It contains useful information as the cluster ID, slots management information and optional data to transmit to the devices. Figure 3.14 shows the beacon frame structure.

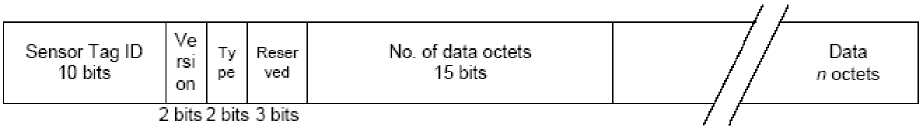


Figure 3.13: UWEN sensor tag frame structure

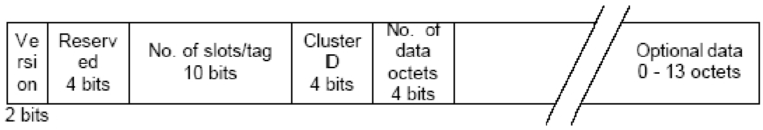


Figure 3.14: UWEN beacon frame structure

The AP frame is used when a cluster has some command or data to send to a sensor tag. In this case any AP inside the cluster can be used for the purpose using the downlink slot that immediately follows the uplink slot of the sensor tag. For this reason neither the source and destination addresses are used in the AP frame because the source can be any AP in the cluster and the destination is implicitly known by the downlink slot position. Figure 3.15 shows the AP frame structure.

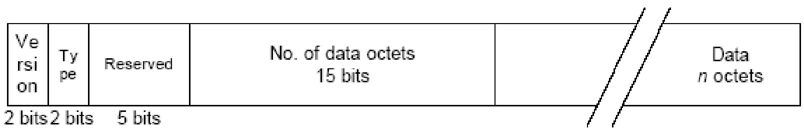


Figure 3.15: UWEN AP frame structure

3.3.3 Functional Description

This section provides a description of the MAC functionality. It describes the association procedure and the use of reserved slots.

Association and disassociation

This procedure shall begin when a device changes or enters in a new cluster. The process start with a random selection by the device of a uplink slot from the random access period and sends an association request. If the receiving AP is a member of the old cluster then the association request shall be discarded. Else, if the receiving AP is a member of the new cluster then the AP shall begin an association routine. After recording the uplink slot in which the device has sent the request, the request can be sent to the registration server. The server shall check the number of devices allocated in that cluster to check if there is space for the new device and, in case of success, alter its association table and end back the updates to all the APs and the devices in the clusters (old and new ones). Now, if the AP receiving the updates find that the device ID is already present in its cache it means that the AP belongs to the old cluster and then the device ID shall be simply removed from its cache and from now all the packet received from that device shall be discarded. Else, if the AP doesn't have the device ID in its cache it means that the AP belongs to the new cluster and then the device ID shall be added to its cache and a reply of the association request shall be sent to the device in the appropriate downlink slot.

Use of Reserved Slot

There are four types of slots: random access uplink slots, random access downlink slots, reserved uplink slots, and reserved downlink slots. The random access uplink slots can be used only for association and multi-hop set-up communications. The random access downlink slots are only used by access points for association communication and any other general information. The reserved uplink slots can only be used by the sensor tag that they have been assigned to, or in certain cases by a tag that is being multi-hop forwarded. The reserved downlink slot can be only used by an access point for any kind of communication to the sensor tag owning those downlink slots. The device will have these reserved slot for as long as it stays within the cluster network so, by default, if it doesn't have any data to transmit it shall transmit a special positioning frame in the beginning of its uplink slots. When a device joins a cluster the AP shall assign a number of reserved slot depending on the network condition. The AP can also dynamically increase or decrease the number of reserved slots assigned to each devices. The device cannot request an higher number of reserved slot unless it's forwarding another tag's information.

Chapter 4

Analysis and Simulation

4.1 Energy Model for UWB MAC

The aim of this section is to show how the energy analysis model for multi-hop MAC [3] can be used to study the MAC of the IEEE 802.15.4, IEEE 802.15.4a and PULSERS devices.

The model assumes that the process of data arrival is Poisson-like and the number of nodes in the network approaches infinite, therefore the probabilities used are exponential. The model consist of the energy consumed in a network in the transmission of data taking into account average contention times, average backoff times and possible frame collisions. The evaluation of the energy consumption is done by investigating the probabilities of transition from one MAC protocol state to another state and the related times consumed in transmit, receive, idle and sleep. In the model, one consumes energy in the process of arriving to a state. The states themselves are transitory and with certain probabilities one of all possible paths is chosen to arrive to a new state (in some case the same state as before).

4.1.1 MAC Analysis

The energy consumption model for the MAC employed in the IEEE 802.15.4 and IEEE 802.15.4a devices can be found in figure 4.1.

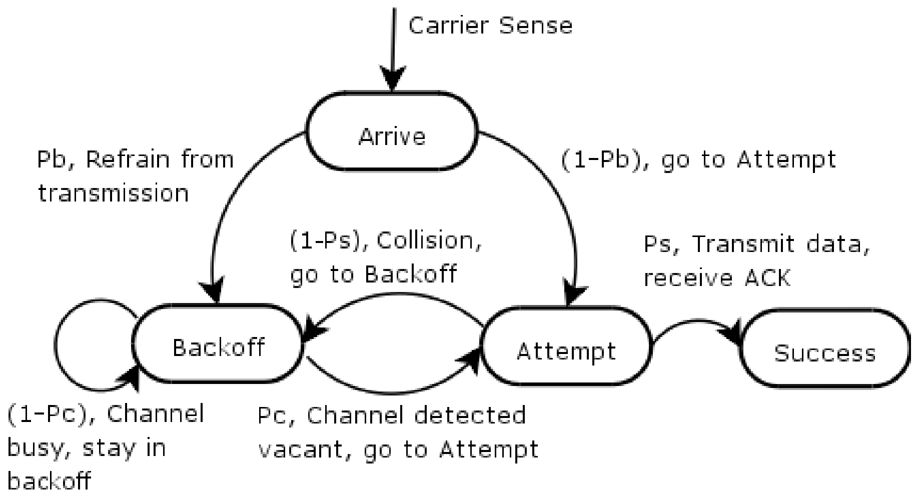


Figure 4.1: Transmit energy model for CSMA/CA.

There are four different states: *Arrive*, *Backoff*, *Attempt* and *Success*. The Arrive state is the entry point of to the system for a node with new data to transmit and, in the case of CSMA-CA protocols, a carrier sensing is always done before arriving to the *Arrive* state which consumes E_{Arrive} Joules of energy. Figure 4.1 leads a system of equations that if solved gives the average energy consumption. Let E_{TX} equal the expected energy consumption by a node with new data at the *Arrive* state until the node reaches the *Success* state. Let $E(A)$ equal the average energy consumption on each visit by the node to the *Attempt* state, and let $E(B)$ equal the energy consumption on each visit to the *Backoff* state. On every arrival to one of the states energy is consumed. This energy consumption consists of certain times and the time needed to transmit and the time spent in a specific transceiver mode.

There are probabilities attached to each of the arrivals depicting a certain exponential probability to choose that path. The sum of all the probabilities out of a specific state is always 1. To reach the *Success* state which is the exit point of the data transfer , all the possible transitions starting from the *Arrive* state and ending at the *Success* have to be calculated. The average energy consumption upon transmission from the point of packet arrival from the upper layer to the point of receiving an ACK frame is in general of the form

$$E_{TX} = E_{Arrive} + P_{prob1}E(A) + (1 - Pprob1)E(B), \tag{4.1}$$

$$E(A) = P_{prob2}E_{Success} + (1 - Pprob2)E(B), \tag{4.2}$$

$$E(B) = P_{prob3}E(A) + (1 - Pprob3)E(B), \tag{4.3}$$

where $P_{prob\{1,2,3\}}$ are different probabilities related to arrive to a certain state, $E_{Arrive}$is the carrier sensing energy consumption when coming to the *Arrive* state and $E_{Success}$ is the expected energy consumption upon reaching the *Success* state from the *Attempt* state.
For CSMA-CA, presenting the probabilities, the times and the transceiver modes explicitly, Eq. 4.1 translates to

$$E_{TX} = T_{CS}M_{RX} + (1 - P_b)E(A) + (1 - P_b)T_{RT}M_{TX} + P_bE(B) + P_bN_1M_{RX}. \tag{4.4}$$

In Eq. 4.4 the notation is:

- M_{TX} is the transceiver transmit power consumption and is related to the time consumed arriving to a state. Similarly, M_{TX} is transceiver reception power consumption.
- T_{CS} is the time required for carrier sensing.
- T_{RT} is the time required to change the transceiver state from receive to transmit.
- P_b is the probability of finding the channel busy during the carrier sensing.
- N_1 considers the backoff window and the number of the slot passed before attempt another carrier sensing.

Similarly, it is possible to do the same analysis from the *Backoff* and *Attempt* states as from the *Arrive* state. Respectively, for $E(A)$:

$$E(A) = P_S T_{PKT} M_{TX} + P_S \psi M_{RX} + (1 - P_S)E(B) + (1 - P_S)T_{PKT} M_{TX} + \\ + (1 - P_S)T_o M_{RX} \tag{4.5}$$

where

- T_{PKT} is the time required to transmit a whole packet, including the preamble data.
- ψ is the required to transmit a whole packet and receive the proper ACK frame, including the propagation delay.
- T_o is the timeout time.

- P_S is the probability of no collision.

And for $E(B)$:

$$E(B) = (1 - P_C)N_2M_{RX} + (1 - P_C)E(B) + P_CE(A) + P_CT_{RT}M_{TX} \quad (4.6)$$

where

- N_2 is the time spent in the *Backoff* state.
- P_C is the probability of finding no transmission.

Substituting Eq. 4.5 in Eq. 4.6 and then substituting the result in 4.5, $E(A)$ and $E(B)$ can be write as

$$E(A) = \delta + (1 - P_S)(\omega + P_C\delta)(P_CP_S)^{-1} \quad (4.7)$$

and

$$E(B) = (\omega + P_C\delta)(P_CP_S)^{-1} \quad (4.8)$$

where ω represents the energy model's transition from *Backoff* state to *Attempt* state or *Backoff* and δ represents the model's transition from *Attempt* state to *Backoff* state or *Success* state. Their explicit form are

$$\omega = (1 - P_C)N_2M_{RX} + P_CT_{RT}M_{TX} \quad (4.9)$$

and

$$\delta = P_S(T_{PKT}M_{TX} + \psi M_{RX}) + (1 - P_S)(T_{PKT}M_{TX} + T_oM_{RX}). \quad (4.10)$$

Using Eq. 4.7 and Eq. 4.8 in Eq. 4.4 it is finally possible to find the energy consumption during the transmission.
Note that we are not modelling the backoff with a Markov chain but we are using average values modified by G, where G is the normalized, average traffic offered to the channel.

The MAC protocol used in PULSERS devices is slotted ALOHA and the energy consumption model is obtained starting from Fig. 4.1 considering that in this case $P_C = 1$, $P_b = 0$ and from the *Backoff* state there is a direct transition to the *Success* state. Fig. 4.2 shows the model for the slotted ALOHA protocol.

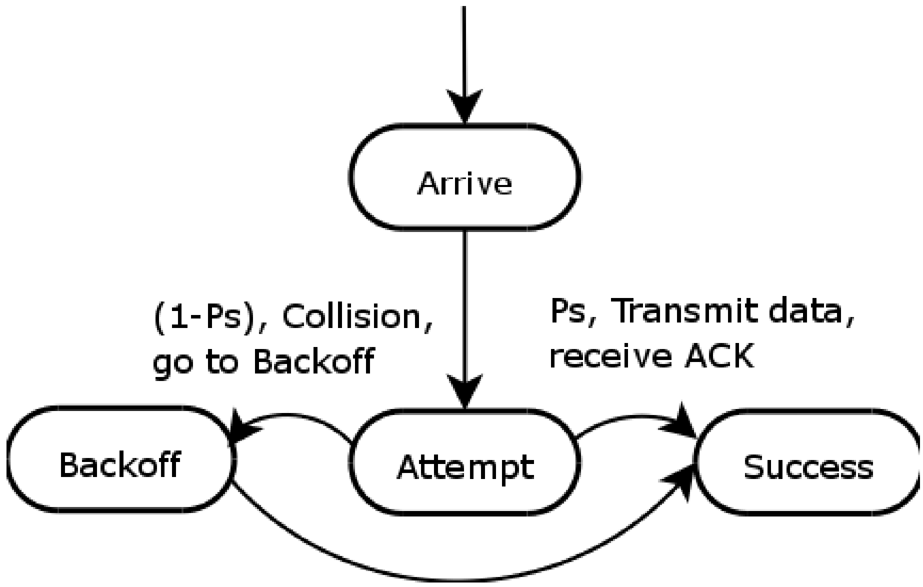


Figure 4.2: Transmit energy model for slotted ALOHA.

Thus, the equations system 4.1 can be written as

$$E_{TX} = E(A), \tag{4.11}$$

$$E(A) = P_S M_{TX} T_{PKT} + P_S \psi M_{RX} + (1 - P_S)E(B) + (1 - P_S)T_{PKT} M_{TX} + \\ + (1 - P_S)T_o M_{RX}, \tag{4.12}$$

$$E(B) = E(A), \tag{4.13}$$

and using substitution

$$E_{TX} = [P_S M_{TX} T_{PKT} + P_S \psi M_{RX} + (1 - P_S)T_{PKT} M_{TX} + (1 - P_S)T_o M_{RX}]P_S^{-1} \tag{4.14}$$

that gives the transmit energy consumption E_{TX}.

The UWEN uses a TDMA protocol to access the media, therefore a different approach to calculate the transmit energy consumption must be considered. The superframe structure showed in Fig. 3.12 suggests the right approach. The device, besides consuming energy during its transmission slots, consumes energy listening the superframe waiting for its time to transmit and also consumes energy changing its transceiver status from transmit, receive and sleep states. Thus, considering the superframe structure it leads to

$$E_{TX} = (T_{SR} + T_B)M_{RX} + (T_{RS} + T_R)M_{SL} + (T_{ST} + 2T_S)M_{TX} + \\ + (T_{TR} + 2T_S)M_{RX} + (T_{RS} + ((((CUS - 1) + (CDS - 1))SS)/BR) + \\ + NGT_G)M_{SL}$$

(4.15)

where

- M_{RX}, M_{TX} and M_{SL} are the transceiver transmit power consumption during receive, transmit and sleep states, respectively.
- T_{SR}, T_{ST}, T_{RS} and T_{TR} are the time employed to change the transceiver state from one to another.
- T_R, T_T, T_S and T_G are the time spent during the reception, transmission, sleep and guard slots, respectively.
- CUS, CDS and NG are communication uplink and downlink slots and the number of guard period for superframe, respectively.
- BR is the bitrate measured in bps.
- SS is the slot size in bit.

Eq. 4.15 gives the transmit energy consumption E_{TX} for UWEN device.

4.2 Simulation

This section explains how the simulator has been used to reach the purpose of our analysis. It will show a brief introduction to the NS-2 simulator, a description of the IEEE 802.15.4 model employed, an introduction of the Directed Diffusion routing algorithm and how the simulator has been set-up for our analysis.

4.2.1 Introduction to NS-2

NS-2 is the second version of NS, a discrete event simulator targeted at networking research. NS-2 provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks.

NS-2 is based on two languages: an object oriented simulator, written in C++, and a OTcl (an object oriented extension of Tcl) interpreter, used to execute user's command scripts. NS-2 has a rich library of network and protocol objects. There are two class hierarchies: the C++ compiled hierarchy and the interpreted OTcl one, with one to one correspondence between them. The compiled C++ hierarchy allows us to achieve efficiency in the simulation and faster execution time, useful for detailed definition and operation of protocols. Then in the OTcl script provided by the user, we can define a particular network topology, the specific protocols, the applications that we wish to simulate and the form of the output we wish to obtain from the simulator. The OTcl can make use of the object compiled in C++ through an OTcl linkage that creates a matching of OTcl object for each of the C++.

Figure 4.3 shows a simplified user's view of NS-2. As shown in the figure the user gives the OTcl script as input for the simulator defining the network topologies and the applications involved in the simulation. Then, after processing that input, the simulator gives as output the results that can be analyzed with appropriate analyzing tools.

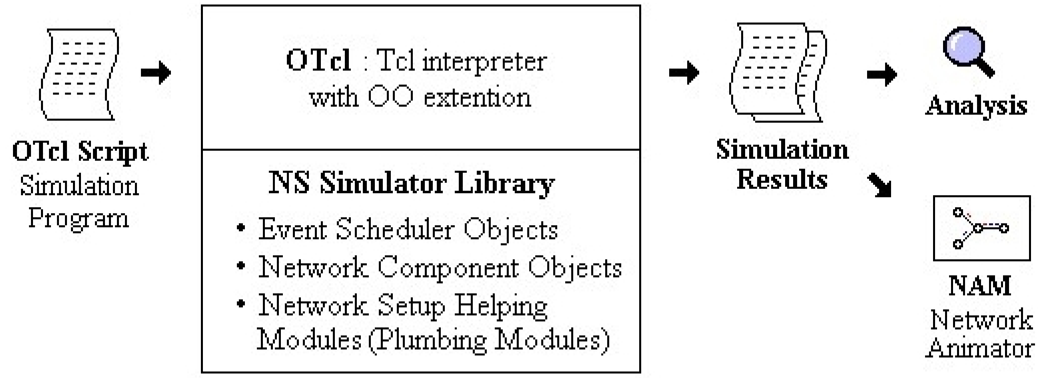


Figure 4.3: Simplified User's View of NS

4.2.2 The 802.15.4 NS-2 Model

The 802.15.4 NS2 simulator [16] developed at the Joint Lab of Samsung and the City University of New York confirms to IEEE P802.15.4/D18 Draft. Figure 4.4 outlines the function modules in the simulator.

The *Wireless Scenario Definition* selects the routing protocol, defines the network topology and schedules events such as initializations of PAN coordinator, coordinators and devices, and starting/stopping applications. It defines radio-propagation model, antenna model, interface queue, traffic pattern, link error model, link and node failures, superframe structure in beacon enabled mode, radio transmission range, and animation configuration.

The *Service Specific Convergence Sublayer (SSCS)* is the interface between 802.15.4 MAC and upper layers. It provides a way to access all the MAC primitives, but it can also serve as a wrapper of those primitives for convenient operations. It is an implementation specific module and its function should be tailored to the requirements of specific applications.

The 802.15.4 PHY implements all 14 PHY primitives.

The 802.15.4 MAC is the main module. It implements all the 35 MAC sub-

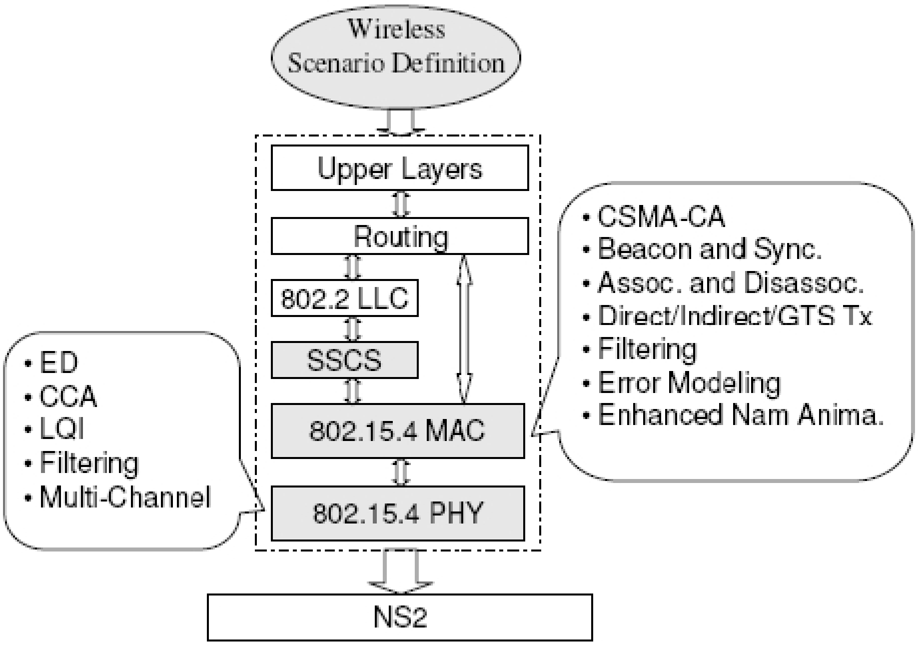


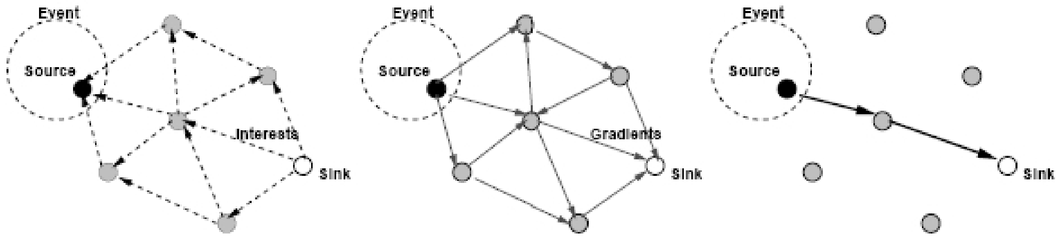
Figure 4.4: NS2 Simulator for IEEE 802.15.4

layer primitives.

4.2.3 Directed Diffusion

Directed Diffusion is a communication paradigm for wireless sensor networks [17] and is significantly different from IP-style communication where nodes are identified by their end-points, and inter-node communication is layered on an end-to-end delivery service provided within the network.

Directed diffusion is data-centric and consists of several elements [18]. Data is named using attribute-value pairs. A sensing task (or a subtask thereof) is disseminated throughout the sensor network as an interest for named data. This dissemination sets up gradients within the network designed to draw events (i.e., data matching the interest). Events start flowing towards the originators of interests along multiple paths. The sensor network reinforces one, or a small number of these paths. Figure 4.5 shows these elements.



(a) Interest propagation (b) Initial gradients set up (c) Data delivery along reinforced path

Figure 4.5: A simplified schematic for directed diffusion

It has been demonstrated that this paradigm is particulary suitable for sensor networks as it has an high energy efficiency and compared to others systems (*i.e.*,: flooding and omniscient multicast) shows very good performances.

4.2.4 Simulations description

The simulation work has been done configuring each node respectively as an IEEE 802.15.4 and IEEE 802.15.4a device. For each kind of device the network has been set up first with a fixed number of sources and sink (5 sources and 1 sink are used in this simulations) and increasing the size of the network to verify how it can affect the performance of the network. Then, the network has been set up with a fixed number of nodes and increasing the number of the sources (from 4 to 16 sources) to verify how the network performances are affected from an increasing number of active sensors. The networks have been created randomly placing the nodes inside an area whose dimension is chosen to have a fixed node density independently from the number of the nodes. The sink node and the sources nodes are randomly selected inside the network. Each node uses the directed diffusion algorithm, the interests were periodically generated every 5 seconds and each source generates two events for second. Events and interests were modelled as 111 byte packets.

The energy model used for the IEEE 802.15.4 devices has been set up to work has a Chipcon CC2420 whose parameters can be found in table 4.1. The IEEE 802.15.4a has been modelled with a generic UWB chip whose parameters are listed in the same table.

The target of the simulation is to compare the two kind of device at different

Parameter	**CC2420**	**UWB IC**
Idle Power	0.2mW	0.2mW
Rx Power	50mW	80mW
Tx Power	50mW	20mW
Sleep Power	0.001mW	0.0001mW
Transition Power	0.2mW	0.2mw
Transition Time	0.001s	0.001s

Table 4.1: Chipcon power parameters

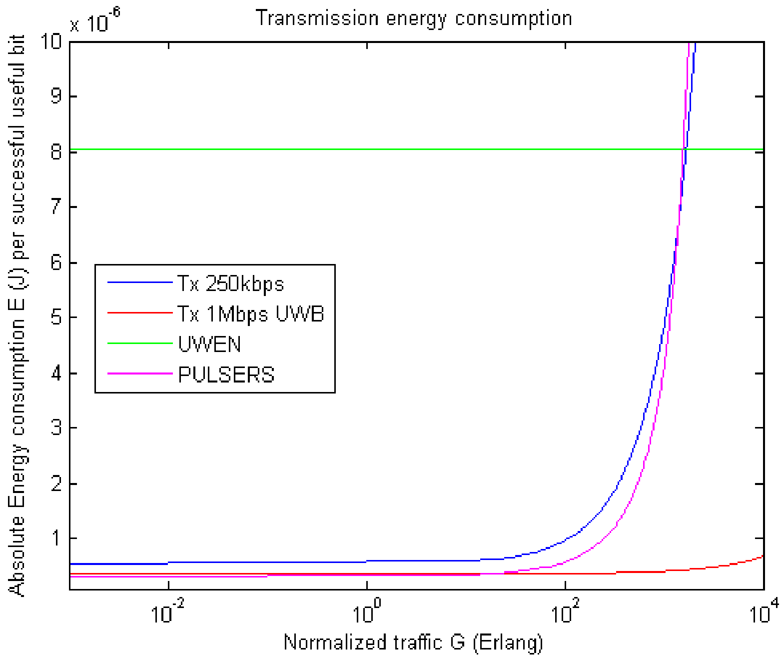
data rate measuring the typical parameters that have a relevance inside a sensor network, such the average delay to deliver successfully an event packet from a source to the sink, the average delivery ratio, that is the ratio between the number of the event packet that are successfully delivered and the total number of event packet generated in the network, and the average dissipated energy to successfully transmit an event packet. This last parameter is useful to analyze the effort done by the network to deliver successfully an event packet.

Chapter 5

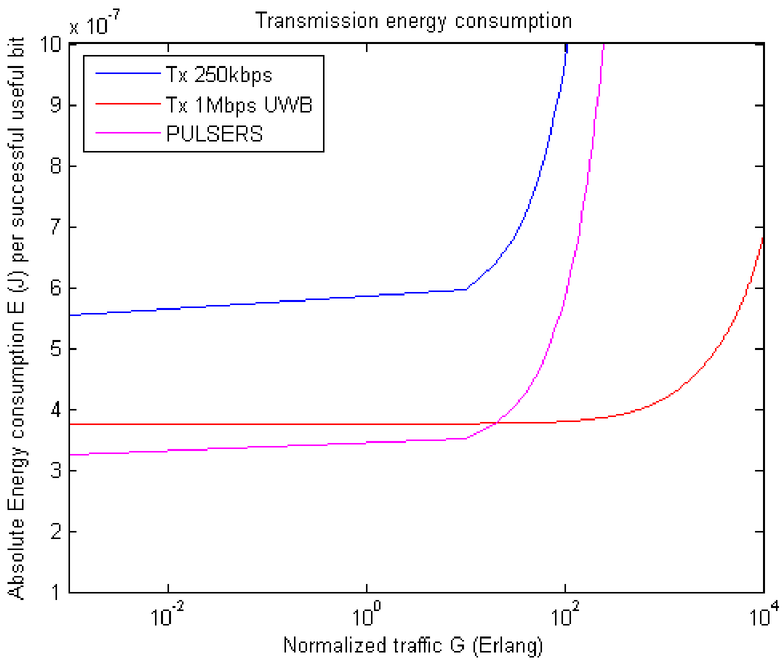
Results

5.1 Results from the energy analysis

This section will shows the results obtained using the energy analysis model, analyzed in the previous chapter, on the MAC protocols presented in Chapter 3. The analysis has been done on the following devices: IEEE 802.15.4 with 250kbps data rate, IEEE 802.15.4a 1Mbps IR-UWB, PULSERS 1Mbps IR-UWB and UWEN a 5Mbps IR-UWB.
Figure 5.1 shows the average dissipated transmission energy for useful received bit obtained in function of the normalized traffic G. The average, normalized offered traffic (in Erlang) is normalized to the capacity of the channel. So, $G = 0$ is no traffic at all, $G = 1$ is the capacity of the channel, $G = 10$ is 10 times the capacity of the channel, etc. $G = 10$ means that the data input rate to the system (meaning all the nodes) exceeds the capacity of the channel to support that traffic by a factor of 10. In numerical terms, when $G = 10$, and the channel capacity (data rate) is 1 Mbps, all the nodes aggregate arrival rate of data packets is 10 Mbps causing fierce contention on the channel. Erlang itself is a unit-less number. This peculiarity can be seen



(a) Average dissipated transmission energy



(b) Detail of the average dissipated transmission energy

Figure 5.1: Comparison of the average dissipated transmission energy

in Figure 5.1(a) where the random access protocols are almost constant for value of G included in the interval $[0 - 100]$ and then they diverge for value of G greater than 100. This means that for a traffic offered to the network greater than 100 times the channel capacity the collision and the contention algorithm employed bring the whole network to the congestion. The UWEN system, being based on TDMA, is totally unrelated from G since each node transmit only in its own slot without any contention. In the other hand we have a worst energy efficiency and this is visible in Figure 5.1(a).
In Figure 5.1(b) is showed a detail of Figure 5.1(a) to show better and to comment the performance of the three random access MAC. It is evident the energy saving obtained using the UWB systems instead of the IEEE 802.15.4 devices. This gain can be imputed to the lowest reception and idle power. It is to be noted the point where the devices begin to diverge. In the IEEE 802.15.4a devices this point is greater than PULSERS devices that use slotted ALOHA: for this devices, as expected, the congestion point is lower. Despite it utilize the same access algorithm of the IEEE 802.15.4a, the IEEE 802.15.4 has itself a congestion point lower than the former. This can be imputed to the higher data rate of the IEEE 802.15.4a that allow to send the data faster keeping the channel busy for a shorter time, reducing the collision probability.

5.2 Results from the simulations

This section will show the results obtained through the simulations done with the methodology explained in the last Chapter. The simulation has been done on the following devices: IEEE 802.15.4 with 40 kbps and 250 kbps data rates, IEEE 802.15.4a 1Mbps IR-UWB and PULSERS 1Mbps IR-

UWB.
The Figures 5.2 shows the results of the comparison of the performance of beaconless networks at different data rates. The network is a network with constant sources and sinks nodes number but with a global nodes number variable. The occupied area has been dimensioned to have the same nodes density in all the simulations. In this way is possible to evaluate how much the performances are affected by the network dimension. the generated events have a dimension of 111 bytes, thus we are in condition of a network that generates events of big dimensions.
The Figure 5.2(a) shows the obtained values of the Event Delivery Ratio (EDR). The EDR is the ratio between the total number of generated events and the total number of the events received correctly. This parameter gives an indication of the reliability of the network from the point of view of the event delivery and is more reliable when the EDR value is close to 1. From the figures is possible to view that the device working at 40kbps has an EDR lower than the devices working at 250 kbps and 1Mbps that, instead, have similar value of EDR. This can be imputed to the low value of data rate and to the event dimension in fact, in a sustained traffic network, the devices working at 40 kbps are not able to send quickly their events, making bottleneck conditions and packet-loss. The non-regularity of the curves is caused for the collision occurred doing the gradients reinforce phase of the directed diffusion algorithm. The source nodes in fact, after have received the interest from the sink node, diffuse in the network some messages that are used to build the shortest path to the sink node. In the case that some collision happens in the initial phase of this diffusion, blocking the first reinforce messages and then blocking the possibility to diffuse them in the network building a return path, the generated events will be without return path and thus they

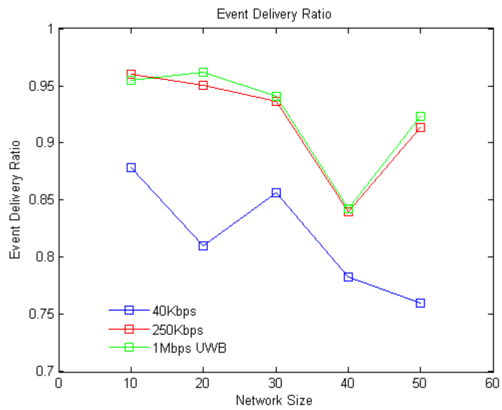
will not flow through the network to the sink node. To be able to receive them correctly again will be necessary to wait till the next interest transmission phase of the sink node.

The Figure 5.2(b) shows the average dissipated energy to send a successful packet. This parameter gives an idea on how much the network is stressed to deliver an event. The UWB system consume considerably less than classic transmission systems, this is due to the lower energy consumption during the transmission and idle phases.

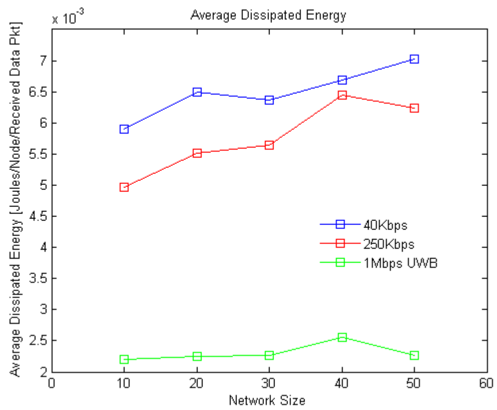
Finally, in Figure 5.2(b) is showed the average time delivery time to deliver an event from the source node to the sink node. It's evident the delay in the event delivery in the network working at 40 kbps, with delay peaks due to the network congestion. Remarkable also the low latency in the UWB devices that, thanks to their high transmission speed, avoid congestions and grant an higher fluency in the delivery.

The Figures 5.3 show the results for the comparison of IEEE 802.15.4 at 250 kbps devices working in beaconless and beacon enabled networks. In Figure 5.3(a) it is possibile to see a point of cross at 30 nodes. Before of that point the beaconless mode obtain better performance than beacon enabled mode, after that point the situation is opposite and the beacon enabled mode grants a better EDR. This happens because in the networks with an high number of nodes, the regular transmission during the superframe grants a better functioning of the network itself than the case of a beaconless network that produces more collisions and packet-loss.

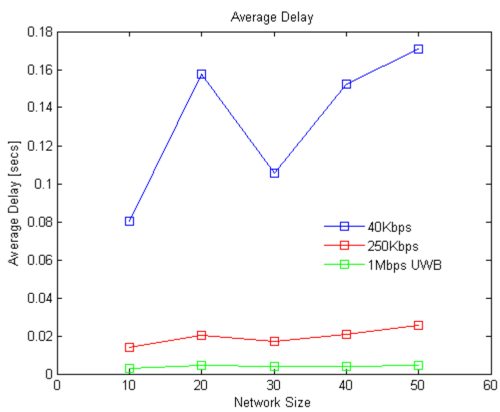
In the Figure 5.3(b) are highlighted the values of the average dissipated energy for received event. The beacon enabled transmission is, ad expected, sensitively more expensive than the beaconless transmission. The peaks at 30 nodes for the beacon enabled network and 40 nodes for the beaconless



(a) Event Delivery Ratio comparison



(b) Average energy consumption comparison

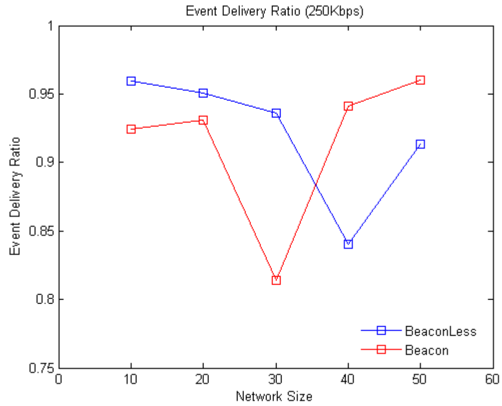


(c) Average delivery time comparison

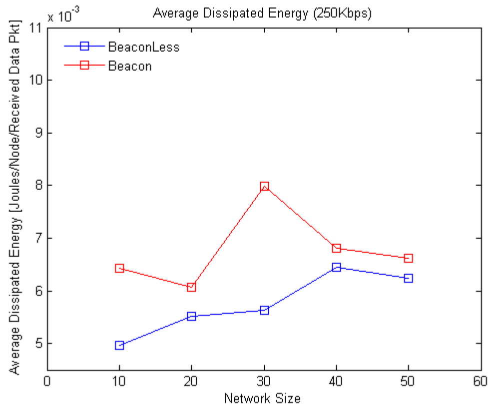
Figure 5.2: Performance comparison for beaconless network at different data rates, first scenario

network show how good is this parameter as an indicator of network issue.
About the average delivery time, in Figure 5.3(c) can be seen that the beacon enabled mode show up an higher delay due to the temporal subdivision in slot of the transmission period.
Finally, in Figure 5.4 is shown the same comparison IEEE 802.15.4a devices at 1 Mbps UWB. Also in this case can be seen from the Figure 5.4(a) the presence of a point of cross at 30 nodes. The EDR values, as anticipated from the Figures 5.2(a) and 5.3(a), are maintained at about 95%.
In Figure 5.4(b) are shown the values for the average dissipated energy for received event and, as expected, the values related to the beacon enabled network are higher than the beaconless one. In comparison with the previous case the dissipated energy values are remarkably lower thanks to the employment of the UWB technology.
In Figure 5.4(c) is shown the average delay of events delivery. In this case is remarkable the time saving in comparison with the previous case. This is due to the high data rate employed that allow to send quickly the events and to minimize the queue.

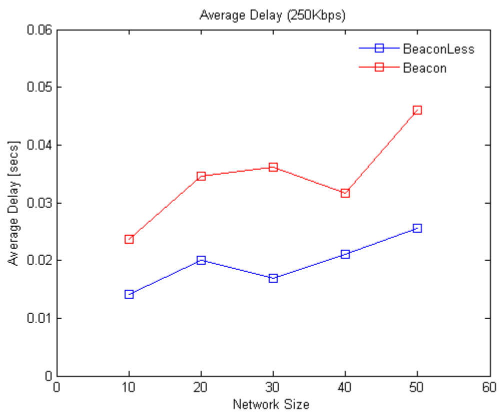
In the second scenario, with a fixed number of nodes and an increasing number of sources, we can immediately seethe behavior of the devices working at 40 kbps, 250 kbps and 1 Mbps in the Figure 5.5. This simulation can help us to evaluate the performance of the network when is subjected to an high generated traffic from the sources.
More accurately in Figure 5.5(a) are showed the EDR for the three devices. As expected, the devices working at 40 kbps are not able to sustain the increasing level of traffic and lead the network to the congestion with a lot of packet-loss. Differently the devices working at 250 kbps and 1 Mbps UWB



(a) Event Delivery Ratio comparison

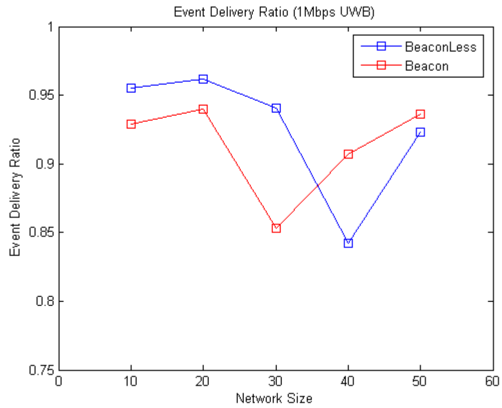


(b) Average energy consumption comparison

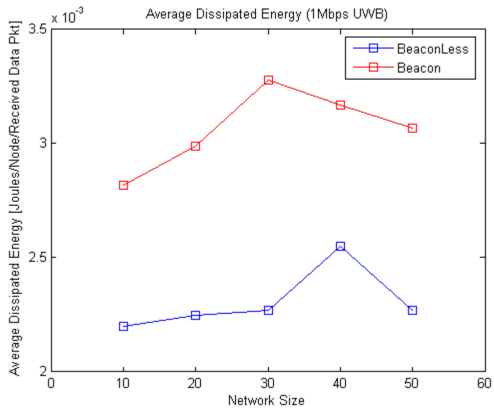


(c) Average delivery time comparison

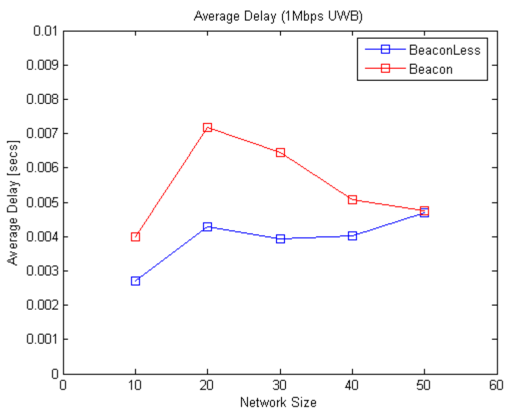
Figure 5.3: Performance comparison for beaconless and beacon enabled networks at 250kbps, first scenario



(a) Event Delivery Ratio comparison



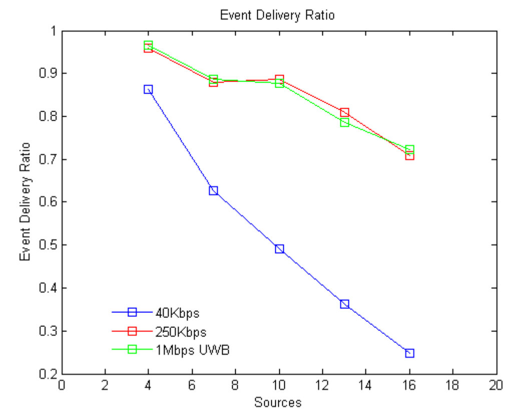
(b) Average energy consumption comparison



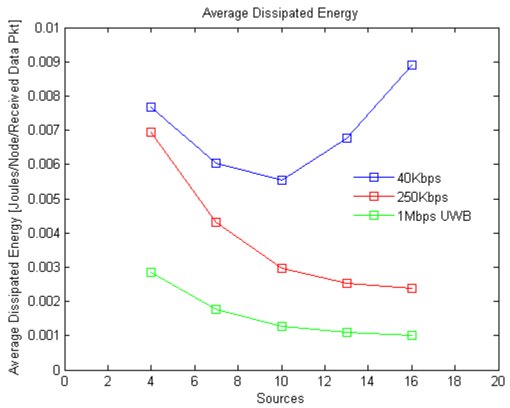
(c) Average delivery time comparison

Figure 5.4: Performance comparison for beaconless and beacon enabled networks at 1Mbps UWB, first scenario

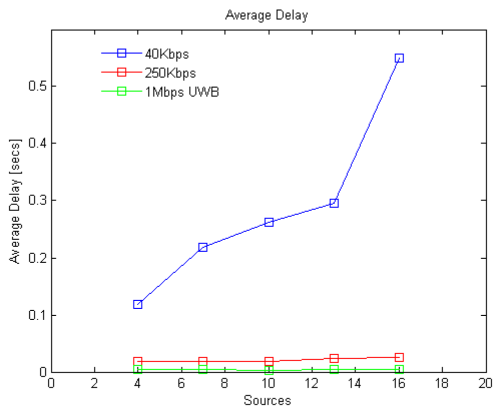
that maintain the same performance that deteriorate increasing the traffic in the network.
In Figure 5.5(b) are showed the average dissipated energy for received event. It is interesting to notice the divergent trend of the graphic related to the 40 kbps devices. More the network is congested more the average dissipated energy diverge. This gives the indication of the behavior for the 250 kbps and 1 Mbps network when the traffic increase further.
In the Figure 5.5(c) are showed the average delivery time for an event. The devices working at 250 kbps and at 1 Mbps UWB show a regular trend, that indicate a good capability to handle the network also with an high traffic. Differently the devices at 40 kbps have a divergent trend that highlight the incapability to handle the generated traffic, as showed in Figure 5.5(a).
The Figure 5.6 shows the comparison results of the IEEE 802.15.4 working at 250 kbps in beaconless and beacon enabled networks. In Figure 5.6(a) are shoed the EDR for this devices, can be seen a similar behavior for the beaconless and the beacon enabled network. This means that the temporal subdivision in slots doesn't grant an improving of the performance when the traffic increase as in the case of fixed value of traffic but with an increasing number of nodes. This is due to the high level of traffic that is not handled correctly neither through a temporal subdivision in slots.
In the Figure 5.6(b) are showed the average dissipated energy for received event. The figure shows results that are similar to the previous ones. At similar conclusion can be come observing the Figure 5.6(c) that shows the average delivery time of an event. As expected the beacon enabled network shows an higher delay, this is due to the subdivision in superframes.
Concluding, the Figure 5.7 shows the results of the simulation of the IEEE 802.15.4a devices at 1 Mbps UWB in a beaconless and beacon enabled net-



(a) Event Delivery Ratio comparison

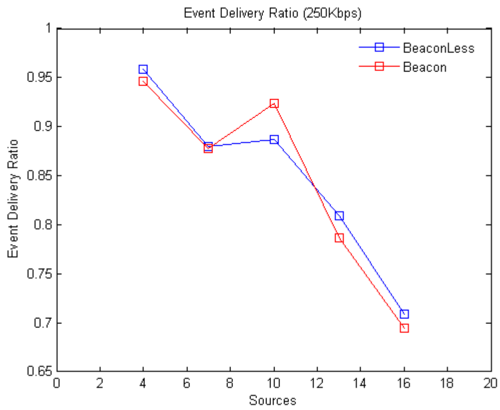


(b) Average energy consumption comparison

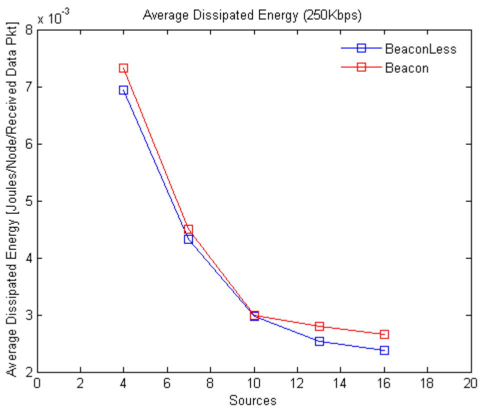


(c) Average delivery time comparison

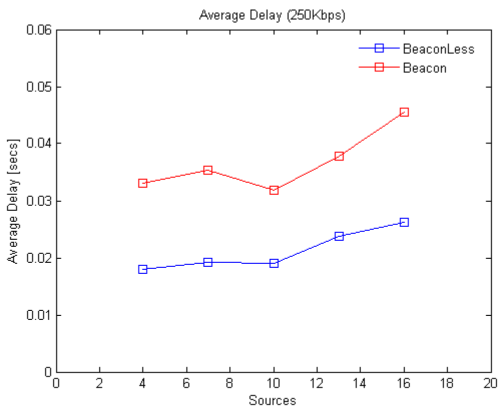
Figure 5.5: Performance comparison for beaconless network at different data rates, second scenario



(a) Event Delivery Ratio comparison



(b) Average energy consumption comparison

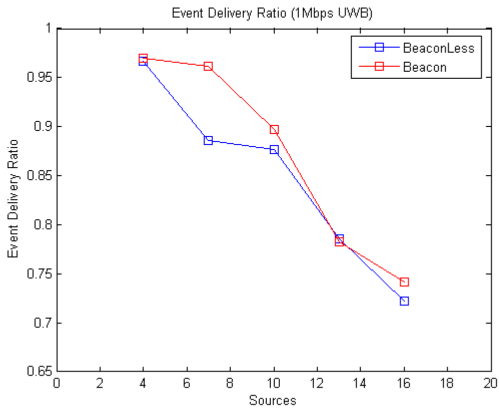


(c) Average delivery time comparison

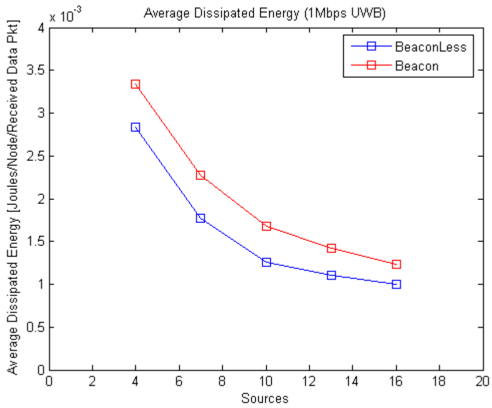
Figure 5.6: Performance comparison for beaconless and beacon enabled networks at 250kbps, second scenario

work. The values of EDR, showed in Figure 5.7(a), are maintained on the values already anticipated in the Figures 5.5(a) and 5.6(a). About the average dissipated energy for received event, from the Figure 5.7(b) can be seen the energy saved thanks to the UWB technology. Finally, in Figure 5.7(c) is showed the average event delivery time. Also in this case the time saving using the UWB technology is remarkable.

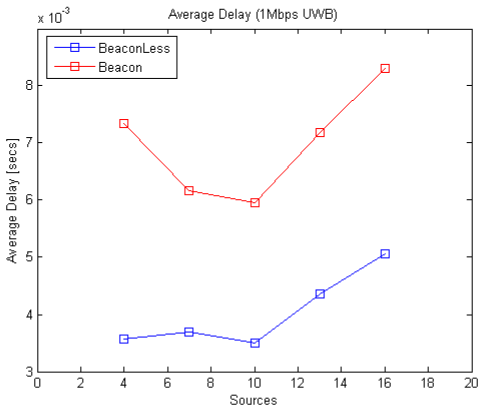
For the simulation regarding the PULSERS devices, after changed the MAC layer of the IEEE 802.15.4 according to the actual specification of PULSERS, are been noticed a lot of issue during the network initialization phase, specifically during the association phase, that have compromised the results of the simulations. The presence of a low number of slots in the superframe reserved to the association procedure caused that, also in a moderated dimension network, the contention of these slots blocks the set-up of the network itself. For this reason any results regarding the PULSERS devices is given.



(a) Event Delivery Ratio comparison



(b) Average energy consumption comparison



(c) Average delivery time comparison

Figure 5.7: Performance comparison for beaconless and beacon enabled networks at 1Mbps UWB, second scenario

Chapter 6

Conclusions

6.1 Conclusions

As we have seen in the previous chapter, in Section 5.1, the UWB systems grant a remarkable energy saving in comparison with the traditional systems. For this reason that devices are suitable to be employed in embedded applications, also thanks to their easy design that grants the production of low cost devices. More specifically, the IEEE 802.15.4a prototype can be employed in application subjected to high traffic level, as big sensor networks or wireless application for PDA or notebook, granting an high battery autonomy that is considered as critical element in mobile environments. The PULSERS systems has shown worst performance increasing the traffic, this is due to the employment of the slotted ALOHA access protocol, but in simply application like 'cable replacement' can be a good low power substitute of the actual IEEE 802.15.4 and Bluetooth devices. About the UWEN devices, the higher energy consumption can be tolerated considering the application type that the devices are going to be employed. They are devices that are going to be used daily, often for few hours, that are going to be destroyed after been used. In this case the economic considerations have the highest priority, the devices with fixed infrastructure and TDMA technology grant lower maintenance costs and a lower impact on the final cost of the product.

About the simulation results, visible in Section 5.2, the sensor networks with the directed diffusion routing algorithm show good performance and the employment of average data rates gives a better guarantee of working when the generated traffic increase. It is anyway visible the advantage of the UWB devices that, thanks to their technology and high data rate, give a lower delivery time and lower dissipated energy. About the PULSERS technology, the simulations don't give good results that, as explained in the previous chapter, can be imputed at the actual superframe structure that grants a limited slots number for the association procedure.

Thus, after all, the technology based on UWB technics actually can be seen as a promising solution for wireless devices, sensor networks and all the applications that need an energy saving. The possibility to obtain an higher data rate, maintaining anyway a lower energy consumption, makes it suitable to be employed in wireless application where the latency time is a critical element. Furthermore, the IR-UWB LDR technology, transmitting short pulses very far between themselves, shows a remarkable advantage in comparison with the SS technology allowing to obtain less collisions and therefore easier access protocols.

6.2 Future Works

The PULSERS system, according to the analysis done, needs a superframe structure revision to obtain a better handling of the CAP slots. This

can be done with a dynamic handling of the CAP duration according to the actual needs.
A new study can be done making the devices employed in the simulations 'cross-layer' devices, allowing the MAC of the devices to modify the superframe duty-cicle according to the traffic generated from the higher layer. This can be traduced in a better handling of the superframe when the traffic level change allowing to obtain better overall performance.

Bibliography

[1] Federal Communications Commission (FCC), *First Report and Order*. ET Docket 98-153, FCC 02-48, Adopted: February 14, 2002 Released: April 22, 2002.

[2] J. A. Gutirrez, E. H. J. Callaway, and R. L. J. Barret, *Low-Rate Wireless Personal Area Networks*, 1st ed. IEEE Press, November 2003.

[3] J. Haapola, Z. Shelby, C. Pomalaza-Rez, and P. Mhnen, *Multi-hop Medium Access Control for WSNs: An Energy Analysis Model*. Center for Wireless Communication (CWC), University of Oulu, 2005.

[4] H. Zimmermann, *OSI reference model–The ISO model for Open System Interconnection*. IEEE Trans.Commun., April 1980, vol. COM-28, no. 4, pp. 425–432.

[5] N. Abramson, "The ALOHA system – another alternative for computer communications," in *Fall Joint Computer Conference*, vol. 37. Montvale, NJ, 1970, pp. 281–285.

[6] L. Roberts, *ALOHA packet system with and without slots and capture*. ACM SIGCOMM Computer Communications Review, 1975, vol. 5 Issue: 2, pp. 28–42.

[7] L. Kleinrock and F. A. Tobagi, *Packet Switching in Radio Channels: Part I–Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics.* IEEE Transaction on Communications, December 1975, vol. 23 Issue: 12, pp. 1400–1416.

[8] P. Karn, "Maca – a new channel access method for packet radio," in *9th ARRL Computing Networking Conference*, September 1990, pp. 134–140.

[9] IEEE Std 802.15.11, *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.* IEEE Press, 1999.

[10] IEEE Std 802.15.4-2003, *Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) - Specification for Low-Rate Wireless Personal Area Networks (LR-WPANs).* IEEE Press, 2003.

[11] Pulsers Working Group, *Definition of UWB scenarios.* PHI, THA, TEL, ROB, ACO, RLB, UAT, CDS, 2004.

[12] ——, *Deriverable D53.2: MAC and Networking Alghorithms Specificartions, Operating Code Specifications, test S/W specificstions (MAC debug) [LDR-LT].* STM, CEA, THA, 2005.

[13] ——, *Deriverable D51.2a: Definition of new concepts/architectures for UWB MAC and networking [LDR-LT], initial version.* CEA, CRM, MIT, ROB, STM, THA, UOR, UOU, 2004.

[14] I. Opperman, Z. Shelby, J. Haapola, A. Rabbachin, and K. Yu, *Revised UWEN system concept.* CWC, 2004.

[15] L. Stoica, I. Opperman, Z. Shelby, and M. Huttunen, *UWEN Tranceiver Architecture.* CWC, 2004.

[16] J. Zheng and M. J. Lee, *A Comprehensive Performance Study of IEEE Std 802.15.4*. IEEE Press Book, 2004.

[17] D. E. J. H. Chalermek Intanagonwiwat, Ramesh Govindan and F. Silva, *Directed Diffusion for Wireless Sensor Networking.* ACM/IEEE Transactions on Networking, 2002, vol. 11 (1), pp. 2–16.

[18] R. G. Chalermek Intanagonwiwat and D. Estrin, *Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks.* In Proceedings of the Sixth Annual International Conference on Mobile Computing and Networks (MobiCOM 2000), August 2000.