Modern ultra-wideband communications: recent overview and future prospects

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Abstract: Regarding the modulation schemes and multiple access techniques, modern ultra-wideband (UWB) communication displays unique features in wideband, high-speed data transmission, low-power consumption and high security comparing to other wireless communication systems. We present a general review of historical development, key features and typical applications on UWB, then briefly discuss its recent progress in IEEE standards, application potentials for broadband wireless access and current benefits. Future development on UWB transmission schemes and challenges of system design, are concisely proposed in contrast to those of several other typical communication systems.

Keywords: ultra-wideband; UWB; modulation; detection; wireless communication; physical layer.

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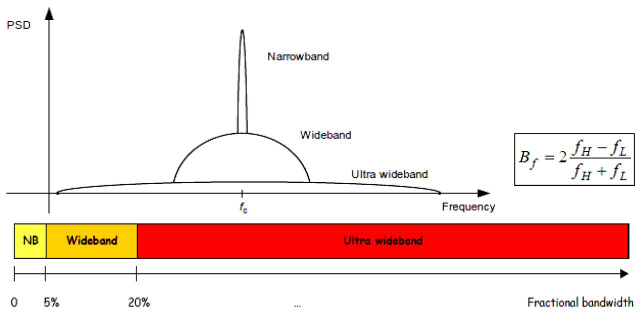
1 Introduction

Substantially emerged as a promising technology that satisfies the rising demand for high-speed wireless indoor networks, ultra-wideband (UWB) communications have been establishing significant advantages of both systematic design and practical use for indoor networking and other wireless communication systems (Alarifi et al., 2016; Ghavami et al., 2004; Siriwongpairat and Liu, 2004; Dueñas, 2005; Gao et al., 2009; Zhang et al., 2010a, 2010b, 2010c; Panda and Patra, 2011; Lv and Bai, 2012; Song, 2012; Sharma, 2013; Dotlic and Miura, 2014; Motroniuk et al., 2015; Raval et al., 2016; Rajanna et al., 2017; Basiron et al., 2017; Herceg et al., 2018; Dwairi et al., 2019; Saeidi et al., 2019; Wang et al., 2019). Digital data such as multivariate signals carrying HDTV (Ghavami et al., 2004) or time-divisible low-speed signals (Siriwongpairat and Liu, 2004) for indoor systems – are sharing resources over a local wireless network. Such kind of small-scale computer networking system displays uniqueness, while consumes extremely high data rate, reasonable cost and very low powers (Ghavami et al., 2004). With its vivid utilisations of impulse radio, sparse spectrum density and enormous bandwidth, the UWB techniques are representing a reliable platform to meet the requirements and attract future wireless indoor networks (Ghavami et al., 2004; Sharma and Bose, 2007; Eteng and Dike, 2013).

1.1 Historical review: What is UWB?

With respect to the Federal Communications Commission (FCC) Standard in 2002, UWB is specifically defined as pulsed communications that use a broadcast bandwidth of over 500 MHz, or 20% of the centre frequency, and operates between 3.1 GHz and 10.6 GHz at limited transmit powers (Ghavami et al., 2004; Dueñas, 2005). Comparison of UWB signals to other signals on fractional bandwidth is depicted in Figure 1.

Figure 1 Comparison for the fractional bandwidth of a UWB signal with narrow/wideband signals (see online version for colours)



In general, UWB represents a unique type of wireless technology, which has the capacity of sending huge data over relatively small distances at the cost of inconstant pulse transmissions on an extremely broad bandwidth (Dueñas, 2005). The imaging and radar implementations of UWB transmit between 1 and 100 mega-pulses per second, while communication systems have between 1 and 2 giga-pulses per second (Dueñas, 2005). This low emitted power means a UWB device matches short range communications (up to 10 metres); however, their battery life is no longer limited by the necessary output power at the antenna, while instead by the techniques of back-end power consumption and pulse detection (Siriwongpairat and Liu, 2004).

1.2 Key features of UWB

The technical merits of UWB are summarised as below:

1 *High rate on data-transmission:* By the Shannon formula that $C = B \cdot \log_2 (1 + \text{SNR})$, it is obviously shown that the channel capacity is proportional to its bandwidth in condition of fixed SNR.

2 *Strong immunity and high accuracy for measuring:* The resolution of extremely short-pulsed UWB signal is lower than 1ns level and hence suppresses the shadowing effects and attenuate fading. Since the narrow pulse filtered multi-path signal reflection, stronger schemes on multi-path resolving may lead to higher precision of ranging.

3 *Confidentiality:* By the use of direct sequence (DS) or time-hopping (TH) spread spectrum (SS) techniques, adopting the input spreading code for decoding, ensures the secrecy of signal transmission. Meanwhile, the rather low-power-spectrum density (PSD) of modulated UWB signals, require special receiver structures, e.g., correlation receiver or rake receiver.

4 *High energy efficiency, extremely low cost and small power consumption:* Non-carrier transmit/receive mode of UWB signal can save the crystal oscillator and the blocks for modulation and demodulation. The simultaneous electronic waves with narrow pulse-shaped data, are often realised through basic station (source power < 1 mW) with long duration of sources.

1.3 Typical applications of UWB

As a fast-developing technology, UWB enables a great number of applications in modern wireless communication networks, medical imaging, radar and localisation systems, to name a few (Siriwongpairat and Liu, 2004; Khuda, 2018). Typical applications of UWB are viewed in three main aspects: the major application is wireless-based UWB, which includes wireless local area networks (WLAN), ad hoc networks, local Wimax, high-speed Bluetooth and other short-range communication links. The second aspect of applications on UWB, takes extensive concerns of multiple-input multiple-output (MIMO) radar techniques, e.g., beamforming, radar imaging and radar ranging, ground penetrating or landmine detection as well as high-resolution through-the-wall radar sensors. The third aspect is UWB-based devices, which include UWB radar sensors for biomedical diagnostics and medical treatment, vital body sign monitoring, collision avoidance, telemetry motion detection, intelligent airbags and geolocations.

The IEEE802.15.3a study group had been dedicated to standardising UWB for indoor local network transmissions since 2002 (Ghavami et al., 2004). In order to normalise channel models and deploy high-data-rate, short-distance communications for major UWB systems, the higher-speed physical layer with standardised parameters had been provided for applications on imaging and multimedia. On the other hand, the 802.15.4 study group, had also defined the low-data-rate applications exploiting UWB technology within physical layer design. Keynote applications of UWB take concerns for location tracking, i.e., scalability to data rates, sensors, longer range positioning and identification in networks (Siriwongpairat and Liu, 2004; Miller, 2003).

The remainder of this paper is organised as follows. The characteristics of UWB modulation and signal detection are discussed in Section 2. IEEE standards and its application potentials of UWB wireless communications are introduced in Section 3. Section 4 presents our prospects for UWB transmission schemes and the latest challenges of its design. Section 5 summarises our conclusions.

2 UWB modulation and signal detection

The signal generation of UWB-based communications can be categorised in two main groups: single-band and multi-band typed approaches. Take the impulse radio as an example for a single-band UWB system: the signal which represents a symbol including serial pulses with extremely low duty cycle, makes very broad bandwidth and leads to a better resolution of multi-path in UWB channels since the pulse is quite narrow (Dueñas, 2005); for a multi-band UWB modulation, it is accomplished by using multi-carrier or OFDM modulation with Hadamard or other spreading codes (Miller, 2003). In this way, UWB systems effectively eliminate delay spread or frequency selectivity of channels.

2.1 System model for UWB transmitters and receivers

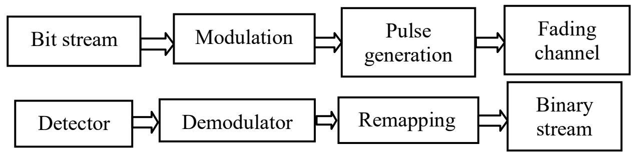
As is adopted by the IEEE802.15.3a standard, standard UWB systems are featured with path loss, shadowing and small-scale fading channel models (Ghavami et al., 2004): the free-space path loss is centred at frequency f_c given by $\sqrt{f_L f_H}$ where f_L and f_H are picked up at the –10 dB edge of waveform spectrum. It is assumed that shadowing has the lognormal distribution with standard deviation of 3 dB, and the small-scale fading is reliable on the Saleh-Valenzuela model (Siriwongpairat and Liu, 2004) with channel impulse response:

$$h(t) = \sum_{c=0}^{C} \sum_{l=0}^{L} \alpha(c, l) \cdot \delta\left(t - T_c - \tau_{c,l}\right) \tag{1}$$

where C and L denotes the number of clusters and the corresponding number of rays with clusters, respectively. $\alpha(c, l)$ presents the gain of the l^{th} multi-path component in the c^{th} cluster, $\tau_{c,l}$ stands for the delay of the l^{th} path relative to the c^{th} cluster arrival time. A block diagram for standard UWB systems (Dueñas, 2005) is shown in Figure 2.

For UWB transmitters, small-pulsed generating antennas represented a compatible match and saved the efforts of upper frequency conversion. Hence, the rather inexpensive broad-width transmitters are directly applicable and hence make substitutions of both the amplifier and the mixer. Meanwhile, UWB receiver did not have any requirement of middle-region frequency processing such that the structures of transmitter and receiver for a typical UWB system can be quite simple, which are sketched in Figures 3(a) and 3(b).

Figure 2 A general block diagram of UWB system model



2.2 Single carrier-based modulation

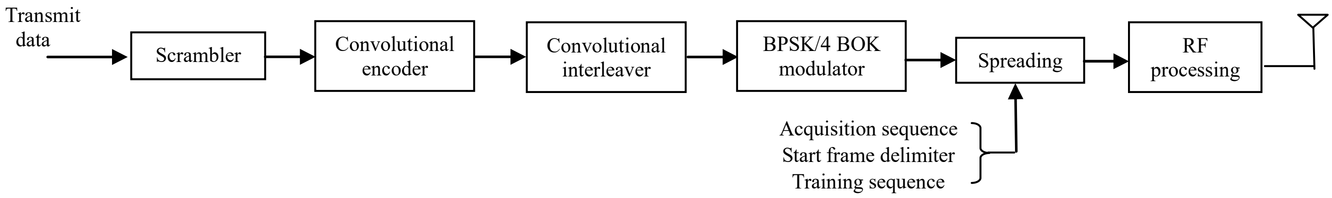
For single-carrier-based modulation of UWB, the pulse position modulation (PPM), bipolar signalling (BPSK), pulse amplitude modulation (PAM), on/off keying (OOK), orthogonal pulse modulation (OPM) and their combinations, stand for keynote schemes. PPM and BPSK are good candidates for UWB due to the fact that they have better bit-energy performance than that of PAM or OOK from theoretic views. The periodical waveforms of PPM and BPSK for UWB modulation (Dueñas, 2005) are depicted in Figures 4(a) and 4(b), where Δ_c denotes the impulse of time delay.

Notably, the M-ary PPM signal is structured as (Dueñas, 2005):

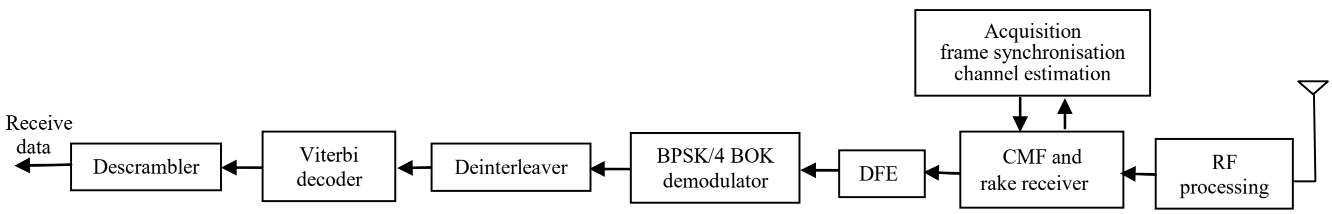
$$\tilde{x}_1(t) = \sum_{k=-\infty}^{+\infty} \tilde{w}\left(t - kT_f - m(k) \cdot T_d\right) \tag{2}$$

where $\tilde{w}(\cdot)$ is the pulsed waveform, $m(k) \in \{0, 1, \ldots, M - 1\}$ denotes the k^{th} M-ary symbol, T_f and T_d represent each symbol period and the modulation delay, respectively.

Figure 3 (a) Structure of a UWB transmitter (b) Structure of the corresponding receiver to a UWB system

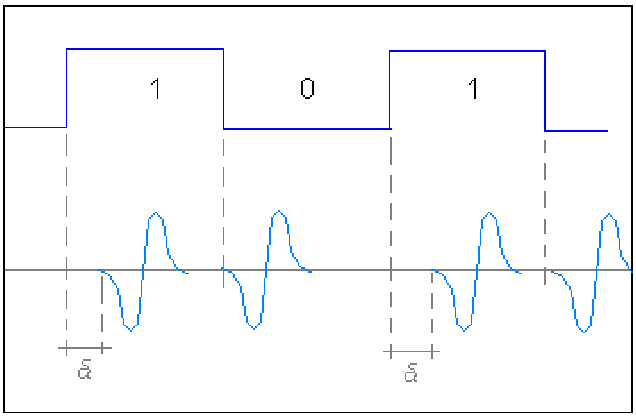


(a)

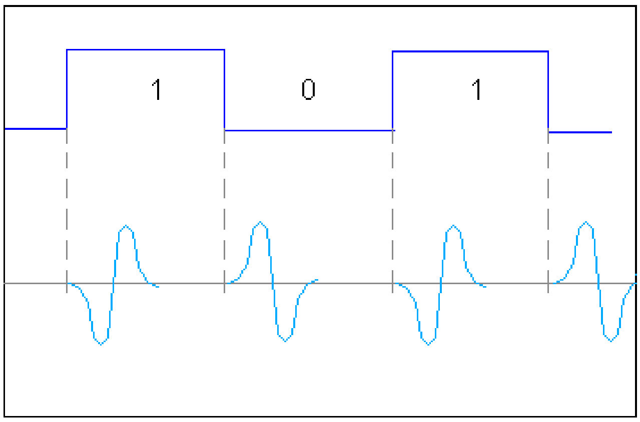


(b)

Figure 4 (a) PPM waveform (b) BPSK waveform for UWB (see online version for colours)



(a)



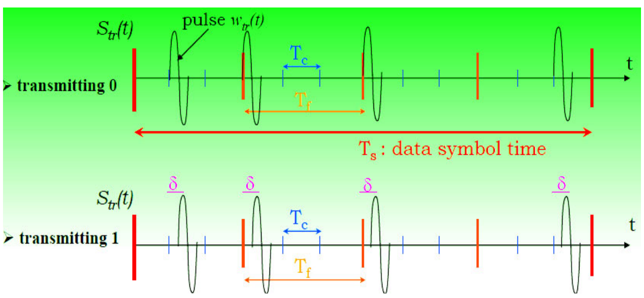
(b)

The BPSK signal for UWB waveform is expressed as (Dueñas, 2005):

$$\tilde{x}_2(t) = \sum_{k=-\infty}^{+\infty} \left[2d(k)-1\right] \cdot \tilde{w}\left(t-kT_f\right) \tag{3}$$

where $d(k)$ denotes the binary data, $\tilde{w}(\cdot)$ and T_f have the same notation as that of PPM signal.

Figure 5 TH-UWB signal with PPM modulation (see online version for colours)

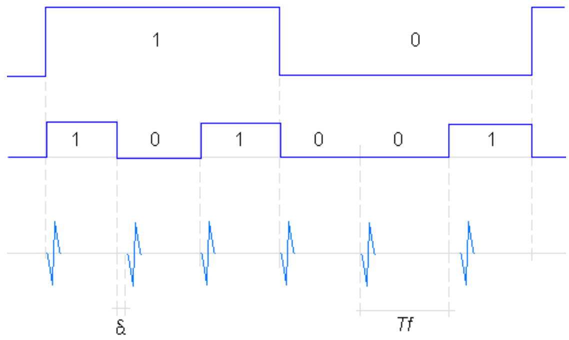


In single-band UWB systems, since multi-users often simultaneously have cooperative sharing of a single UWB spectrum, multiple access techniques have been of great necessity to coordinate with these users. Typical techniques are known as the time-hopping spreading-spectrum (TH-SS) and direct-sequence spreading-spectrum (DS-SS), both of which utilise pseudo-noise (PN) codes to get separate users (Siriwongpairat and Liu, 2004). Figure 5 depicts a TH-UWB signal with PPM modulation, and the transmitted signal can be structured as (Dueñas, 2005):

$$\tilde{x}(t) = \sum_{k=-\infty}^{+\infty} \tilde{w}\left(t-kT_f - c(k)\cdot T_c - m(k)\cdot T_d\right) \tag{4}$$

where T_f, T_c and T_d denote the frame interval, time shift and the modulation delay, respectively.

Figure 6 DS-UWB signal with PPM modulation (see online version for colours)



For a UWB signal generated by DS-BPSK (as depicted in Figure 6), the waveform can be structured as (Dueñas, 2005):

$$\tilde{x}(t) = \frac{1}{\sqrt{N_c}} \sum_{k=-\infty}^{+\infty} d(k) \sum_{n_c=0}^{N_c-1} c(n_c)\,\tilde{w}\left(t-kT_f - n_c T_c\right) \tag{5}$$

where Δ_c denotes the impulse of time delay, T_f denotes the time period of modulated signal impulse.

Two major shortcomings on single carrier-based UWM modulation such as PPM, are recognised as relatively high inter-symbol interference (ISI) and the bit-error rate is not optimal under additive white Gaussian noise (AWGN) channel. In the following subsections, we discuss the multi-band OFDM-based UWB modulation schemes.

2.3 Multi-band OFDM-based UWB modulation

The present main technique of UWB to deal with delay spread, is named as the multi-band (MB) OFDM-based modulation. As proposed on multi-band for IEEE802.15.3a standard (Ghavami et al., 2004; Dueñas, 2005), the entire 7.5 GHz UWB spectrum were divided into 14 sub-bands (each one equivalently occupies a bandwidth of 528 MHz), every sub-band held 128 OFDM sub-carriers with 4.125 MHz bandwidth (as depicted in Figure 7). Modulated OFDM symbols are time-interleaved across sub-bands. Similar as the standard OFDM technique, every OFDM-UWB signal can be constructed by (Ghavami et al., 2004):

$$s_k(t) = \sum_{n=0}^{N-1} d_k(n) \exp(j2\pi n \cdot \Delta f t) \quad 0 < t < NT_s \tag{6}$$

where $d_k(n)$ represents the complex coefficient transmitted in sub-carrier n during the k^{th} symbol period, N denotes the number (transmitted symbols) of the sub-carriers per OFDM block. The sub-carrier frequency is $f_n = f_0 + n \cdot \Delta f$, where Δf is the frequency spacing between two adjacent sub-carriers. The condition of orthogonality requires $NT_s = 1/\Delta f$ when demodulating the OFDM-UWB signal waveform. When $f_0 = 0$, it is proved that the sampled version of the OFDM signal, can be expressed as (Ghavami et al., 2004):

$$s(nT_s) = \sum_{n=0}^{N-1} d_k(n) \exp\left(j \cdot \frac{2\pi nk}{N} \right) \tag{7}$$

Hence, inverse discrete Fourier transform (IDFT) can be used to convert the transmitted symbols into OFDM signal.

Figure 7 UWB Multi-band OFDM spectrum (with sub-bands group division and sub-carriers) (see online version for colours)

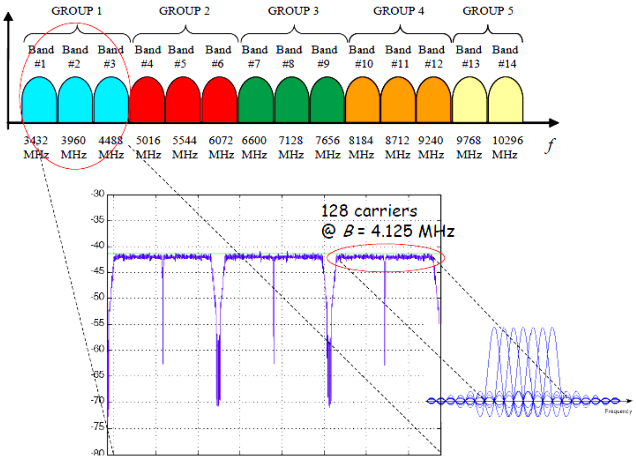


Figure 8 illustrates the frequency interleaving scheme and sample realisations on multi-band UWB. As depicted in Figure 8(a), a time period contains three multi-band UWB signal pulses, where each pulse is arranged with zero prefix, information length and followed by a guard interval for the switching time of transmit/receiver. Following the frequency interleaving scheme of single group multi-band UWB signals, its realisation in both time and frequency domain are displayed in Figure 8(b).

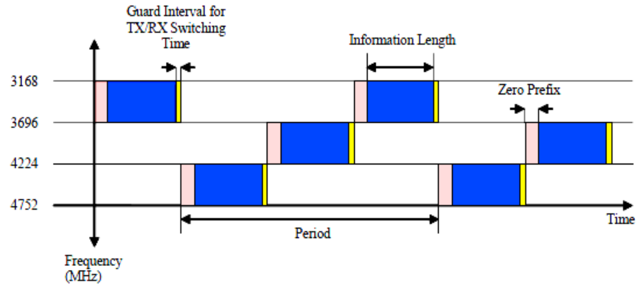
Regarding to system construction, prominent advantages of MB-OFDM-based UWB are recognised as follows:

1 *Simple implementation:* In contrast to no carrier pulse communication, RF and front-end analogue circuits are easy to design; similar advantages work for the analogue-to-digital converter (ADC) part.

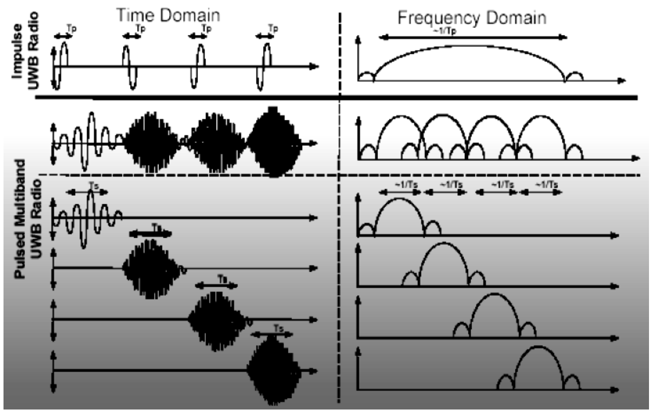
2 *High utilisation efficiency of spectrum:* When the number of sub-carriers rises, the superposition amplitude spectrum from that of each sub-carrier, will display good rectangular features.

However, since MB-OFDM-based UWB system needs FFT and IFFT unites which increased complexity on the implementation, the power consumption also levels up with the booms of systematic complexity. Besides, the inherent peak-to-average ratio (PAR) issue of OFDM, remains to be a problematic issue. On the other hand, due to the limitation of transmission PSD of defined by FCC, the narrow bandwidth of each sub-carrier would lead to the shortage of transmission power, and hence, high data rate communications are difficult to realise. Moreover, since the MB-OFDM adopts even narrow spectrum sub-carrier, the property of accurate positioning is lower than those of TH-UWB and DS-UWB-based modulation schemes.

Figure 8 (a) Frequency interleaving scheme of multi-band UWB signals within one group (b) Realisation of multi-band UWB signals in time domain and frequency domain (see online version for colours)



(a)



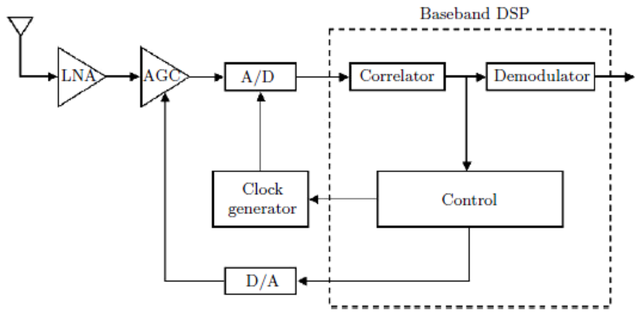
(b)

Nevertheless, MB-OFDM achieves dynamic bandwidth allocation to increase symbol duration, which benefits the capacity of suppressing channel ISI. The communication distance is also longer by MB-OFDM-based UWB system, because of its high-speed and near-perfect energy capturing of weak signals.

2.4 UWB receiver design

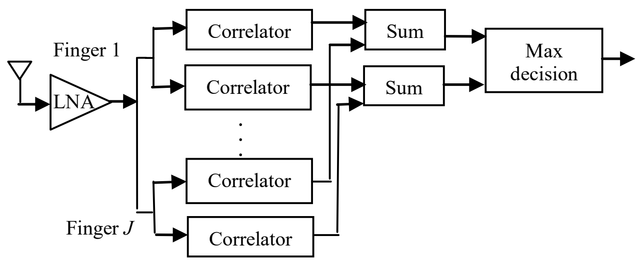
While conventional receivers have poor match on UWB signal demodulation, typical receivers for UWB systems, are regarded as correlation receiver and rake receiver (Miller, 2003). A UWB correlation receiver (Ghavami et al., 2004) is depicted in Figure 9, where LNA is the low-noise amplifier and AGC is the automatic gain control, A/D stands for the ADC and its inverse is denoted as D/A.

Figure 9 Block diagram of a digital UWB correlation receiver



For binary-modulated single-band UWB signal in ideal channels, a correlation receiver is optimum, depending on coherent detection of the main signal components. In other words, referring to local 'template' signals, receiver makes binary decisions on the sign of correlation values (Miller, 2003; Shen et al., 2006).

Figure 10 The Rake receiver with *J* fingers for a UWB system



For multi-path channels with distinct frequency-selective fading, rake receivers are quite applicable for exploiting the multi-path diversity (Soni et al., 2011). Combining some constructive monocycles from different multi-path of a received pulse to improve the UWB system performance, each correlator is synchronised to a multi-path component, and the results make sums for all correlators in the rake model (depicted in Figure 10). Finally, a decision device justifies which symbol was transmitted after analysing the added outputs. In Rake receiver, the path selection techniques contain maximum, partial and threshold selection, the combining methods specifies the options of equal gain combining (EGC), maximum ratio combining (MRC) or minimum mean-square-error combining (NMMSEC) (Miller, 2003).

In contrast to the single correlator case, rake receiver improved performance of UWB signal reception at the cost of increased complexity of having to synchronise several components (specified as Fingers 1 to *J*) and making their gains adjusted. This technique maximises the amount of energy received per symbol, and MMSEC has displayed optimal performance under narrowband interference while its drawbacks are the higher complexity compared to EGC and MRC (Miller, 2003).

3 IEEE standards for UWB: specifications on physical layer

3.1 IEEE standards on UWB communication

Since 2003, the study group for IEEE802.15.3a standard had been attempting to meet an agreement on two major standards of UWB technology: MB-OFDM or DS-CDMA, which technique is upon selection? However, during their meetings, neither MB-OFDM nor DS-CDMA passed the required 75% votes! For high data rate and short-range applications, this proposal was withdrawn in early 2006.

The IEEE802.15.4a standard had specified two physical layers using both UWB and chirp spread pectrum (CSS). An alternative low-rate physical layer of UWB, designated frequencies in three ranges: < 1 GHz, 3~5 GHz, and 6~10 GHz (Ajello and Batra, 2006). The principle interests on 802.15.4a-based UWB, provides high precision ranging and location capability (one-metre accuracy and better), high aggregate throughput and ultra-low-power, increasing scalability to data rates, longer range, and lower power consumption and cost as well.

3.2 MB-OFDM or DS-CDMA: comparison for their PHY layer specifications

In general point of view, MB-OFDM and DS-CDMA have distinct advantages and shortcomings. MB-OFDM is easier to implement, withstands very low-power supply due to its multi-band style. Also, the flexible arrangement of sub-bands, leads to higher efficiency for its frequency band spectrum and hence increased the extensibility of data rate. In contrast, DS-CDMA adopts the style of 'single-band, narrow-pulse' modulation, because the entire frequency spectrum, can be shared by a variety of transmission tasks. Meanwhile, DS-CDMA generates less interference to the presently licensed users, consumes low cost and is prone to realise transmissions of low-power consumption and low data streams.

Most notably, to be frank, MB-OFDM and DS-CDMA have technical contradictions for their products. DS-CDMA are more compatible for media stream; tremendous data transmission and the sample products have been exhibited in early 2004, however, earlier-ahead work of DS-CDMA followed by its staggering progress. On the other hand, MB-OFDM has been catching up with DS-CDMA for its greater advantages on volume, cost and power consumption than the latter one. Chips designed by MB-OFDM had already displayed the capacity to transmit data as fast as 480 Mbit/s several years ago. Keynote technical parameters of MB-OFDM and DS-CDMA are specified in Table 1.

A few major communication companies also participated in settling their preferred UWB technical parameters. Texas instrument and Intel attribute to MB-OFDM alliance, while XTreme Spectrum belongs to the DS-CDMA camp (Ajello and Batra, 2006). The comparison of physical layer proposal from three companies (March 2003), are concisely depicted in Table 2 (Miller, 2003; Shen et al., 2006).

Table 1 Technical standards for MB-OFDM versus DS-CDMA (time-frequency interferometry – TFI, spread spectrum – SS)

Technical standards	*MB-OFDM*	*DS-CDMA*
Number of frequency bands	10 (3 for the first generation)	2
Sub-band bandwidth	528 MHz (4.125 MHz * 128 sub-carrier)	Ranged from 1.268~2.736 GHz
Frequency range	Groups 1–5: 3.168~4.752 GHz; 4.752~6.336 GHz; 6.336~7.920 GHz; 7.920~9.504 GHz; 9.504~10.560 GHz	3.2~5.15 GHz; 5.825~10.6 GHz
Modulation scheme	TFI-OFDM, QPSK	BPSK, QPSK, DS-SS
Error control coding	Convolutional code	Reed-Solomon or convolutional code
Multiplex mode	TFI	CDMA
Link margin	5.3 dB/10 m: 110 Mbit/s; 10.0 dB/4 m: 200 Mbit/s; 11.5 dB/2 m: 480 Mbit/s	6.7 dB/10 m: 110M bit/s; 11.9 dB/4 m: 200 Mbit/s; 1.7 dB/2 m: 480 Mbit/s

Table 2 Comparison of physical layer proposal for IEEE 802.15.3a from major companies

Company	*Texas instruments*	*Intel*	*XTreme Spectrum*
Spectrum allocation (number of bands)	3 (additional bands added in the future)	7 (optional 6 bands applicable in future)	2
Bandwidths	503.25 MHz	550 MHz	1.368 GHz, 2.736 GHz
Frequency ranges	3.168 GHz~4.752 GHz	3.6~6.9 GHz (optional 7.4~10.2 GHz)	3.1 GHz~5.15 GHz, 5.825 GHz~10.6 GHz
Modulation scheme	TFI-OFDM, QPSK	M-ary bi-orthogonal keying (MBOK), QPSK	BPSK, QPSK
Co-existence method	Null-band for WLAN (~5 GHz)	Null-band for WLAN (~5 GHz)	Null-band for WLAN (~5 GHz)
Multiple access method	Not available	DS/FH CDMA, optional CDMA	Avoidance
Number of simultaneous piconets	Not available	Not available	Ternary CDMA
Error correction codes	Convolutional code	Convolutional code, Reed-Solomon code	Convolutional code, Reed-Solomon code
Rates of code	11/32 @ 110 Mbps, 5/8 @ 200 Mbps, 3/4 @480 Mbps	6/32 @ 110 Mbps, 5/16 @ 200 Mbps, 3/4 @ 480 Mbps	1/2 @ 110 Mbps, RS (255, 223) @ 200 Mbps, RS (255, 223) @ 480 Mbps
Link margin	5.5 dB @ 10 m @ 110 Mbps, 10.2 dB @ 4 m @ 200 Mbps, 12.2 dB @ 2 m @ 480 Mbps	6.3 dB @ 10 m @ 108 Mbps, 8.0 dB @ 4 m @ 288 Mbps, 4.0 dB @ 2 m @ 577 Mbps	9.9 dB @ 10 m @ 110 Mbps, 13.2 dB @ 4 m @ 200 Mbps, 3.4 dB @ 2 m @ 600 Mbps
Symbol period	312.5 ns OFDM symbol	3 ns	731 ns (low band), 365.5 ns (high band)
Multi-path mitigation method	1-tap (robust to 60.6 ns delay spread)	Frequency interleaving of MBOK chips; time frequency codes, feed forward filter	Decision feedback equaliser (DFE)

Table 3 Short-range communication parameters for UWB in contrast to others

	IEEE 802.11a	*Bluetooth*	*HomeRF*	*UWB*
Data rate	54 Mbps	< 1 Mbps	1~2 Mbps	> 500 Mbps, up to 1 G
Communication range	10~100 m	10 m	50 m	< 10 m
Transmitted power/capacity	>1W	1~100 mW	> 1 W	< 1 mW
	80 Kbps/m^2	30 Kbps/m^2	50 Kbps/m^2	1,000 Kbps/m^2
Appliances	WLAN, internet gateway	Office connections, I-phone	Indoor voice speech, bit-streams	Short-range multi-media, DVD high-speed gateway
Supporting company	Cisco, Lucent, 3Com	Ericsson, Nokia Motorola	Apple, Dell Compaq	Intel, Motorola, Sony, Sharp

3.3 *Comparison for UWB with IEEE802.11a, Bluetooth and home RF*

Since the range of transmission is about 10 metres, we compare UWB with some other popular technologies on short-range communication to show its advantages and why they are so important. The most frequently used short-range wireless technologies, include IEEE802.11a, Bluetooth and HomeRF.

1 *IEEE802.11a and UWB:* IEEE802.11a is one of the standards for wireless area network drafted by IEEE (Dueñas, 2005). It has the speed of 54 Mbps in physical layer and 25 Mbps in transport layer. The longest communication range of IEEE 802.11a can be 100 metres, while UWB is just used in communications within a shorter distance around 10 metres. However, in the short-range transmission (within 10 metres), the communication rate of IEEE802.11a standard is quite different from that of UWB. In UWB, the transmission speed reaches up to thousands of megabits per second, which is several dozen times higher than that of IEEE802.11a (Dueñas, 2005). Outside the range of 10 metres, limited by the transceiver power, the performance of UWB downgrades quite fast. (From latest report of UWB, the approximate transmission length has been extended to 20 metres so far.) Overall, in the short-range around 10 metres, UWB has apparent advantage compared to IEEE802.11a. On the contrary, outside the communication length of 10 metres, IEEE802.11a has better performance than UWB. In addition, IEEE802.11a consumes much more power than UWB (Miller, 2003; Ajello and Batra, 2006).

2 *Bluetooth and UWB:* Bluetooth stands for a wireless network technology jointly launched by Ericsson, IBM and other three companies in 1998. They founded the Bluetooth Special Interest Groups (SIG), which was in charge of the development of this technology and the assignment of the technique standards. So far, there had been more than 1,800 companies jointed in this group. The transmission distance ranges from 10 cm to 10 m. It adopted the 2.4 GHz ISM spectrum, frequency modulation and hopping frequency technology, displaying a transmission speed of 1 Mbps (Ajello and Batra, 2006).

   From technical point of view for parameters, UWB has obvious advantages compared to Bluetooth. Although they have similar communication distance as well as power consumption, UWB is far better in the communication rate and has been almost several hundred times faster than that of Bluetooth. From the development in the past decade, the only advantage of Bluetooth that overcame UWB, shows that the technology of Bluetooth is relatively mature while UWB has just developed for 15 years while lacks market needs and suffers pricy issues. However, with the progressive development of UWB, this shortcoming will gradually disappear. That is why when UWB first came out people said it would be a killer of Bluetooth.

3 *HomeRF and UWB:* HomeRF shows a wireless networking technology which is specifically designed for home residential environment. It takes use of the protocol supporting TCP/IP transmission in 802.11 specifications. And its performance on voice transmission, is from DECT (cordless telephone) standard. HomeRF is defined in the spectrum of 2.4 GHz, which is unlicensed public wireless spectrum range. It employs an air interface on frequency hopping (change of channels) at 50 times per second. The maximum transceiver power is 100 mW, the effective range is about 50 metres, and the rate range is about 1~2 Mbps. Comparing HomeRF to UWB, they have unique features: HomeRF qualifies long-distance data transmission, but the rate is quite low; the transmission distance of UWB is only one-fifth of HomeRF, while the speed is hundreds of times or even thousands of times on that of HomeRF (Heidari, 2008; Hurt, 2003).

In sum, the three popular standards on short-distance wireless communications, display different features in a few aspects. Sometimes these technologies compete with each other; however, in practical applications areas, they complement with each other. It is irresponsible to just say that UWB can replace some technology. Take the aircraft as a metaphor, it is fast and stable, but still cannot totally replace a bicycle. Each technology has the application areas of their own.

The technology standards and differences (Shen et al., 2006) between four technologies (IEEE 802.11a, Bluetooth, HomeRF and UWB), are summarised in Table 3.

4 Summary and prospects

In retrospect to the popular short-range communication schemes, great potential has been exhibited in UWB for its enormous data transmission and storage capacity. Besides, higher resolution is reliable to larger bandwidth of UWB signal. Future trend of UWB applications, would mainly consider carrier-less transmission (with low-cost CMOS technology, low data rate), accurate indoor UWB localisers (measuring propagation times to overcome the weakness of GPS), ad hoc network structure and the cable substitutions (Wood and Aiello, 2008). Due to the unique advantages of data transmission rates and restricted from emission power of UWB techniques, its crucial application domain must be high-speed wireless data transmission within a short range of distance, which matches a variety of applications in current WLAN and personal area network (PAN) (Shen et al., 2006).

The booming demands of military service and domestic digital amusement, promote a bright future of UWB. The application of UWB, can be mainly divided into military and civilian applications. In the military aspect, it meets the requirements of large-capacity, low-interception (LPI/D) and high-rate characteristics of military communications.

UWB is capable of realising the combination of three functions of ranging radar, localisation and communication, especially suitable for radar high detection resolution and miniaturisation, the UWB-based wireless devices are easy to install on small aircraft and mobile vehicles. Besides, UWB technology has a wide range of applications in the field of wall/ground imaging detection radar, warning radar, high-precision positioning navigation system. Marketing of UWB is also extensive in the fields of civilian wireless PANs as well as fast wireless data transmission (Shen et al., 2006). In addition to the aforementioned WLAN, ad hoc network, UWB-based wireless USB technology, personal space network, outdoor peer-to-peer network and car-mounted system, take security, reliability, low-power consumption and other characteristics of UWB technology into account, exploit flexibility and high degree of freedom on its transmission technology, expand its function of distincting targets, improve compatibility and reliability of modern WLAN communication technologies, and suggest great potentials in prospective development.

While UWB technology on localisation is widely used due to high precision, some universal problems still exist in practical use: in terms of market demand, the real needs represented by UWB is still relatively limited, where many enterprises believed that many UWB-related topics are not worthy of large-scale investment (Song, 2012). There are still less requirements on positioning of movable objects (such as workshop workers and robots, etc.), and future demand is uncertain. High cost is also an issue that cannot be ignored: due to the complicated structure and limited demand of UWB system on localisation, UWB still has more than ten times the price difference in terms of base stations and tags localisation in contrast to Bluetooth and WIFI technologies. DW1000 represents the first single-chip wireless transceiver related to UWB positioning technology, which has quite a few algorithms on integration; however, its actual precision error of debugging is still large, and the product data and technical support are both insufficient. In addition, due to some related issues in UWB principle and power, it also affects the expected positioning accuracy and transmission distance. These UWB related issues call for subsequent exploration with some intersections of industry, robots as well as the internet of things (IoT), and improve localisation accuracy and transmission reliability of signals.

Recently, theoretical investigations and practical design studies on UWB technology both made some achievements. For instance, an algorithm on anomaly detection and target localisation was proposed for cluster-based UWB wireless sensor networks (Karapistoli and Economides, 2013), which achieved high detection accuracy while still preserving low-level communication overhead. Meanwhile, various types of UWB antennas enriched their applications on high-speed transmission of communication systems. For instance, the printed circular monopole antenna and rectangular microstrip antenna had been advocated as good candidates for UWB applications (Raval et al., 2016), a comprehensive research of applied UWB antennas was carried out for possible applications in communication field, where the printed elliptical monopole antenna was regarded as a perfect integration of several merits such as simple structure, wide bandwidth, broadside radiator with 3D radiation patterns (Saeidi et al., 2019). Several UWB-related research topics are crossly associated with breast cancer detection and diagnostic testing (Khuda, 2018), high-dimensional data processing (Zhang et al., 2010a, 2010b, 2010c; Shao et al., 2019a, 2019b) as well as some other cybersecurity related approaches such as real-time analysis and autonomic author identification on internet relay chat (IRC) threat detection (Bernard et al., 2018; Shao et al., 2017; Shao et al., 2018), a classification scheme in the related channels using deep-autoencoder neural networks (Shao et al., 2019a, 2019b), and the broadband microwave photonics time-reversal module for indoor wireless communication and UWB remote sensing (Wang et al., 2019).

Technical innovations and beneficial interests of UWB stimulate great concerns within the global range. The goal of UWB technology is represented as ‘swifter, further and broader’. Many well-experienced and newly participated researchers, are devoted to such a domain of technology. Thanks to the belief of UWB, not only it is favourable by practical domestic users for high-speed data transmission and obscured object detection, but also it is fast developing and becoming more mature with the promotion of military needs and market business.

5 Conclusions

Our work links an overview of modern UWB communication from crucial features, real designs, physical layer standards to practical applications. We have presented UWB modulation and signal detection, the relevant IEEE standards with application potentials of UWB, and the comparison of some technical parameters between different realisation schemes towards UWB and among short-range wireless communication systems in industrial view. We discussed the current problems and the challenging issues of UWB transmission schemes in a few aspects on indoor localisation techniques and their extended applications.

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