CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In radio technology, UWB is used in short-range communication systems, given its low energy consumption Ley et al. (2017). Moreover, given its flexibility in generating different types of ultra-short pulses (that form trains of pulses), UWB has been used in extending the coverage ranges and enhancing the quality of the received signal.

Impulse-radio (IR) UWB systems are the first to use the wideband communication concept in a power-limited system. UWB communication has two types, namely, single-band (or IR) and multi-band. UWB was initially called 'IR,' Adsul (2013). Several proposals have been submitted to IEEE802.15.3a and IEEE802.15.4a on the basis of single-band and multi-band UWBs.

Controlling the rates, codes and shapes of pulses at different levels is considered an interesting feature of UWB that has been utilised in several applications, Misra (2015). Especially in radar, image processing and multimedia communication systems Bi (2018).

This chapter reviews IR-UWB systems, including their transmitter structure, channel model and receiver structure. The existing architectures and frameworks related to IEEE 802.15.4a and IEEE 802.15.3a are also reviewed along with the cross-layers, dynamic settings and applications of IR-UWB systems.

A critical analysis of the existing UWB solutions that have been proposed in the literature is also presented to highlight the research gaps and the lack of a global UWB solution that can serve applications with different data rate requirements across various distance scenarios.

2.2 FCC Regulations

Until 2002, commercial applications had been severely restricted from the use of a wide range of GHz bandwidth due to spectral allocation difficulties. However, the First Report and Order issued by FCC (2002) did not license the two DC-960 MHz and 3.1 GHz–10.6 GHz RF frequency bands for commercial UWB applications. FCC also sets specific requirements for UWB communication for bandwidth and emission levels. Following the FCC, most regional spectrum regulators around the world refused to allow parts of the radio spectrum to be licensed on commercial UWB systems despite the slight variation in frequency and emission levels in different countries. UWB spectral rules in the US and Canada are somewhat more relaxed but in Europe and in Asia are strictly followed, FCC (2002). Wireless technologies are known as UWBs according to the FCC study if their signals have the following characteristics:

a. An absolute bandwidth (BW), at least 500 MHz: Kumar & Gupta (2019) Absolute bandwidth is a difference from the strongest frequency component of the signal spectrum between the highest (f_H) and lowest frequency components (f_L) measured at -10 dB below this frequency. BW is computed as.

$$f_H - f_L = BW \geq 500\ MHz \quad (2.1)$$

b. At least 20% of the centre frequency (f_c) of the signal spectrum is a fractional bandwidth (B_f). B_f From bandwidth is determined as.

$$B_f = \frac{BW}{f_c} \geq 20\% \quad (2.2)$$

Where, $f_c = \frac{f_H + f_L}{2}$.

As UWB signals usually cover several frequency bands (sometimes within the GHz range), it becomes inevitable to share RF spectrum together with other communications systems, leading to severe interference. To make such a coexistence feasible with or without interference, FCC developed a very low PSD for UWB, which falls into the noise floors of most current narrowband systems, FCC (2002). PSD is the ratio between the transmitter's total power (P in watts) and the bandwidth of its signal (BW in hertz) and is provided by, Nakache & Molisch (2006).

$$PSD = \frac{P}{BW} \tag{2.3}$$

For commercial UWB applications, FCC provides for peak isotropic radiated power (EIRP) equivalent of –41.3 dBm / MHz (or 74.13 nW / MHz). FCC (2002). EIRP refers to the maximum antenna power provided that this antenna is a radiator isotropic and is defined as Nakache & Molisch (2006) :

$$EIRP = P_T - L_S + G_A \tag{2.4}$$

Where the transmitter power isP_T, the L_S system loss and the peak antenna gain is G_A Table 2.1 compares the emission communications of UWB with other common wave wireless systems, Ghavami et al. (2007).

Table 2.1: Emission Levels Of Popular Wireless Communication Systems

Communication System	Bandwidth	Total Power Transmitted	Power Spectral Density
AM radio	75 KHz	50 kW	666*10^3 W/MHz
Television	6 MHz	100 kW	16*10^3 W/MHz
Cellular systems	8.33 MHz	500 mW	60 W/MHz
Broadband Wi-Fi	20 MHz	1 W	0.05 W/MHz
UWB	7.5 GHz	0.5 mW	6.67*10^-8 W/MHz

Source: Ghavami et al. (2007)

As Table 2.1 shows, even with full use of frequency bands from 3.1 GHz to 10.6 GHz, the maximum power a UWB transmitter can emit is only approximately 0.5 mW.

The wide bandwidth occupied by the UWB emission can interfere with the extra approved bands in the frequency spectrum. The damping oscillation of waveforms are caused by the sharp peaks in the spectrum with a small bandwidth, and these peaks interfere with communication systems. According to Tuovinen et al. (2015), the desired UWB waveforms provide the flat frequency domain spectrum in FCC regulations. Rayleigh, Gaussian, Laplacian and modified Hermitian monocycles cubic waveforms, as well as their examples, are non-damped waveforms with a flat spectrum. Table 2.2 Aiello & Rogerson (2003) Saji (2016) shows the operating frequencies (centre frequencies) of UWB and their possible bandwidths and compares them with those of unlicensed narrow and wideband communication technologies in the US Aiello & Rogerson (2003) Saji (2016).

Table 2.2: US Spectrum Allocation For Unlicensed Bands Use

Unlicensed Bands	Operating Frequency (GHz)	Bandwidth (MHz)
ISM at 2.4 GHz	2.4 to 2.4835	83.5
U-NII at 5.15 GHz	5.15 to 5.35	300
UWB	3.1 to 10.6	7500

Source: Saji (2016)

DC-960 MHz unlicensed frequency bands can be used for LDR-UWB implementations. The EIRP is adjusted to an extremely low level (–75.3 dBm / MHz) for 0.96 GHz to 1.61 GHz of the RF spectrum to protect the signals of the UWB systems against potential interference from GPS signals given that the PSD of These GPS signals is within a similar range. The main frequency bands that can be used for UWB commercial HDR applications, which are considered to be the key advantage of

UWB, therefore range between 3.1 GHz and 10.6 GHz, Tsang & El-Gamal (2005). However, to prevent any interference from WLAN signals (WLAN 802.11a) operating at a 5 GHz range, a lower frequency band of 3.1 GHz to 5.0 GHz or upper-frequency bands of 6.0 GHz to 10.6 GHz should be used during the development of UWB communication systems.

2.3 UWB Signalling Schemes

As commercial UWB is deregulated and free to use, numerous signalling schemes have been developed over the years, Wei et al. (2019). However, a number of organizations, such as the IEEE LAN / MAN Standards Committee, have established some standards to ensure compliance between devices using different UWB schemes. One such standard is multi-band orthogonal frequency division multiplexing (MB-OFDM) introduced by Task Group 3, (IEEE 802 Part 15.3, 2003), which attempts to standardise HDR-UWB by using either IR direct sequence (DS) UWB (DS UWB) or MB-OFDM signalling modes. Meanwhile, another task group, IEEE Std 802.15.4a, Proposed a standard LDR physical layer by using UWB for the exact spectrum of Wireless Personal Area Networks (WPAN) in 2007. While these regulations are still not recognised universally, they aim to standardise UWB systems development.

2.3.1 MB-OFDM

MB-OFDM is a carrier-based UWB networking scheme initially supported by the MB-OFDM Alliance (now known as Wi-Media Alliance-based MB-OFDM), Xu et al. (2018). The spectrum is categorised into smaller frequency bands, and each bandwidth includes 500 MHz multiple UWB signals that are transmitted simultaneously as they operate at different frequencies and do not interfere with one another, Assefzadeh & Babakhani (2016) . The whole 3.1 GHz to 10.6 GHz UWB range in this scheme is divided into 14 uniform sub-bands which are divided into 5 groups. As shown in Figure 2.1, each sub-band has 528 MHz in bandwidth Saha et al. (2019).

Source: Saha et al. (2019)

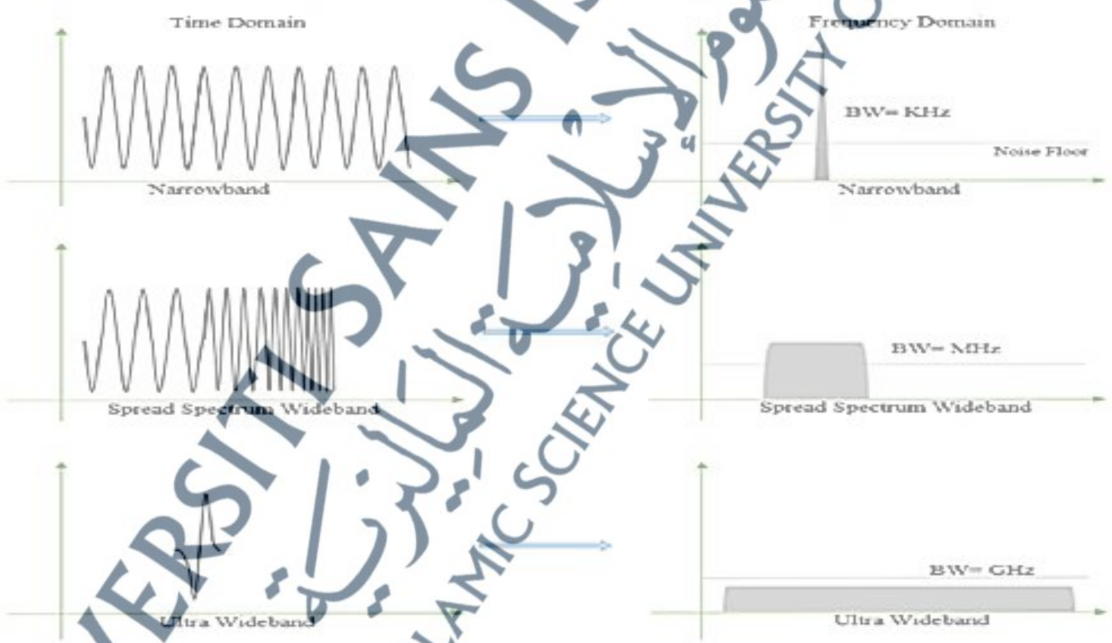
Figure 2.1: MB-OFDM Frequency Band Plan

The data bit stream is divided into different substreams and integrated into OFDM sub-bands as LDR parallel streams. Each parallel stream is modulated by a single parallel yet orthogonal sub-carrier. Because sub-carriers can be spaced to one another, overlapping is possible so that spectrum modulation is very efficacious Zou (2011). The MB-OFDM Multiband Design provides flexibility in the design of UWB systems in accordance with international spectrum regulations, Nikookar & Prasad (2008). If there is no interference with a narrow band system the system will delete one band or a group of MB-OFDM with minimum performance degradation. For example, group # 2 or a sub-band can be turned off in order to mitigate signal distortions from WLAN (802.11a) at 5 G. Each sub-band in MB-OFDM has a longer symbol duration than IR, which minimises inter-symbol interference and increases multipath immunity, Nikookar & Prasad (2008).

The main advantage of MB lies in its efficient use of the available spectrum and its flexibility to coexist with other wireless technologies given that each of its separate bands is being treated independently. The complexity of the transceiver architecture in MB-OFDM increases with the data rate, thereby raising the requirements for powerful processing engines and additional power, while synchronization is possible, Nikookar & Prasad (2008).

2.3.2 IR-UWB

As discussed above, IR-UWB schemes use ultra-short pulses of nano/sub Nanosecond length for signalling. While these pulses do not carry information, these pulses are encoded with one available IR modulation scheme, including position and polarity, to create a pulse series. The data depend on and are obtained from the categories of design constraint, application, power consumption, hardware complexity, operation range, data rate and capacity Ebrazeh & Mohseni (2015). Figure 2.2 compares IR-UWB with conventional wireless schemes in the time and frequency domains.



Source: Nekoogar (2005).

Figure 2.2: Comparison of Narrowband, Wideband And IR Schemes

DS-UWB and time-hopping (TH) UWB (TH-UWB) are two prominent subcategories of IR-UWB Minoli & Occhiogrosso (2018). In DS-UWB, data-encoded IR pulses are continuously transmitted Bagwari et al. (2018), and each user is allocated with different pseudorandom sequences. Meanwhile, in TH-UWB, data-encoded IR pulses are transmitted only in specifically allocated time slots for each user.

IR-UWB modulation options include Pulse Amplitude Modulation (PAM), binary phase-shift keying (BPSK), on-off keying (OOK) and pulse position modulation (PPM). UWB is considered an orthogonal processing method with the best modulation option. However, its BER performance is affected by PPM waveforms. Accurate detection of pulses is required for accurate synchronisation and channel estimation. Energy detection and correlation detection are the two main categories in a UWB receiver with low cost, poor BER and easy implementation F. Chen et al. (2017). The receiver of the correlation is used to develop the template signal, which in turn is acquired via code synchronisation. The received signal is then multiplied by the output, and the result is integrated with the resolution blocks. The receiver of the rake is included in the bank of correlates and is synchronised by specific multipath components Moschevikin et al. (2016). The multipath fading environment uses the multipath components of a signal spread in time that are obtained by using rake receivers. However, rake receivers are highly complex and have low power consumption, thereby making them unsuitable for the implementation. Moschevikin et al. (2016).

IR-UWB can be applied either as a carrier less or as a carrier-based, Lee & Ghovanloo (2019). In the carrier-less IR-UWB, an impulse signal is generated to eliminate the carrier's requirement for the wireless channel transmission so that the BB pulses are already in the RF range. Without the carrier signal, oscillator and mixer specifications and the steps involved in up / down RF conversions are omitted, and thus the transceiver structure is simplified, Xu et al. (2018).

In a carrier-based IR-UWB, the signal is generated by mixing a higher frequency carrier and increasing the energy DC range to a targeted UWB band in the RF spectrum Lee & Ghovanloo (2019). The carrier-based IR-UWB can be implemented either by the up-conversion of BB pulses to the desired band in the UWB RF spectrum or by performing a direct on-off switching operation on the oscillator whilst generating pulses Zou (2011). The carrier-based IR-UWB has few advantages, including its improved spectral efficiency (thereby increasing system capacity) and accurate timing resolution (with less signal processing steps at receivers, especially at quadrature ones) Peilin et al. (2018).

Qi & Katayama (2016) Developed an improved IR- UWB communication system based on sub-band collection. This system, which they called an enhanced multiband IR-UWB (MIR-UWB) system, enhances the elasticity of the spectrum distribution, the sub-band range and the variety of data broadcast rates by choosing fractional sub-bands via a planning algorithm with a set of pulses. The spreader and receiver provide the BER under the Additive White Gaussian Noise (AWGN) channel. The results show that the amended MIR-UWB system outperforms the conservative MIR-UWB system under the AWGN channel and at the same data transmission rate. Data transmission rate and BER performance are evaluated by using an appropriate combination of system parameters.

However, using the carrier increases the power consumption and complexity of the IR-UWB transceiver architecture. Moreover, generating a carrier that can cover a wide bandwidth becomes problematic at high frequencies, Gozalpour et al. (2018).

2.4 IR-UWB System Architecture

IR single short BB signals are generated for communicating data. These signals are used in a very large spectrum and must follow certain spectral criteria. Each signal has a very low energy to maintain low power levels, can be used for UWB transmission and reduces the risk of interference with other narrowband communication technologies Kishida et al. (2015) given its very low energy; moreover, many signals are combined to carry one bit of information and to ensure a high-speed application Taylor (2020).

Agrawal & Kshetrimayum (2017) proposed a UWB communication system model that is built as a single link communication system and includes three major blocks, namely, a transmitter, a channel and a receiver.

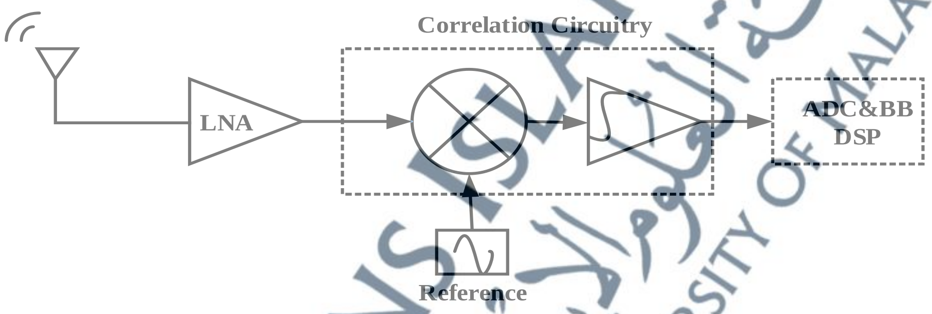
The transmitter and receiver structures for an IR-UWB application are shown in Figures 2.3 and 2.4, respectively.

Source: Jeff Foerster et al. (2001)

Figure 2.3: UWB Transmitter Architecture

Figure 2.3 illustrates the transmitter architecture for an IR-UWB system. The IR-UWB transmitter includes a clock source, modulation, pulse shaping block and antenna. One of the greatest benefits of the UWB transmitter relative to IR is that the former does not need to employ complex circuitry, such as frequency synthesisers, which contain phase-locked loop (PLL), voltage-controlled oscillators (VCO) and mixers Jeff Foerster et al. (2001).

Moreover, given the EIRP power mask of the FCC, the averaging emitting power from 3.1 GHz to 10.6 GHz is below –41.3 dBm/MHz, which means that the total emitted power is approximately 0.55 mW. Therefore, a power amplifier (PA) is not needed to boost the emitting power. PA, PLL, VCO and mixers are critical parts of conventional transmitters. Apart from their complex structures; these components are difficult to implement and expensive. Besides, an IR-UWB transmitter has a short design cycle, is moderately easy to implement and has a low cost, especially for the mass production for consumer electronics, given that this transmitter lacks a complex circuitry.



Source: Jeff Foerster et al. (2001)

Figure 2.4: UWB Receiver Top-Level Architecture

Figure 2.4 shows the IR-UWB receiver architecture, which contains a receiver antenna, low noise amplifier (LNA), reference circuitry, correlator, analogy to digital converter (ADC), BB and digital signal processing (DSP). The reference circuit generates the pulse template for direct conversion into a multiplier, the integrator serves as a low pass filter, and the signal is fed into the ADC for further signal processing. The transmitter, channel and receiver of IR-UWB are described in detail as follows.

2.4.1 IR-UWB Transmitter

The impulse-based UWB transmitter consists of multiple modules that work together until the designed pulses are formed and generated. These modules are described in detail below.

2.4.1.1 FCC EIRP Power Mask

All radio communication applications are subject to different regulations on how much power can be emitted in a specific frequency band. The purpose of these regulations is to prevent interference with other nearby subscribers or in the same frequency band Ghavami et al. (2007). Table 2.3 shows the spectral mask mandated by the FCC for indoor and outdoor UWB systems. The power spectrum density (PSD) of the emitted UWB signal must be well controlled to avoid conflicting with the FCC EIRP regulation for UWB applications.

Table 2.3: Spectral mask regulated by the FCC for indoor/outdoor UWB systems

Frequency Band (GHz)	Indoor EIRP Limit (dBm/MHz)	Outdoor EIRP Limit (dBm/MHz)
0-0.96	-41.3	-41.3
0.96-1.61	-75.3	-75.3
1.61-1.99	-53.3	-63.3
1.99-3.1	-51.3	-61.3
3.1-10.6	-41.3	-41.3
>10.6	-51.3	-61.3

Source: Alarifi et al. (2016)

2.4.1.2 IR-UWB Pulse Shaping

Given that the PSD of the IR-UWB-emitted signal is directly related to pulse type, pulse width and amplitude, pulse shaping is critical for any IR-UWB application. The pulse generator (PG) is the key circuit block in an IR-UWB system that generates UWB impulse signal trains for both transmitting and receiving channels. Designing UWB has five critical aspects. Firstly, the UWB pulse width must be very short and well-controlled to ensure a very high data rate of up to Gbps. Secondly, the pulse shape should be optimised for the desired UWB PSD. Thirdly, the generated UWB pulse trains must comply with the FCC EIRP power mask whilst allowing a maximum signal emission. Fourthly, the low-power design is desirable for many mobile and handheld applications. Fifthly, a carbon-metal oxide semiconductor (CMOS)-based PG design is highly desirable for low-cost and power UWB systems on a chip Cappelletti et al. (2017).

For IR-UWB, the FCC bandwidth requirements and the maximum EIRP level must both be considered whilst generating pulses. An approximate relationship between pulse duration (τ) and bandwidth (BW) of the IR is given by Cappelletti et al. (2017).

$$BW \approx \frac{1}{\tau} \tag{2.5}$$

Therefore, to achieve the FCC required a minimum bandwidth of 500 MHz, the pulse width should be extremely small, ideally ranging from sub-nanoseconds to a few nanoseconds. Another primary factor, EIRP, depends on the amplitude of IR pulses and pulse repetition rate (PRR). The maximum permissible EIRP for commercial UWB is –41.3 dBm/MHz. The PSD of an impulse-based technology is given by Schires et al. (2018).

$$v_f = v_t\left[\frac{\tau}{T}\right] \tag{2.6}$$

where v_f is the power spectral amplitude of the signal spectrum, v_t is the root mean square amplitude of the pulses, τ is the width of the pulses and T is the PRR.

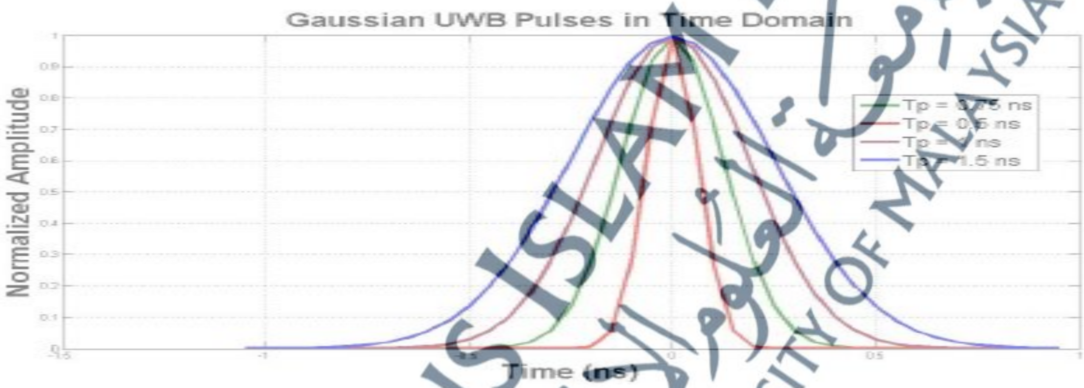
Given the ultra-short pulses, the duty cycle of the IR-UWB signal is very low, thereby facilitating an increase in PRR and PSD. To keep the PSD within the FCC limits, the amplitude of the pulses must be lowered. In other words, the PRR and energy in each IR pulse can be tuned depending on the application requirements. The following application scenarios are then proposed Nikookar & Prasad (2008):

- **Low data rate applications:** Pulses with high energy and low PRR, which will increase the communication range of the system with a trade-off in data rate.
- **High data rate applications:** Low energy pulses with high PRR, which will increase the data rate of the system with a trade-off in communication range.

The FCC has not defined any specific pulse shape for IR-UWB communication systems. Therefore, any pulse shape that follows the FCC-defined UWB emission limit and bandwidth requirement can be used. Apart from meeting the FCC requirements, the energy efficiency and performance of the system must be considered whilst generating the IR pulses, given that both these factors are closely related to the pulse shape. The smooth and stable ‘rise’ and ‘fall’ edges of the pulse reduce the formation of sidebands (or side lobes) that do not carry any useful information and typically fall outside the allocated frequency range, thereby making them undesirable components of the UWB spectrum in the RF band. Using appropriate pulse shapes and suppression techniques can reduce the amount of energy wasted in the formation of side lobes. Potential UWB impulse waveforms include Gaussian pulse and its derivatives, Hermit pulse, Rayleigh function curve, chirp signal and Manchester monocycle, all of which are often used in IR-UWB Jian Zhang et al. (2005). Amongst these waveforms, the Gaussian pulse and its derivatives are preferred because of their condensed PSD properties and low sidelobe; moreover, these waveforms are the easiest ones to generate, thereby making them ideal for signalling Xin Wang et al. (2009). The Gaussian pulse and its derivatives also are widely used in IR UWB studies [Taylor (2018);Mokole & Sarkar (2016);Taylor (2020); Haidar Taki et al. (2019); R. Zhang & Song (2016); Pannuto et al. (2018)]. These waveforms can be mathematically modelled as follows by using the Gaussian function Ghavami et al. (2007):

$$G(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\left(\frac{x^2}{2\sigma^2}\right)} \quad (2.7)$$

Where σ is a standard deviation. Figure 2.5 shows the Gaussian pulses in the time domain (where T_p denotes the pulse duration) the different T_p can be in varied 6 of the determine different levels of Gaussian derivative up to 11 derivatives. These pulses are mathematically expressed as Ghavami et al. (2007)



Source: Ghavami et al. (2007)

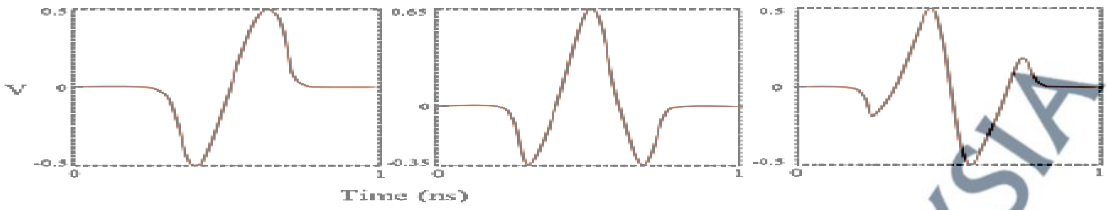
Figure 2.5: Gaussian Pulses Of Width 'T_p' In The Time Domain

$$y_{g1}(t) = K_1 \left\{ e^{\left(-\frac{t}{\tau}\right)^2} \right\} \quad (2.8)$$

where K_1 is a constant, τ is the time-scaling factor, and time t is the pulse duration Ghavami et al. (2007). Gaussian monocycle, doublet and successive derivatives are derived from the Gaussian pulse function. Monocycle, as the first derivative of the Gaussian pulse, is expressed as Ghavami et al. (2007)

$$y_{g2}(t) = K_2 \frac{-2t}{\tau^2} \left\{ e^{\left(-\frac{t}{\tau}\right)^2} \right\} \quad (2.9)$$

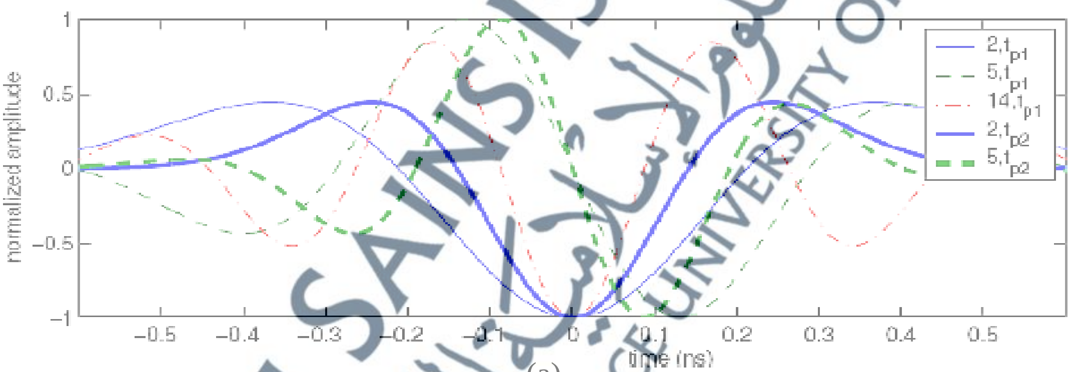
where K_2 is a constant. The shapes of the first three derivatives of the Gaussian pulses are shown in Figure 2.6.



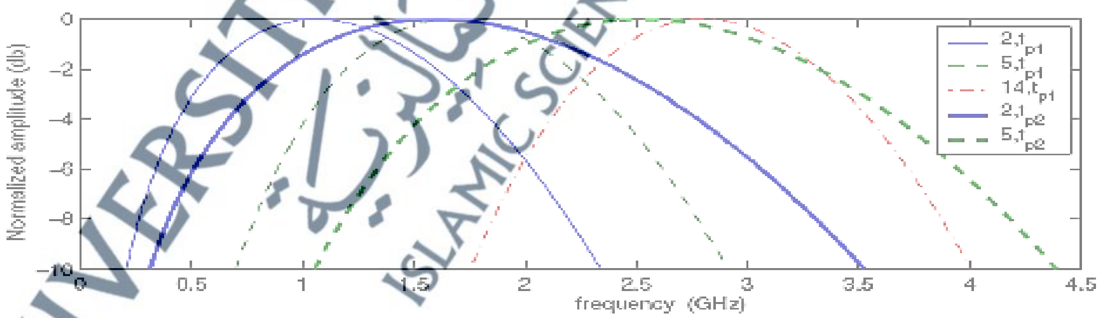
Source: Ghavami et al. (2007)

Figure 2.6: First Three Derivatives of The Gaussian Pulses In The Time Domain

The time and frequency domain characteristics of the Gaussian function pulses significantly change according to the order of the pulses. Jian Zhang et al. (2005) discussed the time and frequency domain characteristics of Gaussian pulse derivatives in detail and examined their propagation properties, the capacity of a system that uses a pulse-type in each scenario and the interference that a Gaussian derivative can bring to a system.



(a)



(b)

SourceJian Zhang et al. (2005)

Figure 2.7: (a): Nth Order Gaussian Pulses With 't_p' Pulse Widths In The Time Domain, (b) Nth Order Gaussian Pulses With. 't_p' Pulse Widths In The Frequency Domain

Figures 2.7 (a) and (b), which are taken from Jian Zhang et al. (2005), show the RF spectrum positions of Gaussian derivatives in accordance with the order of the derivatives and pulse widths (where '2', '5' and '14' refer to the order of Gaussian derivatives, whereas 'tp1' and 'tp2' refer to the width of the pulses).

a. A comparison of the 2nd, 5th and 14th order Gaussian pulses reveal that as the order increases, the pulse spectrum shifts towards higher frequency bands in the RF spectrum without any significant changes in the bandwidth.

b. For the same order of Gaussian pulses, reducing the pulse duration (tp1 > tp2) increases the bandwidth.

c. The pulse spectrum slightly shifts towards higher frequency bands in the RF spectrum along with a decreasing pulse duration regardless of the order of the pulses Jian Zhang et al. (2005).

If the UWB system is carrier less, then using higher-order Gaussian derivatives should be ideal given that these derivatives move the BB signal from the DC range to the RF range Kim & Joo (2005). However, given the complexities involved in generating higher-order Gaussian pulses, most studies prefer the first two derivatives (monocycle and doublet) of the Gaussian pulse for IR-UWB pulse generation [Serres et al. (2006); Han & Nguyen (2002); Jianliang Zhang et al. (2007)]

Although the Gaussian monocycle and doublet do not contain any DC components and are easy to generate, their frequency bands fall below 3.1 GHz in the RF spectrum, which is outside the RF spectrum prescribed by the FCC for commercial UWB systems. This problem can be solved by reducing the pulse duration, which moves the pulse spectrum to higher frequency bands above 3.1 GHz and filters out the lower frequency components. Other alternative solutions, such as using a carrier modulation and generating Gaussian pulse derivatives as a ‘gated function’, have also been discussed in the literature [Fernandes et al. (2008);Kianpour et al. (2017)].

2.4.1.3 IR-UWB Modulation Scheme

Pulse shaping aims to determine a proper waveform for carrying the user information and achieving data transmission. The function of modulation is to add the information of the user into the analogy UWB pulse. The basic modulation approaches being used in UWB systems will be described in detail in this section.

Intuitively, modulation can be classified into time- and shape-based modulation.

A. PPM

Pulse Position Modulation (PPM) is a time-based modulation approach that is frequently applied in the literature. In this approach, each pulse is delayed or sent in advance of a regular time scale. Afterwards, a binary communication system can be established with a forward or backward shift in time. By specifying different time delays for each pulse, an M-art system can be created. For example, the data can be created by the delay parameter τ_i to create pulses s_i as shown in equation 2.10, where t represents time. [Yajnanarayana et al. (2014); H Taki et al. (2016);Niemelä et al. (2016)].

$$s_i(\boldsymbol{t}) = p(t - \tau_i) \tag{2.10}$$

For convenience, if we only have i=1 and i=0, then we have $s_1(t) = p(t - \tau_1)$ and $s_0(\boldsymbol{t}) = p(t - \tau_0)$.

The advantage of PPM mainly lies in its simplicity and ease of control delays. However, for UWB systems, extremely fine time control is necessary to modulate pulses with nanosecond or picosecond accuracy. Given these benefits, many studies have used PPM signals to achieve performance improvements [Yajnanarayana et al. (2014); H Taki et al. (2016);Niemelä et al. (2016)].

B. Pulse Amplitude Modulation

Pulse Amplitude Modulation (PAM) is a form of signal modulation where the message information is encoded in the amplitude of a series of signal pulses. For example, to employ zero-order Gaussian pulse as pulse shape, we can have equations 2.11 and 2.12 to stand for ‘0’ and ‘1’, respectively, by using PAM: [Yajnanarayana et al. (2014); H Taki et al. (2016);Niemelä et al. (2016)].

$$S_0(t) = A_0(\frac{1}{\sqrt{2\pi\sigma}})e^{\left(-\frac{t^2}{2\sigma^2}\right)} \quad (2.11)$$

$$S_1(t) = A_1(\frac{1}{\sqrt{2\pi\sigma}})e^{\left(-\frac{t^2}{2\sigma^2}\right)} \quad (2.12)$$

In some PAM systems, the amplitude of each pulse is directly proportional to the instantaneous modulating-signal amplitude at the time the pulse occurs. In other PAM systems, the amplitude of each pulse is inversely proportional to the instantaneous modulating-signal amplitude at the time the pulse occurs. In other systems, the intensity of each pulse depends on some characteristics of the modulating signal apart from its strength, such as its instantaneous frequency or phase.

C. OOK

On-Off Keying (OOK) is similar to PAM. For UWB applications, OOK can be characterised as a pulse shape modulation where the shape parameter s is either 0 or 1.

$$s_i = \sigma_i\, p(t) \quad where\;\; \sigma_i = 0\; or\; 1 \quad (2.13)$$

For example, the ‘on’ pulse is created when σ_i=1, whereas the ‘off’ pulse is created when σ_i=0. Therefore, we have S_1=p(t) and S_2=0.

D. BPSK

Binary Phase Shift Keying (BPSK) is the simplest form of phase-shift keying. BPSK employs two phases that are separated by 180º in pulse. Therefore, BPSK can also be called 2-PSK or bi-phase modulation (BPM). BPM is easily understood as the inversion of specific pulse shape, and we use the following equation to create a binary system based on the inversion of the basic pulse p(t):

$$s_i = \sigma_i \, p(t) \quad where \;\; \sigma_i = \pm 1 \tag{2.14}$$

For a binary system, the two resultant pulse shapes can be defined as S1=p(t) and S2=-p(t). One of the reasons for using BPM is the resulting 3 dB gain in power efficiency. [Yajnanarayana et al. (2014); H Taki et al. (2016);Niemelä et al. (2016)].

E. Comparison of UWB modulations

The most common IR-UWB modulation techniques are PPM and BPM. The main advantages of PPM modulation lies in its simplicity and ease of control delays. However, the synchronisation between the receiver and the transmitter must be considered in addition to the creation of large spectral peaks. The main advantages of BPM modulation lies in its simplicity and efficiency. However, BPM is only used in binary communications. No serious attempt has been made to use either PAM or OOK in UWB systems. The major challenge in OOK is detecting the absence of a pulse in the presence of multipath. By contrast, PAM has many disadvantages. For instance, the 'AM signal which has a smaller amplitude is more affected to noise than that with a larger amplitude. Furthermore, more power is required to transmit a higher amplitude pulse' do Nascimento (2007).

2.4.1.4 Enabling Multiple Access in a Single Band UWB

The modulations described in the previous subsections do not have multiple access capability. To achieve multiple accesses, a randomisation technique is applied to the transmitted signal to reduce the spectral peaks and subsequently minimize interference.

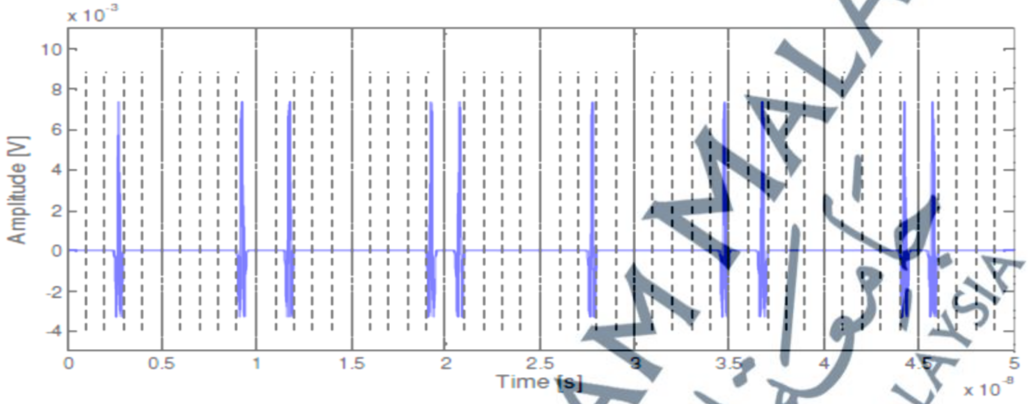
Several important techniques for enabling multiple access in IR-UWB systems have been proposed in the literature, such as the time-hopping (TH) technique, which is used for LDR and HDR UWB. TH-UWB may be considered similar to the well-known narrowband TH spread spectrum (THSS). The UWB and spread spectrum take advantage of the expanded bandwidth do Nascimento (2007). However, in IR-UWB, the narrow UWB pulses are directly generated having an extremely large bandwidth, while in conventional spread-spectrum sinusoidal signals are modulated with a carrier. Besides, the bandwidth for UWB signals has to be higher than 500 MHz, while for spread spectrum techniques much lower bandwidth is considered. Otherwise, the basic idea of both technologies is the same.

A. Time Hopping Ultra-Wideband (TH-UWB)

Time Hopping Ultra-Wideband (TH-UWB) is a random-access spread spectrum technique. UWB pulses are transmitted having pseudo-random positions. TH-UWB can be combined with PAM, PPM, and PPM-PAM modulations.

The transmission of multiple radio impulses encodes each data symbol shifted in these technologies do Nascimento (2007). However, in IR-UWB, the directly generated narrow UWB pulses have extremely high bandwidth, whereas in conventional spread spectrum techniques, the sinusoidal signals are modulated with a carrier. Moreover, the bandwidth for UWB signals must exceed 500 MHz, whereas spread spectrum techniques require a much lower bandwidth. Apart from these considerations, TH-UWB and THSS have the same basic idea.

The transmission of multiple radio impulses encodes each data symbol shifted in time. To avoid collision amongst pulses, spread spectrum systems use a pseudorandom code generator. The generated code, which is called a periodic pseudorandom noise code (PN) do Nascimento (2007), is used to determine the actual interval in which the output signal is transmitted. Each user is assigned by code. Therefore, UWB signals may be transmitted by multiple users without interference. Figure 2.8 presents a sample binary PPM modulation for a user with the pseudo-random code ‘3 5 2 5 1’.



Source: do Nascimento (2007)

Figure 2.8: Transmission Of Bits ‘1 0 1 0 1’ For TH Code ‘3 5 2 5 1’ Via 2-PPM Modulation

Xiong Wang et al. (2018) designed a waveform solution for broadband satellite communications. To types of waveforms, namely, constant envelope multicarrier waveforms and single-carrier impulse-based waveforms, are compared in Table 2.4.

Table 2.4: Time hopping

	Uplink	**Downlink**
Q\V-band	42.5-43.5 GHz 47.2-50.2 GHz 50.4-51.4 GHz	37.5-42.5 GHz
W-band	81-86 GHz	71-76 GHz

Source:Xiong Wang et al. (2018)

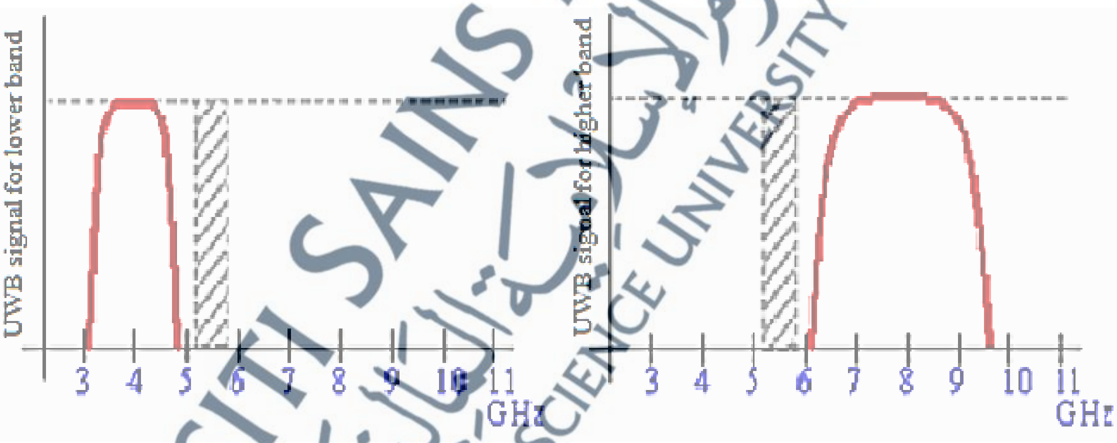
Malik et al. (2016) examined the anti-jamming capability and low-probability interception of a TH system. The large bandwidth of this system overlaps with several frequency bands and is either used to establish narrowband services or intentionally jammed from enemies. The anti-jamming performance of TH-UWB has been analysed in many studies to mitigate interference from both the transmitter and receiver. At the receiver side, the narrowband is analysed by using Code Division Multiple Accesses (CDMA). This method uses a nonlinear prediction filter to reject or reduce narrowband jamming and a transmitter to improve the anti-jamming performance of the TH system.

Xiong et al. (2017) used the composite number in the group intrusion destruction algorithm for reasoning UWB wireless sensor networks. Compulsion-based TH-UWB radios are mostly appropriate given their low cost, low power consumption and positioning over a large frequency band. The narrowband clients and the intercessions of ultra-wideband client were estimated, and narrowband client and interruption happened in the UWB radiators to another prior wireless communication system. The various in narrowband band interventions immediately a direct course enormous request versatile obstruction, and the novel was high request lattice rout strategy was utilised. The numerical simulation, which was interfering acknowledgement edge of period jumping based ultra-wideband WSN systems, was significantly modified by the complex coefficient cyclic course high request system versatile puzzles. The system was performed before the demodulation part, and it was suitable for front end in-band interruption end of the non-lucid drive-based ultra-wideband remote sensor organize which was performed with the rake recipient and multiuser indicator [Yajnanarayana et al. (2014); H Taki et al. (2016);Niemelä et al. (2016)].

B. DS-UWB

Direct Sequence (DS-UWB) is a single band technique based on the transmission and reception of short pulses. Many users can share the same spectrum without interference by using orthogonal codes based on CDMA. Each user is assigned a unique code. DS-UWB signals can be modulated via PAM, OOK or PPM-PAM.

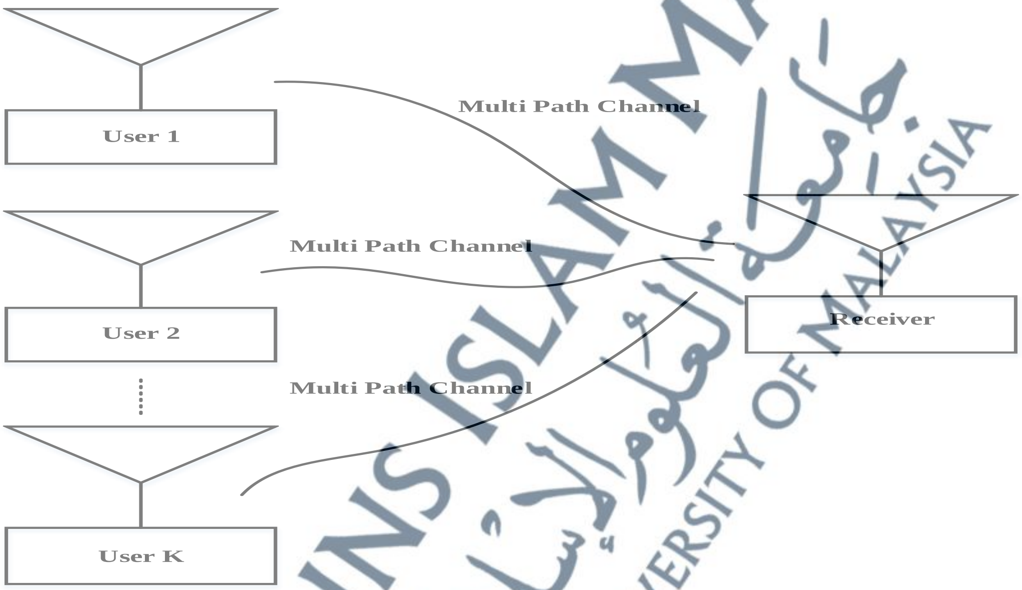
To enhance efficiency, DS-UWB supports operations in two bands, namely, a low band of 1.75 GHz that occupies the spectrum from 3.1 GHz to 4.85 GHz and a high band of 3.5 GHz that occupies the spectrum from 6.2 GHz to 9.7 GHz (Figure 2.9). Given the possible interference from 802.11. A WLAN, the 5 GHz–6 GHz frequency range is avoided do Nascimento (2007). Both these bands can be used either simultaneously or separately.



Source: do Nascimento (2007)

Figure 2.9: DS-UWB Spectrum

Bai et al. (2018) developed an orthogonal balancing code based on UWBs over different path channels, as shown in Figure 2.10. The offset stacking UWB structure achieves an adjustable data rate transmission by using a ground-breaking offset stacking scattering technique. DS-UWB achieves a flexible data rate by using spreading intonation methods. The performance of the two systems of the multipath channel is evaluated in terms of BER. The Orthogonal Complementary Code achieved a better performance (OCC) based UWB system and has been compared with a unitary-code-based UWB system.



Source: Bai et al. (2014)

Figure 2.10: Multi-User UWB Communication System

2.5 UWB Channel Model

The propagation environment through which a signal passes from a transmitter to a receiver is referred to as the channel Ghavami et al. (2007). Given the wideband nature of UWB applications, the propagation phenomena differ between the lower and higher bands of a spectrum Oppermann et al. (2005).

However, similar to any other signal in a wireless medium, IR-UWB signals undergo attenuation and distortions in the communication channel. IR signals are also prone to fading and multipath interference, which make the received signal at the receiver considerably different from the radiated signal from the transmitter. However, the channel behaviour of an IR-UWB signal significantly differs from that of a conventional signal. The distorted UWB signal at the receiver can be modelled as Zou (2011)

$$r(t) = \sum_{i=0}^{L-1} \alpha_i S(t - \tau_i) + n(t) \quad (2.15)$$

where *r(t)* is the received signal, L is the total resolvable multipath component, αi is the attenuation specific to the l-th path, τ_i is the path propagation delay and n(t) is the double-sided Gaussian noise with a spectral density of $(N_0/2)$.

IEEE 802.15 Chore Group 3a (TG3a) evaluates many indoor and indoor-outdoor channel models to determine which of these models is fit for the UWB channel characteristics. Amongst these models, the modified Saleh–Valenzuela (S-V) model J Foerster (2003) has been recommended by the IEEE as a reference channel model Oppermann et al. (2005). For the UWB channel model, given the fine delay resolution of the UWB pulse, the multipath arrivals are in clusters rather than in a continuum. UWB channel measurements also show that the fading amplitudes follow a lognormal distribution. In their final report on WPANs issued in February 2003, the IEEE 802.15.TG 3a proposed a detailed channel model for UWB communication systems. This model presents a detailed description of the UWB channel model and serves as an important step in UWB channel research. Many studies [Irahhauten et al. (2004; N. Liu et al. (2008; Molisch (2005)] have examined the channel model and localisation for UWB communication system design. Readers can refer to [Oppermann et al. (2005); Ghavami et al. (2007); J Foerster (2003); Molisch (2005); Irahhauten et al. (2004);Alarifi et al. (2016)] for additional details.

Dong et al. (2016) extensively discussed IR-UWB channel modelling. One channel model for IEEE 802.15.4a, the subgroup mentioned in 802.15.4a (2007), also uses the S-V model, as shown in Table 2.5 Molisch et al. (2011). The S-V model is one of the most widely used wideband propagation models that define the resolvable multipath components' delays and amplitudes by using random probability distributions Molisch et al. (2011).

Table 2.5: Channel modelling for IEEE 802.15.4a

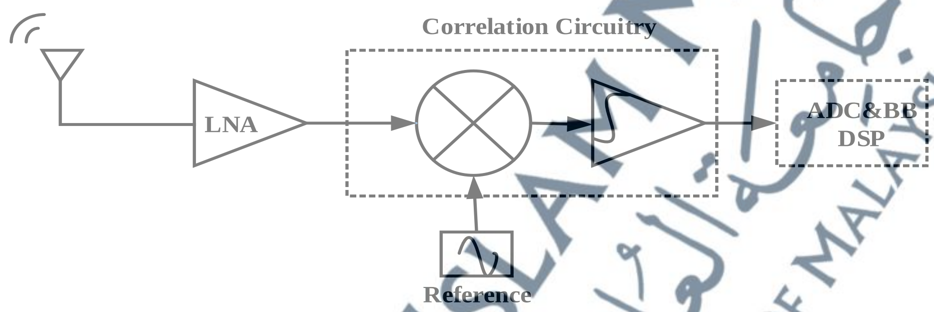
Channel Model	Type	Category	Range (m)
1	Residential	Line of sight	7-20
2	Residential	Non-line of sight	7-20
3	Indoor office	Line of sight	3-28
4	Indoor office	Non-line of sight	3-28
5	Outdoor	Line of sight	5-17
6	Outdoor	Non-line of sight	5-17
7	Industrial	Line of sight	2-8
8	Industrial	Non-line of sight	2-8
9	Open outdoor	Non-line of sight	-

Source: Molisch et al. (2011)

Gao & Chen (2017) proposed channel loss models of UWB radio wave broadcast from 2 to 10 GHz usages. The environment of 2 to 10 GHz short-range application of UWB and programmed loss under different application environment based on IEEE 802.25.4a protocol. The zig bee application circuit is used to test the IEEE 802.15.4a and Okumura (OM) channel loss models. The IEEE 802.15.4a channel model achieves high precision and using both zig bee and IEEE 802.15.4a is deemed suitable for channel loss estimation systems.

2.6 IR-UWB Receiver

Recall from Figure 2.8, the generated TH-PPM UWB pulses can be received with special design anntenia as analog signal with proper amplification using LAN filter then, can be correlated with the reference signal to generate the matching digital outputs. This is the ADC unit that can be used an electronics devices as shown in figure 2.11



Source: Gao & Chen (2017)

Figure 2.11: IR-UWB Receiver Top-Level Structure

Aside from the receiver antenna, the Low Noise Amplifier (LNA) can also serve as a front-end amplifier. A template reference circuit generates the UWB pulse template, which will be fed into the multiplier in the following stage. Given that no carrier is used for the IR-UWB system (that is, no frequency shifting occurs), a simple time-domain direction conversion should be enough for signal demodulation. The multiplier takes the reference and RF inputs and then multiplies them to conduct a correlation type demodulation. An integrator block follows the multiplier that serves as a low pass filter for signal processing and then outputs the integrator that is digitised by a high-speed, low-resolution Analogy To Digital Converter (ADC) circuit for digital signal processing (DSP) or host applications. The synchronisation, correlator speed and power control should be considered during the actual design implementation, Gao & Chen (2017).

2.7 Link Budget Design and Analysis for UWB

Link budget analysis mainly aims to determine the maximum distance between the transmitter and receiver to ensure reliable communication for predetermined transmission rates, ranges, transmission powers and error rates and to make provisions for the capacity of the system and coexistence with other systems. The link budget analysis in UWB systems may greatly differ from that in conventional systems, especially impulse-UWB systems, because whilst the average and maximum power in narrowband systems are essentially the same (even if it is not the average power that is of interest), given that pulses with a particularly low duty cycle are often used in UWB systems, the average power may not be useful. Moreover, given its large bandwidth, the pulse may be deformed by the receiving and sending antennas, whereas the active surface gain of the latter most likely will not stay constant across the entire frequency band.

This section presents a link budget design that is used in small range solutions. The analysis focuses on the digital BB implementation, the physical layer design and the experimental validation of indoor or outdoor UWB systems. Wireless communication systems are developed along with their corresponding link budget patterns and are analysed by using the physical values of parameters. The full digital coherent architecture corresponds to BB algorithms, Gao & Chen (2017).

An impulse-based UWB system with precise ranging and low rate communication has been constructed in the literature. The link budget analysis considers the design methodology, and the digital receiver corresponds to BB receiver algorithms. The design solution was achieved the network number of pulse per bit, throughput, pulse duration, transmitted signal power, minimum receiver sensitivity, the link margin, and communication coverage. The design resolution was scheduled with the link design, which is analysed by using applicable parameters with their associated values listed in Table 2.6.

Table 2.6: IR-UWB Link Budget For Precise Ranging Low Rate Communication

Parameters	Units	Values
Throughput	Mbps	0.85
Distance	M	30
Bandwidth	mHz	500
Average transmitter power	dBm	-14.3
Duty gain	dB	15.1
Transmitter peak power	dBm	0.7
Centre frequency	Hz	096
Path loss 1 meter	dB	45.5
Path loss d meter	dB	29.5
Receiver power	dBm	-74.3
Receiver AWGN noise floor	dBm	-87.0
Receiver noise figure	dB	8.0
Average noise power	dBm	-79.0
Pulse per symbol	-	16
Processing Gain	dB	12.0
Minimum Eb\N0	dB	8.0
Implementation loss	dB	3.0
Link margin	dB	5.8
Minimum receiver sensitivity	dBm	-80.1

Source: Oh et al. (2009)

The multiuser interference of the IR-UWB is statistically analysed, and the physical parameters of signals are used to design the link transmitter and receiver, which was located about the 1 meter from the distance of 1.5 meters. The multipath environments are measured by using certain parameters, which values are shown in Table 2.7.

Table 2.7: Parameters And Their Values

Parameter	Values
Pulse of deration T_p	2ns

chips of duration T_c	2ns
frame length N_c	128
Number of duration N_u	Random
Sampling frequency	2
Central frequency	2Ghz
Bandwidth	4.05GHz

Source: Merz (2008)

The link budget wireless communication is identified by the strength and signal quality at the receiver side. The link budget is essential in validating the RF in UWB systems. A proper UWB radio parameter is crucial in evaluating data rate, BER and service coverage. The transmitter is used to evaluate the received signal. The distance, frequency, LOS settings and link types are included as link budget settings. The budget is used in a pulse-shaped field, and the HDR of UWB products are used in the link budget and in residential and office environments. The specific link budget is then validated by performing several measurements at various distances ranging between 1 m and 20 m. The low power, high speed and low cost of indoor applications are all considered in the measurements.

Matching the receiver side to the maximum SNR is a difficult task. The multiple UWB budget is measured to inspect signal propagation and outdoor or indoor scenarios. The receiver development is investigated by using specific communication parameters. A UWB outdoor measurement is designed and applied in surveillance. The channel modelling, transceiver structures, low and high rate of indoor and outdoor environmental applications were the design development of the communication model. The link budget is analysed, and a scheme is developed to explore those UWB parameters that are used in communication cross-layers.

Jawad et al. (2014) designed a link budget with a tuneable impulse-based UWB with a wireless sensing and identification infrastructure. IR-UWB signal Model: PPM as the coding method was generated the UWB in short-range pulses train, and these methods were simple and ultra-low power Radio Frequency Identification (RFID) and WSN nodes.

2.8 Advantages of Impulse-Based UWB

High data rate: UWB can achieve HDR in transmission, and the bandwidth increases along with volume. Shannon's equation provides the maximum rate in which the data can be transmitted without any error. However, this equation is restricted in terms of bandwidth and signal-to-noise ratio (SNR),

$$A = B\log_2(1 + \frac{S}{N}) \tag{2.16}$$

where

$maximum\ channel\ capacity\ \left({}^{bits}/_{second}\right), A$

$bandwidth\ of\ their\ channel\ (Hz), B$

$powerof\ signal\ \ (watts), S$

$power\ of\ noise\ (watts), N$

Low requirement cost: UWB transmission is carrier less it controls the antenna. UWB also requires a lower number of components, including sinusoidal transmitters and receivers, compared with previously proposed systems, thereby reducing the costs and allowing the use of small devices. However, UWB requires certain electronic devices, such as wireless sensors.

Penetration ability: The application of UWB benefits or relies on the ability of a communication system to penetrate physical objects that are typically found at home and office environments. UWB systems operating on the low centre frequencies still they provide their capacity. The high centre frequency with the lower ability of UWB and the objects are due to the shorter wavelength. The relationship between frequency and wavelength can be expressed as Jawad et al. (2014)

$$\lambda = \frac{s}{f} \quad (2.17)$$

where

$wavelength\ in\ meters\ (\lambda)$

$frequency\ in\ Hz\ (f)$

$s\ is\ the\ speed\ of\ light - 299{,}792{,}458\ {}^{m}/_{s}$

Accurate ranging and location detection: the narrow transmit provides the UWB radios are providing a good time domain resolution, and it allow the location and position determination.

Multipath resistance: The UWB system has narrow pulses that provide wide bandwidth and are separated with fine resolution of reflected pulses at receiver.

Inherent robustness to multipath fading: Given its large bandwidths, UWB is very robust to multipath fading. Signal propagation is achieved by using the multipath fading channel model, where the transmitted signals reach the receiver through multiple paths. This model causes constructive and destructive interferences and shifting in the signal, whereas the sum of out of phases causes destructive interference along with multipath fading. Given the wideband of UWB, the transmitted signal is resistant to multipath propagation. The narrow pulses prevent multiple reflections from combining and destroying the receiver. The multipath components are used to improve the signal reception via the rake receiver or channel equalisation, whereas narrow pulses can be prevented via multiple reflections.

Noise-like signal: UWB pulses are transmitted at very low power levels, and the signal may demonstrate some pseudo-randomness due to noise, and it can be like noise signal or interception or detection.

Frequency and data transmission: UWB achieves accurate frequency and high-speed data transmission rate in personal wireless devices.

Ability to transmit data at high rates: UWB is mainly used for short ranges, such as residential or personal networks, and especially for medical applications where high-resolution medical images need to be wirelessly transferred to doctors for their proper diagnosis. UWB can also be utilised in medical radar applications to continuously monitor the movement of patients confined in intensive care units. UWB systems have replaced wireless transfer technologies, such as Bluetooth, due to their many benefits, which are summarised as follows.

- Low power consumption and the requirement for complex components, such as the Power Amplifier (PA) used in the transmitter.
- High security during data transmission.
- The use of CMOS transmitters, which do not consume much energy in battery-powered devices.

UWB systems have been extensively used in several areas, including

- distributing audio, video and other types of data in wireless channels,
- preventing collisions amongst radars,
- precise tracking for geolocation services,
- detecting intrusions and
- radio frequency identification and tagging.

The main advantages of UWB are summarised in Table 2.8.

Table 2.8: Advantages And Benefits Of The UWB Channel

Advantages	Benefits
Co-existence with current narrowband and wideband radio services	No expensive licensing fees
Large channel capacity	High bandwidth and support for real-time high-definition video streaming
Low transmit power	The high degree of security and low detection and intercept probabilities
Resistance to jamming	Reliability in hostile environments
Robust performance in multipath channels	High signal strength in adverse conditions
Simple transceiver architecture	Enables ultra-low power, smaller from factor and better mean time between failures, all at a reduced cost.

Source: Rout & Das (2017)

2.9 Challenges in Impulse-Based UWB

IR-UWB systems also face several challenges, the most important of which is their complex design. Robust code synchronisation algorithms with heavy processing requirements are needed at the receiver to achieve synchronisation, especially in multipath environments, if IR technology is used. Moreover, wideband circuit elements generally have higher power consumption and are more difficult to build compared with narrowband circuit elements. These problems result in the uneconomical implementation of IR-UWB systems via CMOS P.-M. Wang et al. (2020).

Meanwhile, the low PSD and simple architecture of IR pulses keep the transmitter design simple and energy-efficient. However, the received signal level at the receiver is usually very low, thereby making the use of PA inevitable in practice. A coded ultrashort pulse train also requires a long synchronisation time and produces overhead because of its heavy processing requirements. These factors lead to complex and power-hungry receiver design requirements Nikoukar et al. (2018).

UWB systems mainly target short-range, HDR and portable communication devices that require small circuit designs and antennas and can operate under varying channel conditions. However, designing convenient antennas with small dimensions poses a problem given their wide bandwidth and nonlinearity C.-X. Wang et al. (2016).

Very few UWB standardising groups are available in IEEE, and the UWB spectrum is heavily unregulated, thereby resulting in potential interference between two UWB systems that share the same frequency bands.

2.10 IEEE Standards for Short-Range Communications

The IEEE 802.15, standardisation of specifications for Bluetooth wireless devices as defined by IEEE, is applied for WPANs. This standard mainly applies for short-range, low-power, low-cost and small networks and allows communication between two working groups, namely, the IEEE 802.15.3a, which is used to achieve HDR in short-range applications, and IEEE 802.15.4a, which is aimed at communications with high precision ranging from an ultra-low power.

Pothuganti & Chitneni (2014) reviewed the wireless procedures of Bluetooth, UWB and Wi-Fi. These four protocol standards were used in the small range of wireless communication with less power consumption. The Zig bee was calculated with a reliable wireless network observing and regulator the networks. Wi-Fi was focused in computer to computer networks as delay or substitution of cabled networks.

2.10.1 Bluetooth over IEEE 802.15.1

The IEEE 802.15.1 standard depends on wireless radio systems that are used for short-range communications and as substitutes to cables for computer peripheral devices given their low cost. Bluetooth devices were serving the master in Pico-net, and one or more Bluetooth devices were allocations as slaves. The slave communicates only the master in point to point under the regulator of the master.

2.10.2 UWB over IEEE 802.15.3

The IEEE 802.15.3 standard is used for small indoor-range high-speed wireless communications. Established in 2001, the IEEE 802.15.3a Study Group defined a new physical layer to serve the requirements of those companies that wish to deploy HDR applications, such as video, imaging and multimedia applications, with a minimum data rate of 110 Mbps at a short range of 10 m. As the prevailing PHY solution in IEEE 802.15. TG3a, MB-OFDM is a carrier-based system that divides the UWB bandwidth into different sub-bands. Meanwhile, DS-UWB is a compulsion-based system that increases an input bit with a distribution code and conveys the data controlling element of the symbol with a small pulse.

The IEEE 802.15.3a was not specifically made to be a UWB standard group, but the best candidate for a new alternative was the UWB technology. The purpose of this study group was to provide a high-speed physical layer. This standard should also coexist with all existing IEEE 802.15 physical layer standards with a robust multipath performance Taylor (2018).

2.10.3 Zig Bee over IEEE 802.15.4

The standard conditions were low rate WPAN for modest devices which consumed nominal power and operated in POS of 10m. Two devices participate in an LR-WPAN network. The FFD serves three functions, namely, as a PAN coordinator, a coordinator and a device. A concentrated function device was intended for the application, which was extremely simple in the light switch and passive infrared sensor.

2.10.4 Wi-Fi over IEEE 802.11a\b\g

It was included with the IEEE 802.11.a/b/g Standards for (WLAN). It was allowed the user to the internet at broadband speeds when it was connected with the AP in ad hoc mode. The IEEE 802.11 includes several components that interact with one another to provide WLAN services and support the mobility of the upper layers. The architectural components are used to interconnect the basic service set in a distribution system (DS).

The wireless standards are evaluated in terms of their data coding efficiency, transmission time, power consumption and protocol complexity and are compared in terms of their radio channel, network size, security and coexistence mechanisms. The suitability of the network protocol was mainly used in real applications.

The IEEE 802.15.4a, which is applied in the design of WPAN-targeted radio interfaces, is described in the following sections on the basis of the findings of Jinyun Zhang et al. (2009).

2.10.5 IEEE 802.15.4a

According to Niemela et al. (2017), IEEE criteria are used in IR-UWB. These criteria include HDR and IEEE 802.15.4 to achieve a minimum WPAN rate in different path fading. The applications were imaging and multimedia were provided the HDR and speed for IEEE standard of UWB PHY.

The IEEE 802.15.4a standardisation group was established in 2004 to develop a new PHY layer for WSN and other WPAN applications. The main goals of this group were to improve the IEEE 802.15.4 standard with enhanced communications and node distance evaluation capabilities to enable its application in geolocation services. This standard is mainly used in WPAN contexts. One technology that uses such standard is Bluetooth, which is developed specifically for WPAN applications and proposes a radio range of up to 10 m 802.15.4a (2007).

The final draft of the P802.15.4a standard was approved in March 2007 and was published in June 2007, 802.15.4a (2007) This draft presents detailed information about the PHY layer, including its modulation/coding schemes, multiple access and ranging related waveforms as well as MAC-layer-related modifications to the IEEE 802.15.4-2006 standard. Accordingly, many studies have examined the development of the IEEE 802.15.4a standard [Sharma et al. (2017); Zayani et al. (2011); Silva & Hancke (2016); Ye et al. (2012); Tiemann (2016)].

2.11 PHY Layer Specifications in UWB Communication Systems

The IEEE 802.15.4a standard presents two options for designing the PHY layer. Between these options, the UWB low-rate WPAN (LR-WPAN) is designed to provide robust data communications and to improve ranging precision via TH-IR. To achieve these goals, the UWB PHY has the following features:

- Low PSD. The regulations concerning UWB in different parts of the world have defined PSD levels of up to −41. 3 dBm/MHz in best-case scenarios.
- Multiple bands and operating frequencies within each band. The devices must avoid using an occupied band or a band that is forbidden in the country where they are being used.
- Re-configurability. The devices must be able to modify the symbol timing and the shape of the pulse either to efficiently use the channel with good transmission conditions and a large number of communicating nodes or to

allow coexistence with other spectrum users. This reconfigurability is managed by using specific commands that allow higher layers to perform reconfigurability tasks.

Sanam et al. (2015) reconfigured the controlling signal parameter in the PHY level to allow some tuning flexibility. A trade-off was observed amongst three variables in wireless communication systems.

Communication can be established between any UWB device and a coordinator or amongst coordinators. However, a mandatory 850 kb/s data rate must be fulfilled along with other optional variable data rates, such as 110 kb/s, 1.70 Mb/s, 6.81 Mb/s and 27.24 Mb/s.

WSNs are heterogeneous by definition, that is, they are formed by nodes with different capabilities and requirements [Section III-D, 802.15.4a standard (IEEE 802 Part 15.4, 2007)]. Therefore, a network must have at least one FFD (i.e., one device that implements all optional features of the standard). This FFD is less cost-sensitive because of its reduced number and is usually connected to a permanent power supply. Owing to these particularities, FFDs are often configured to perform network coordination and other complex tasks that other nodes may be unable to perform. By contrast, sensors are reduced function devices (RFDs) that often lack stringent limits on complexity and energy consumption. The standard PHY layer is designed in order for FFDs and RFDs to achieve optimum performance through flexible modulation, coding and multiple-access schemes (MCMs).

An FFD may employ a high-power-consuming reception method based on coherent reception, whereas an RFD may use a simple energy-efficient non-coherent receiver based on energy level detection. Such a flexible MCM keeps the possible performance of the FFD almost intact, that is, the performance of the FFD with a flexible MCM is almost as good as that of an FFD with a fixed MCM. The rest of this section describes specific features and designs of the IEEE 802.15.4a standard.

The frequency and bandwidth of UWB signals result from the trade-off between the performance of FFDs and the low complexity of RFDs. A larger UWB band allows higher transmit powers and granularity in delay for TH. However, the complex design of the receiver increases along with bandwidth. Non-coherent receivers favour narrower bandwidths because they cannot efficiently combine the resolved multi-path components. Meanwhile, coherent receivers can achieve recombination by using a correct number of rake fingers as stated by Rendevski & Cassioli (2015). The last parameter taken into account for the trade-off between performance and compatibility is clock frequency, which increases the signal bandwidth and energy consumption, especially in rake receivers. These considerations have led the IEEE 802.15.4a standard to favour a 500 MHz bandwidth for all mandatory modes. Optional modes may use bandwidths of up to 1.3 GHz by bonding 3 500 MHz channels. Table 2.9 lists the UWB bands defined in the IEEE 802.15.4a standard along with the regulatory domains where these bands are admissible.

Table 2.9: IEEE 802.15.4a UWB Frequency Bands

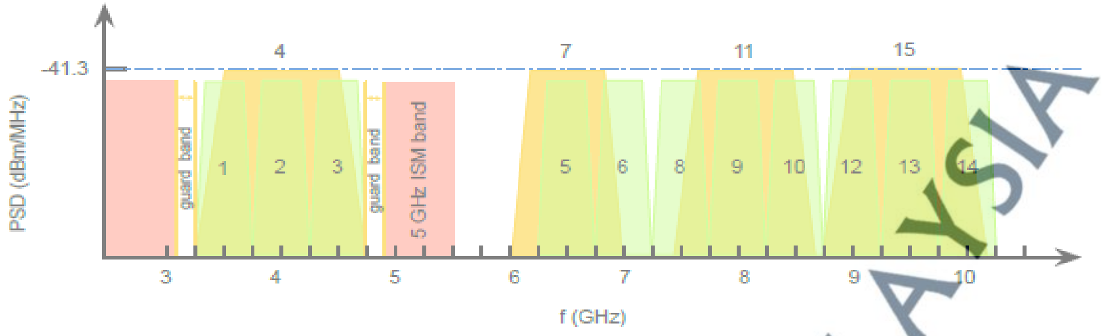
Frequency	**Band centre frequency (MHz)**	**Bandwidth (MHz)**	**Allowed in**		
			USA	EU	JPN
0	499.2	499.2	X		
1	3494.4	499.2	X	X	
2	3993.6	499.2	X	X	X
3	4492.8	499.2	X	X	X
4	3993.6	1331.1	X	X	X
5	6489.6	499.2	X	X	
6	6988.8	499.2	X	X	
7	6489.6	1081.6	X	X	
8	7488.0	499.2	X	X	X

9	7987.2	499.2	X	X	X
10	8486.4	499.2	X		X
11	7987.2	1331.2	X		X
12	8985.6	499.2	X		X
13	9484.8	499.2	X		X
14	9984.0	499.2	X		X
15	9484.8	1354.9	X		

Source: Salman et al. (2010)

All centre frequencies in Table 2.9 can be derived from 13 MHz or 19 MHz crystal oscillators Salman et al. (2010). The 5 GHz ISM bands are kept empty due to possible interference with narrowband systems, such as 802.11n Wi-Fi. The repartition of these bands is illustrated in Figure 2.12 (in the 3.1 GHz–10.6 GHz unlicensed ISM band).

The IEEE 802.15.4a standard is designed to work with both coherent and non-coherent receivers. To serve this function, a hybrid modulation scheme based on TH-IR, BPSK and PPM has been developed by Zhao et al. (2007). In this scheme, each bit is coded in a pulse burst that is sent either in the first or second half of the PPM period. A non-coherent receiver then integrates the signal and detects whether the pulse is in the first or second half of the PPM period. By contrast, a coherent receiver correlates with the awaited pulse burst and improves the SNR by a factor of N, where N is the number of pulses in a burst. Multiple access is allowed through TH. The burst waveform is sent in a different slot of the PPM half-period. The TH sequence is pseudo-random and is unique to each node. A second multi-user separation technique is used by coherent receivers and is based on the burst waveform, which is also unique to each node. This hybrid modulation, coupled with TH multiple access, allows both FFD and RFD to send and receive messages to and from each other with no knowledge of the fact that the other node is an FFD or RFD.



Source: Zhao et al. (2007)

Figure 2.12: IEEE 802.15.4a UWB Band Plan

A systematic Reed–Solomon (RS) code is used to improve transmission performance Genser et al. (2009). A 1/2 convolutional code then encodes the data by using two modulation schemes, that is, the systematic bit is sent through PPM, whereas the parity bit is sent through BPSK with the phase of the burst waveform. Different levels of decoding can be implemented in a receiver. The simplest receiver decodes neither the RS encoding nor the BPSK convolutional parity check. By contrast, a complete receiver can apply turbo decoding by exchanging soft information between two decoding units.

The last part of the PHY layer described in the IEEE 802.15.4a standard deals with preambles and synchronisation. The hybrid modulation scheme creates specific needs for the preamble and synchronisation parts. Perfectly balanced ternary sequences (PBTSs) are proposed as solutions to this problem. Using PBTSs allows all receivers to synchronise the incoming message, and coherent receivers can benefit from the complex synchronisation of PBTSs and are 3 dB higher compared with non-coherent receivers. The preamble sequences are either 31 or 127 bits long, and all the allowed sequences are defined in the standard. Each network must use a different preamble sequence to avoid interference amongst multiple networks that use the same standard.

2.12 MAC Layer Specifications of UWB Communication Systems

The IEEE 802.15.4a standard allows the application of different medium access control (MAC) schemes. The ALOHA scheme is a mandatory scheme for any node that does not require checks before transmission. Although the ALOHA scheme allows the design of simple nodes, an optional CDMA MAC protocol has been developed for star networks of up to seven nodes and the controller. A PAN coordinator is then used to attribute permanent time slots to nodes that send requests to join the time division multiple access (TDMA) super-frame. One drawback of the TDMA super-frame is that it may only allow up to seven guaranteed time slots. Another function of the PAN coordinator is to guarantee synchronisation with the TDMA super-frame. Carrier sense (CS)-based optional MAC schemes are also defined in the standard to reduce the chances for a non-TDMA compliant node to interfere with a TDMA frame. This scheme uses specific preambles that are multiplexed with data and are periodically inserted in the payload. A clear channel assessment (CCA) scheme listens to this specific preamble and delays the transmission if a single occurrence of this preamble is detected, Saeed et al. (2010).

This standard describes one mandatory and extremely simple ALOHA MAC scheme. A more complex TDMA-based scheme has also been proposed to guarantee an improved performance with an increasing number of nodes. A simple CS optional scheme has also been described to prevent interferences from an RFD in a TDMA-coordinated channel.

2.13 Gap Analysis for Impulse-Based UWB Cross-Layer

In traditional wireless systems, a clear boundary is observed between the PHY and MAC layers. Specifically, the main goal of the MAC layer is to organise access to the PHY layer, which is responsible for the actual transmission of information amongst nodes. In general, these two layers do not interact as the MAC layer has no control over the transmission rate and power generated by the PHY. In PHY-aware MAC designs, the MAC layer can access some or all parameters of the PHY layer. For example, the power or rate can be dynamically adapted to mitigate the level of interference Mendes & Rodrigues (2011).

Different optimisations have been proposed in the literature to overcome the use of IR-UWB wireless nodes in future applications. However, the proposals for new applications of IR-UWB wireless nodes have introduced challenges that need to be addressed. The most efficient way of solving these problems is using cross-layer approaches to consider the behaviour of protocols at each layer. The key problems of future IR-UWB wireless nodes and their potential cross-layer solutions are discussed as follows.

The mobility of future wireless networks has been highlighted in Le Boudec & Vojnovic (2005), given that various services should be provided with convenient throughput. Perez-Guirao et al. (2007) proposed a cross-layer MAC design for IR-UWB networks to highlight the benefits of controlling the channel access rate of IR-UWB. The access rate is determined by the pulse rate (pulses/sec), modulations and error coding rate. The benefits of this design have been quantified as network throughputs for peer-to-peer and star network topologies. The simulation results show that the proposed MAC layer design has an improved link quality, which can be attributed to the fact that the structure of the IR-UWB signal reduces the total interference and maximises the network throughput.

The accurate ranging and positioning of IR-UWB sensor networks is a concern in MAC-aware PHY layer design [T. Wang (2012; Wu et al. (2011)]. The MAC layer is adapted to LDR-UWB, and its ranging detection depends on the exchange of control packets. In this case, the ranging information provided by MAC is treated as an input to a distributed positioning protocol. The simulation of the positioned terminals and the percentage of positioning errors are then evaluated, and the results highlight the excellent ranging accuracy of the MAC-location aware design.

Cross-Layer Design for distributed signal detection under resource-constrained scenarios is presented in Fabeck et al. (2008), who aimed to minimise the probability of errors in a distributed system at a fixed level of total transmission power. Their proposed design demonstrates considerable performance gains compared with uniform power assignment for both parallel and serial network topologies.

Davaslioglu et al. (2016) proposed a cross-layer optimisation for network energy efficiency (CLOEE) maximisation for IEEE 802.15.6 IR-UWB WBANs. CLOEE derives a closed-form expression from determining the optimal frame size subject to minimum rate constraints and then searches for an optimal number of pulses per burst. The simulation results reveal that CLOEE achieves the same performance as an exhaustive search and demonstrates significant improvements in energy efficiency (by one order of magnitude) and transmission range (by a factor of two) compared with static strategies.

Melodia & Akyildiz (2010) proposed a cross-layer control unit (XLCU) to ensure QoS for WMSNs and used geographical forwarding to control the flows and hop-by-hop QoS requirements. XLCU controls the scheduling and rate assignment of TH-IR-UWB, thereby preventing collisions and idle listening, improving throughput and reliability and reducing delays.

A centralised nonlinear programming problem for optimal routing, scheduling and power control was defined in Shi et al. (2006), who also proposed a heuristic algorithm for solving the optimisation problem in large networks. Shi & Hou (2008) later included rate assignment as an optimisation problem and then derived closed-form expressions by calculating the capacity of WSNs.

Karvonen et al. (2015) proposed an energy-efficient cross-layer architecture for WBANs with impulse-based UWB. This architecture uses the cross-layer model, which focuses on the physical PHY and MAC layers. This architecture highlights the important characteristics of these layers. An OOK modulation depends on the PHY with impulse UWB signalling, and an energy detection receiver is non-coherent. A contention-based mode that follows the IEEE 802.15.6 standard was used in the MAC protocol and the standard slotted ALOHA. This cross-layer model was used to compare the energy efficiencies in uncoded and coded transmissions. An energy consumption model was also developed to compare the coded and uncoded rates.

Ren & Liang (2008) proposed a new cross-layer MAC called throughput maximised MAC (TM-MAC), which divides UWB pico-nets into sets and calculates the optimal scheduling and transmission rate to minimise interference. TM-MAC increases the throughput by up to 22% and reduces the packets transmission time by up to 32% compared with the IEEE 802.15.3 standard.

Chehri et al. (2009) studied the effects of rate and power allocation for sensor nodes travelling on the same route and observed that individually optimising the routes can increase the difficulty of meeting end-to-end delay constraints. Therefore, they have proposed a novel design that reduces the energy consumption of these nodes by using a modulation scheme and transmission power. This design reduces the energy consumption of these nodes by up to 51% compared with the fixed-rate and power scheme.

Mohammadi et al. (2014) addressed the rate schedule problem in IR-UWB wireless body area networks (WBANs) and the minimum energy required to stabilise the queuing system. They proposed a cross-layer approach to integrating the PHY models of IR-UWB WBANs with the existing higher-layer scheduling policies proposed in Neely (2007) and Neely (2006) to come up with an explicit design model for these networks. They also calculated the required energy consumption for sensing, processing and communication in solving the optimisation problem, whereas [Neely (2006, 2007; Rebeiz et al. (2012)] only considered transmission energy in their scheduling algorithms.

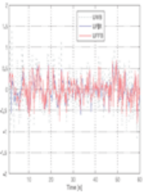
Davaslioglu et al. (2016) evaluated the performance of IR-UWB cross-layer ranging protocols under on-body channel models with body area networks. Where this deals with the positioning performance of the 3-Way ranging protocol (3-WR) in a WBAN, this purpose is a new cooperative algorithm to improve the number of estimated positions with a conditional permutation of the on-body anchors. They initially evaluated and analysed the positioning success rate under a realistic mobility scenario and then used two scheduling strategies, namely, broadcast single node localisation and aggregated and broadcast, along with a TDMA-based MAC layer. 3-WR estimates the distance between two nodes placed on the body with the transmission of three packets. The wireless transmission is based on IR-UWBs. However, these transmissions may be lost through the WBAN channel, thereby resulting in a 'poor positioning service'. To address this problem, developed a physical layer based on IR-UWB with three channels, namely, (1) an empirical, theoretical model based on the on-body CM3 path loss channel (anechoic chamber), (2) a simulated channel calculated via ray-tracing by using the PhyLayers simulator and (3) an experimental channel model obtained by measurements. They eventually found that the channel affects the positioning success rate, which decreases as a function of the sensitivity threshold at the receiver. Long- and short-term analyses of virtual anchors should be performed to improve positioning performance.

Table 2.10 summarises the advantages and disadvantages of the IR-UWB-related solutions proposed in the literature.

Table 2.10: Comparative Analysis Of The Solutions Proposed In The Literature

Research	Proposed model	Simulations	Experiments	Link budget analysis	Validation	Application
Irahhauten et al. (2008)	UWB link budget in the near field, which is initially affected by the phase error depending on the considered bandwidth.	The received power, as a function of distance for different dipole antennas, is compared with the results of calculation and simulation processes.	Measurements are conducted at different distances by using time-domain techniques.	The effects of antenna parameters, including size and distance between antennas, are examined.	Validation is performed on the basis of the agreement amongst the calculation, simulation and experimental results.	Extremely short WPAN applications
Volos et al. (2009)	Using an antenna–pulse coupling gain for specific Tx–Rx pairs	None	Several TD measurements ranging from 1 m to 20 m are conducted to estimate the received Eb/No and to compare the traditional Friss formula with the proposed coupling gain method.	The narrowband limitation in the traditional link budget is addressed by using an antenna–pulse coupling gain to estimate the received power.	The accuracy of the proposed method is verified by conducting several measurements from 1 m to 20 m.	Extremely short WPAN applications
Juengkittikul & Promwong (2009)	Studying the free-space link budget evaluation scheme for the transmission gain of IR-UWB systems that consider the distortion of the transmitted waveform due to the	None	The biconical and periodic dipole antennas are tested from 1 GHz to 12.4 GHz to show the gains in different orientation angles.	The link budget of IR-UWB is evaluated as the effects of two broadband antennas on transmitted waveform gains.	Validation is performed by comparing the transmission gains of two types of broadband antenna.	Extremely short WPAN with a distance of 1 m between sending and receiving antennas.

	antenna.					
L. Liu et al. (2009)	Modelling human blockage effects in LOS UWB WiMedia communication links.	Simulations are performed to evaluate the human blockages in three WiMedia UWB radio link set ups.	Tx and Rx antennas are fixed with a distance of 3 m, and a person stands between these antennas to block the line of sight (LOS) and obtain the statistical parameters of the channel.	The effects of human body blockages on the wireless link are studied, and then the channel is modelled and its performance is evaluated.	The proposed model is validated under different link budget setups and its performance is evaluated.	High-speed short-range wireless medical applications
Lecointre et al. (2008)	Reconfigurable IR-UWB hardware design for data rate, spectrum and range.	Simulations are conducted to evaluate BER in different IR-UWB settings.	None	A global solution for distinct applications with varying demands	Validation is performed according to different budget link settings combined with the performance analysis for BER.	Wireless applications with different needs for data rates and power consumption
Lecointre et al. (2010)	A largely reconfigurable IR-UWB transceiver	Simulating a BB architecture for an IR-UWB transceiver	Tests are performed for different physical parameter values of the IR-UWB pulse generation.	The transceiver chip duration, pulse duration, bit duration and occupied bandwidth for different data rate requirements are reconfigured.	Validations are performed by conducting experiments.	Applications that require data rates of 4 Mbps to 125 Mbps with different received signal BER qualities under various distance scenarios.
Davasligolu et al. (2016)	Cross-layer optimisation for the energy efficiency of IEEE 802.15.6 IR-UWB WBANs	Simulations are performed to ensure the generation of signals that satisfy the data rate requirements and have minimal power consumption.	None	To achieve a joint optimisation of the payload size of the generated signal and the number of pulses to optimise energy efficiency under the constraints of	None	Low-power wireless nodes used in WBANs (near-field wireless communications)

				minimum data rates.		
Guizar et al. (2016)	Performance of IR-UWB cross-layer ranging protocols under on-body channel models with a body area network	Simulated channel model calculated by ray-tracing via the PhyLayers simulator	Experimental channel model built on the basis of the measurements of on-body anchors	To check the settings of certain channel models that can affect the positioning success rate detection of wireless nodes in WBANs.	The validation results agree with the theoretical channel model analysis results, the calculations of the simulated channel model and the measurement of the experimental channel model.	Accurate position detection of WBANs (near-field wireless communications)
Xu et al. (2018)	Adaptive robust INS/UWB-integrated human tracking using UFIR filter bank	that Nopt can be obtained at the test stage by semi-physical simulation for the planned path. The problem complicates if Nopt is required to be obtained in real time. In this section, we compare the localization errors produced by the UFIR filter with Nopt obtained in the traditional way (off-time) and by the proposed UFFB, in which Nopt is estimated	The human tracking system combining the INS- and UWB-based measurements is sketched in Fig. 1. Both the body frame (b-frame) and the navigation frame (n-frame) used in this work are also shown in Fig. 1. As can be seen, the main blocks here are the loosely-coupled integrated model and the data fusion algorithm			accurate human localization, different global navigation satellite systems (GNSS) are widely used. For example, the three dimensional (3-D) map-aided GNSS is proposed in [4] and the 3-D building model-based pedestrian positioning method using the global positioning system (GPS)/global navigation satellite system(GLONASS)/ quasi-zenith satellite

		at each time index k (on-time).				system (QZSS) is designed in [5]. However, the GNSS signals may be blocked in indoor environments [6] that limits applications for the satellite-based systems. For indoor environments, different kinds of local positioning systems (LPS) have been proposed to employ the short-distance communication technologies and replace the GNSS signals
Wei et al. (2019)	digital frequency tunable IR-UWB transmitter with an approximate 15th derivative Gaussian pulse generator	Cadence Assura software and post-layout simulations are performed using SpectreRF	The proposed IR-UWB transmitter has been implemented and fabricated using SMIC 0.18 µm CMOS 1P6M process. The microphotograph of the IR-UWB transmitter is shown in the red polygon box of Fig. 6, with a die area of 0.245mm2 including ESD circuits and		The entire design has been implemented and fabricated using a standard 0.18 µm SMIC CMOS process. Chip measurement results show that the center frequency of output signals varies	Precision Navigation Technology and Application

PADs. The core circuit of the transmitter occupies 0.02mm2	in the range of 3.1–10.6 GHz when tuning a control voltage. The signal spectrum meets the UWB spectral mask requirements specified by the FCC. The output signal has a peak-to-peak amplitude of 56mV with an energy dissipation of 12.5 pJ/bit. Compared to the state-of-the-art designs in the literature, the chip area and tunable frequency range are improved by at least 33% and 53%, respectively

The key problems to be faced by future IR-UWB wireless nodes and the solutions summarised in Table 2.10 all suggest that no IR-UWB solution based on cross-layer MAC-aware PHY architecture can tune the physical parameters to achieve an optimised wireless performance in terms of data rate, distance and BER (or throughput) by connecting such architecture to the communication link-template of all the physical, and channel model parameters and settings to achieve optimized performance under certain wireless application requirements. This research aims to highlight and address this problem.

2.14 Summary

This chapter reviews the relevant state of the art and highlights the advantages and disadvantages of UWB compared with other short-range wireless systems. The reviewed topics mainly include IR-UWB systems with a modulation technique and a transceiver architecture, the existing architectures and frameworks related to the IEEE 802.15.4a and IEEE 802.15.3a standards, the applications related to cross-layer solutions and the limitations of the existing UWB systems proposed in the literature. The next chapter will discuss the specifications of the proposed adaptive impulse-based UWB that can be used in scenarios with different communication data rates and ranges.