Introduction to Ultrawide-band Communications

Dr Murat Eskiyerli, CEng, MIET
Revolution Semiconductor

HISTORY AND BACKGROUND

Impulse based radio frequency (RF) communications are not an exactly new idea. The first demonstration of the radio frequency communications, the spark gap transmission experiments performed by Heinrich Hertz in 1890s were a form of impulse based RF communications. Later, Marconi also used it when he claimed to have transmitted Morse Code sequences across the Atlantic Ocean in 1901 [1, 2].

With rapidly increasing numbers of radio transmitters flooding the airwaves after the Marconi's successful and well-publicized experiments and causing significant and detrimental interference with each other, the very wide frequency bands occupied by spark-gap transmitters were viewed as a waste of the scarce usable frequencies by then available radio technology. Consequently, very strict limits on the output power and frequency bands of the RF transmitters were introduced by the various regulatory bodies around the world to mitigate the interference problem. With the introduction of amplitude and later frequency modulation methods, the narrow-band communications became the norm. The development of the super-heterodyne receiver by Armstrong by 1917 allowed the selection and amplification of the narrow-band modulated signals with relative ease. In fact, the spark-gap RF transmissions were completely stopped by 1920.

At about the same time, the time domain analysis of the radio frequency signals and systems fell out of favour with the introduction of the Fourier Transforms and Bode plots to the analysis of the modulation methods. One notable exception were the state-space system analysis methodology developed by the Soviet researchers in 1950s. In state-space analysis, The linear systems are analysed in time-domain by considering the time derivatives of the so-called state variables, tied to the some fundamental integration operation in the system.

The modulation methods that are unique to the impulse radio systems were first used in the Second World War. The British Army used a pulse position modulation based radio in the North Africa theatre, which was later copied by AT&T for a the US Army [3].

UWB RADARS AND IMAGING

The radar applications was first to prove the viability of the radio frequency wide-band impulses in certain use cases [4]. UWB radars utilize very short electro-magnetic pulses in tens to hundreds picoseconds duration to These type of radars demonstrated several advantages over more conventional radars technologies [2, 5]. Some of these advantages are:

1. Due to shorter extent of the pulse in space [1], finer radar resolutions can be achieved.
2. As the pulse durations are very short, transmitter duty cycles can be very low reducing the average power consumption.
3. Low power spectral density of the UWB radars make them less susceptible to intercept and electronic countermeasure (ECM) attacks.
4. UWB radar designs can be realized in low-cost radio-frequency integrated circuits, while the signal processing blocks can use application specific integrated circuits (ASIC) or field programmable gate arrays (FPGA).

RENEWED INTEREST IN IMPULSE RADIO

In 1950s and 1960s, a new crop of researchers around the world began to investigate the impulse radio communications. In 1960s, the researchers once again began to look at the electromagnetic waves as waves in time-domain instead of frequency domain, leading to a new field of research, time-domain electromagnetics [2].

REGULATORY BACKGROUND

Ultra-wideband RF data communication transceivers had garnered a lot of attention starting early 2000s as they were potentially offering much higher data rates compared to then prevalent WiFi standards, IEEE 802.11a/b/g. In 2002, the Federal Communications Commission of USA has issued a new definition of the ultra-wide band signals in its ”First Report and Order” [4]. According to FCC, the radio frequency signals needed to satisfy one or both conditions to be classified as a ultra-wide band sginal:

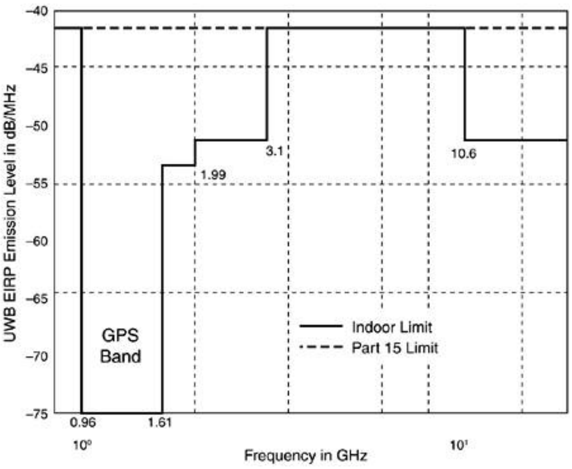
1. At least 500 MHz -10 dB bandwidth, or
2. Fractional bandwidth larger than 20% of the centre frequency of the band.

Complying with these definitions seemed to be vital for the integrated circuit and system companies working on UWB radio technology as it allowed these systems' emitted RF spectrum:

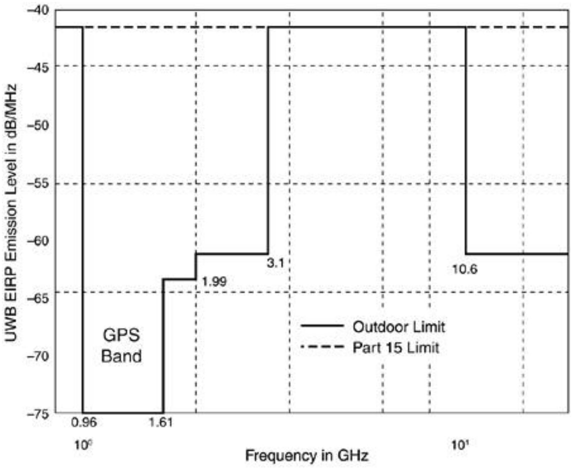
1. to overlap other licensed narrow-band RF transmitters without requiring a license and
2. to access a very wide bandwidth of at least 500MHz, but potentially up to 7GHz at once.

[1] A pulse's spatial extent is the multiplication of the pulse duration and the speed of the light.

The price to be paid for these seeming generosity of the FCC was the fact that it burdened UWB emissions with very severe emission limits. FCC placed separate limits for indoor versus outdoor emissions for the UWB communications systems. In both cases, the UWB communication devices needed to operate between 3.1 GHz to 10.6 GHz with a *maximum effective isotropic radiated power* spectral density of (EIRP) -41.5 dBm/MHz . FCC defined indoor emission limits are shown in figure 1a while the outdoor emission limits are plotted in figure 1b. Indoor and outdoor emission limits were designed to protect some significant infrastructure frequency bands from the interference due to UWB signals. For example, the GPS transmissions at 1.2276 and 1.5754 GHz, or planned L5 frequency in 960-1215 MHz band were thought to be significantly vulnerable [6]. The outdoor emissions were even more severely restricted in around crucial ISM bands by an additional 10 dB (see figure 1b). Only handheld devices are allowed to operate outdoors [4].



(a) UWB indoor emission limits as defined by FCC in 2002.



(b) UWB outdoor emission limits as defined by FCC in 2002.

FCC also allocated another spectrum mask for the through-wall UWB imaging radars. They included ground penetrating radars, through-wall imaging systems, surveillance systems and medical imaging devices. Interested readers can refer to [6] for further information.

Finally, the vehicular radar systems for cars and other vehicles were allocated the band between 22 GHz and 29 GHz. The European Union later pushed the vehicular radar manufacturers to shift the operating frequencies to even higher frequencies centreing at 79 GHz.

UWB EMISSION REGULATIONS IN EU

Other regulatory authorities around the world have created their own versions in the following periods. These regulations have generally followed the FCC regulations with some variations. European regulations were devised as a result of the compatibility studies done in CEPT[2], a coordinating body for European telecommunications and postal organizations. The European Telecommunications Standard Institute (ETSI)[3], responsible for the standardisation of the information and communication technologies in Europe.

Work in CEPT regarding the protection requirements of th radio services from UWB emissions led to the conclusion that 6 to 8.5 GHz band was the preferred solution for the Europe [7]. CEPT's Electronic Communications Committee decided that UWB emissions in 4.2 GHz to 4.8 GHz bands could be only allowed without any detect-and-avoid (DAA) and/or Low Duty Cycle (LDC) interference mitigation techniques until the end of 2010[4] (the shaded area in figure 2). The highest allowed EIRP emission value in this band is -41.3 dBm/MHz in -13dB band. UWB transmitters implementing LDC mitigation techniques can continue to operate in the 3.4 GHz to 4.2 GHz frequency band with a -41.3 dBm/MHz EIRP spectral density after the end of 2010. ETSI standard contains additional requirements such as minimum -13dB operational bandwidth of 50 MHz, a PRF (Pulse Repetition Frequency) larger than 1 MHz and the transmitter timeout to avoid continuous transmission without any received signals. The reduction of the required minimum bandwidth from 500 MHz to 50 MHz for UWB signal definition is one of the most important divergences of the ETSI standard from the FCC definition.

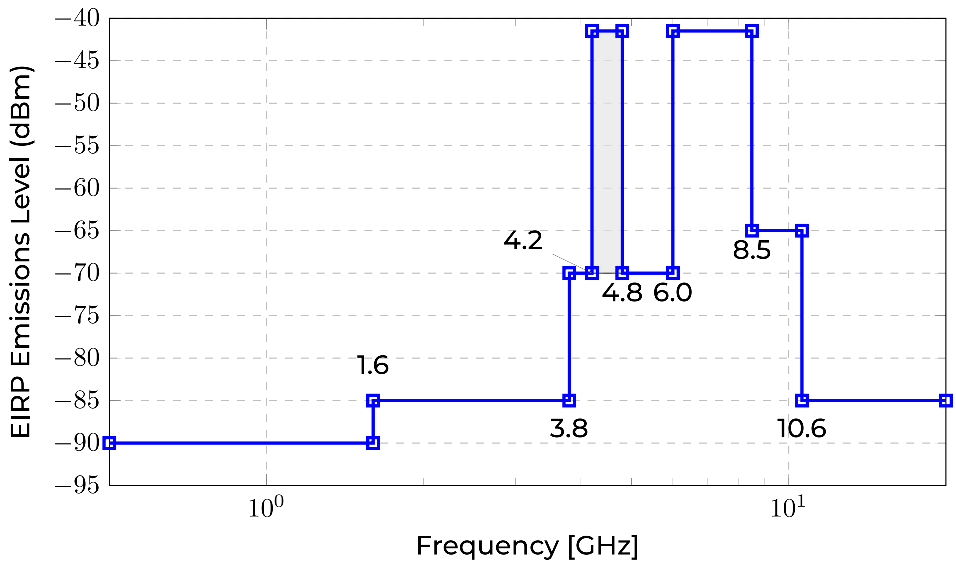


Figure 2: UWB Frequency allocation graph according to ETSI EN 302 065 V1.2.1 standard.

[2] http://www.cept.org
[3] http://portal.etsi.org
[4] ETSI EN 302 065 V1.1.1 standard was published in February 2008.

UWB COMMUNICATIONS USE CASES

Shannon-Hartley theorem, also known as the channel capacity theorem, states that the information transmission capacity of a band-limited channel with additive white Gaussian noise [5] is a function of the average signal power P_{av} and signal bandwidth, W [**Nguyen212**]. The Shannon capacity theorem can be written as:

$$C = W \cdot \log_2 \left(1 + \frac{P_{av}}{W \cdot N_0}\right) \tag{1}$$

In other words, a signal can be transmitted over this channel with an arbitrarily small error probability as long as the the data rate, r_b is smaller than the channel capacity, C.

We can rewrite equation 1 in terms of the normalized channel capacity C/W and energy per transmitted bit, where $P_{av} = C\,E_b$. Hence equation 1 can be rewritten as

$$\frac{C}{W} = \log_2 \left(1 + \frac{C}{W}\frac{E_b}{N_0}\right) \tag{2}$$

We can recast the equation 2 in terms of E_b/N_0 as:

$$\frac{E_b}{N_0} = \frac{2^{(C/W)} - 1}{C/W} \tag{3}$$

As could be seen from the equation 1, the channel information carrying capacity increases linearly with increasing bandwidth of the signal, while only increases logarithmically with the increasing signal to noise ratio for the signal. This is why ultra-wideband communication has gathered significant interest for its potential for very high-speed data communications without requiring complex modulation and demodulation schemes. Very high data rates with much lower signal-to-noise ratios than the conventional narrow(er) band communication systems could be achieved using UWB signals.

Figure 3 shows the plot of energy per bit to noise spectral density ratio (E_b/N_0) in dB vs. the normalized channel capacity (C/W) limit defined by the Shannon's channel capacity theorem (eq. 2). The shaded area below the curve is the normalized channel capacity where we can guarantee error-free transmission of the information for a particular E_b/N_0 ratio. For example, we cannot have a 10 Gbps data rate when the channel bandwidth is 1 GHz and

[5] Additive white Gaussian noise is a generally accepted model for thermal noise in communication channels.

E_b/N_0 is 10 dB. It should be noted that it is not possible to guarantee error-free transmission at any rate when E_b/N_0 is below -1.69 dB. It is called the *Shannon Limit*. The Shannon channel capacity theorem denotes an upper limit for the error-free data transmission rate for a particular E_b/N_0 ratio when the noise in the channel is assumed to be AWGN. It does not tell us anything about how this limit can be reached.

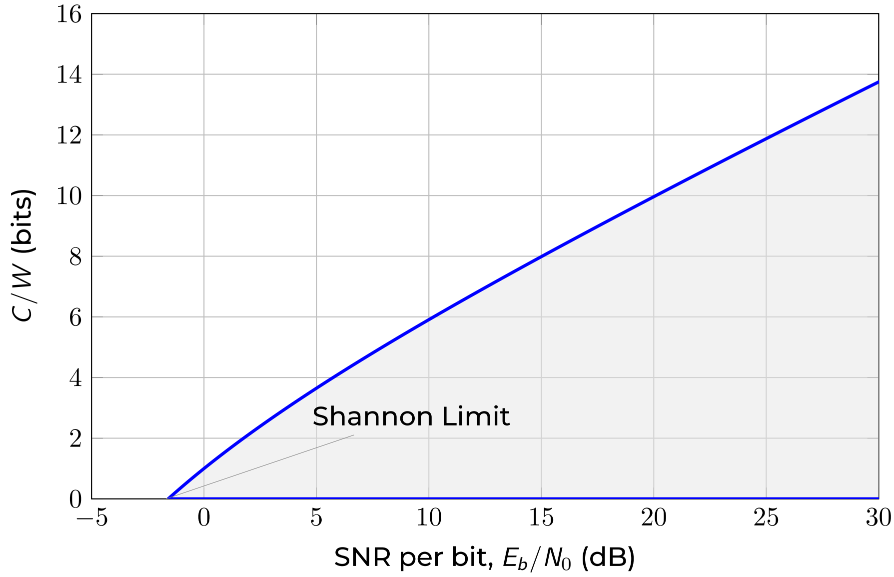


Figure 3: Shannon Limit as a function of E_b/N_0 in dB.

In UWB systems, the channel bandwidth is quite often much larger than the targeted data rates. The strict emission limits on the UWB emissions by the transmitters created a significant data rate vs. range trade-off for UWB communication systems. To understand it better, we need to make a couple of assumptions:

1. The receive and transmit antenna gains are constant over the channel bandwidth.
2. The main signal path between transmitter and receiver is line-of-sight.
3. Transmitter's output power over the bandwidth is constant.

Considering that an UWB transmitter's EIRP is at maximum -41.3 dBm/MHz, the total transmitted output power over the bandwidth, B (in MHz), can be expressed as:

$$P_T(dbm) = -41.3(dBm) + 10\log_{10}(B/10^6) \tag{4}$$

Assume that the UWB signal has a 1 GHz bandwidth assuming that the power spectral density for the signal has a boxcar shape. Then, the EIRP at the transmit antenna is equal to $P_T = -41.3\,dBm + 30\,dB = -11.3dBm$.

From the Friis' equation, the free space path loss in dB is given by:

$$L[dB] = 20\log_{10}(d)[m] + 11[dB] - G_T[dB] - G_R[db] - 20\log_{10}(\lambda)[m] \quad (5)$$

where λ and d are the wavelength of the radio frequency signal and the distance from the transmitter to the receiver, respectively. G_T and G_R are the transmit and receive antenna gains over the isotropic antenna for a particular transmitter and receiver configuration. We assumed that transmit and receive antenna gains are constant over the signal bandwidth. On the other hand, the path loss over the bandwidth will considerably change if the transmit and receive antenna gains are assumed to be constant over the same bandwidth. For the moment, we will assume that the average path loss is the same or very close to that of the signal at the centre of the band.

To frame the discussion regarding the achievable data communication rate and distance with UWB systems, we will look into a hypothetical system's link budget. The link budget calculations are used to account for all the losses from the output of the transmit antenna until the decision circuit in the receiver to determine whether the range and bit-error-rate specifications are achievable for a particular communication signal chain.

The system specifications are summarized in table 1.

Specification	Description	Value	Unit
BW	Signal bandwidth	1	GHz
PSD	Power Spectral Density	-41.3	dBm
P_T	Average Transmit Power	-11.3	dBm
G_T	Transmit Antenna Gain	0	dB
f_c	Centre Frequency	6.5	GHz
P_{1m}	Path Loss at 1 m	44.7	dB
n_p	Path Loss exponent (LOS)	2	
G_R	Receiver Antenna Gain	0	dB
N_o	Thermal noise at 290 K in 1 Hz	-174	dBm/Hz
NF	Noise figure of the receiver	10	dB
N_0	Input referred noise in 1 Hz	-164	dBm/Hz
$(E_b/N_0)_{\mathtt{min}}$	Minimum E_b/N_0 at the input	11.1	dB

Table 1: Specifications for a hypothetical UWB Communication System.

In this example, the transmit and receive antennas are omni-directional, i.e. a gain of 0 dB in all directions. The path loss calculations are referred to 1 m to allow for different loss exponents at longer distances due to multipath fading effects. Increasing the distance by 10 times will increase the path loss by another 20dB when the receiver is in the line-of-the-sight of the transmitter and the multipath effects are ignored. The average received power in the receiver's antenna is determined by subtracting the path loss from the average transmit power 1:

$$\begin{aligned} P_R &= P_T - L(d) \\ &= -11.3\text{dBm} - 44.7\text{dBm} - n_p\,10\log(d/1\,\text{m}) \\ &= -55.8\,dBm - n_p\,10\log(d/1\,\text{m}) \end{aligned} \tag{6}$$

The RF power incident at the receiver antenna, P_R, vs. distance between the transmitter and receiver assuming line-of-sight (LOS) communications is plotted by the red line in figure 4. The line-of-sight communications assumption means that the loss-exponent is assumed to be equal to 2. This is in fact an unrealistic assumption as the UWB systems normally work indoors where many different echos of the transmitted signal is received by the receiver due to multi-path reflections in the environment. Later we will relax the multi-path assumption and evaluate the implications of loss-exponents higher than 2 due to multi-path fading effects.

We need to keep in mind that not all of the energy incident on the receiver antenna would be used in the decision circuit. There are a number of reasons: inevitable losses due to parasitics in the receiver circuits or imperfect transfer of the power between the functional blocks due to component spreads. An **implementation loss** factor, IL is added to account for these effects, in this example equal to 6dB. As the signal has a relatively large bandwidth of 1 GHz, the **fading margin**, is much lower than the narrowband receivers at 4dB. From E_b/N_o, N_o, NF, ,FM, and IL specifications, we can calculate the required energy per bit, E_b as follows:

$$\begin{aligned} E_b &= N_o + NF + E_b/N_o + IL + FM \\ &= -174 + 10 + 11.1 + 6 + 4 \\ &= -142.9\text{dBm/Hz} \end{aligned} \tag{7}$$

where the multiplications are replaced by additions as the all quantities are logarithmic either referred to 1dBm or another quantity.

The average received power required for this energy per bit E_b number can be deduced by multiplying it by the bit rate, r_b. Here we assume that every bit corresponds to an impulse, as in the coherent detection of the binary phase-shift keyed (BPSK) impulses.

$$\begin{aligned} P_{\text{th}} &= 10\log(r_b) + E_b[\text{dB}] \\ &= 10\log(r_b) - 142.9\text{dBm/Hz} \end{aligned} \tag{8}$$

Looking at figure 4, the fundamental problem with the UWB data communications can be easily identified. Due to the very low allowed RF output power levels prescribed by the various jurisdictions, the UWB systems can only realize their high-data rate communications premise at very short ranges. The required minimum power threshold values at the receiver input for the four different target data rates are also shown in this figure. The *implementation loss* term, *IL*, equal to 8 dB in this example accounts for the any unavoidable loss of the signal power due to multitude of causes in the receiver signal chain. In figure 4, the 10 Mbps communication is only possible at a distance of 2 m, while the data rate can not be higher than 1 kbps at 800 m.

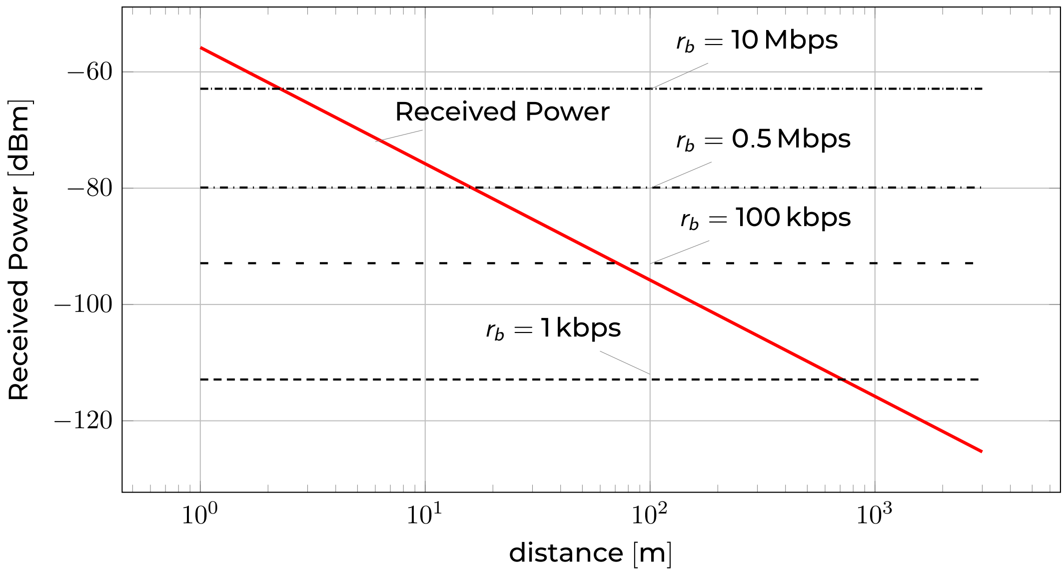


Figure 4: The received power vs. required power for a certain data rate.

A caveat in reading the range vs. possible data rates from the figure 2:

Although it is possible to have communication distances up to 800 m with a data rate of 1 kbps, it may not be physically feasible to send those pulses using with a handheld device.

To understand this fact better we need to remember that the received power levels in figure 4 are averages where the energy per bit, E_b is multiplied by the bit rate, r_b, or the pulse repetition frequency, **PRF** when each impulse encodes a bit. When the average transmitted power is −11.3 dBm and the pulse repetition frequency is 1 kbps, the energy per pulse at the output of the transmitter is:

$$\begin{aligned} E_{b,T} &= --11.3\,\text{dBm} + 10\ \log(1\,\text{kbps}) \\ &= 74.1\,\text{nJ} \end{aligned} \quad (9)$$

Without covering the details of possible UWB pulse shapes, we will here assume that the transmitted pulse is a truncated sine-wave with a duration of 2.5 ns. This means that the pulse consists of 16 cycles with a centre frequency of 6.5 GHz. For such a truncated sine-wave, the peak voltage, V_p at the transmit antenna can be calculated as:

$$\begin{aligned} V_p &= \sqrt{\frac{2E_{b,T}R_{\text{ant}}}{\tau_p}} \\ &= \sqrt{\frac{2 \cdot 74.1\,\text{nJ} \cdot 50\,\Omega}{2.5\,\text{ns}}} \\ &= 2.96\,\text{kV} \end{aligned} \tag{10}$$

Thus, the peak voltage at the transmit antenna is almost 3000 V! This is clearly not achievable with commercial battery-powered power amplifiers in handheld devices.

One method of decreasing the amount of energy to be transmitted by pulse is to partition the pulse energy between several thousand and few hundred thousands pulses [4]. One problem with this approach is the fact that although the pulse energies can be integrated coherently, the noise energy per pulse would be also added. Total signal to noise ratio when n pulses are integrated would only increase by $\sqrt{n}$ assuming that the integrator has no losses and the noise between the pulses are uncorrelated.

Another very popular method to use the very wide bandwidth of UWB systems, is to use spread-spectrum signal processing techniques to spread the each bit over many pulses [8].

In the following sections we will look in to typical use cases for UWB communication systems.

HIGH DATA RATE COMMUNICATIONS

Even before the FCC approval of UWB transmissions in 7.5GHz band between 3.1 to 10.6 GHz frequencies albeit within tight emission limits, the first divergent ideas about how to utilize the new available RF spectrum were aired by various entities. IEEE has naturally come to the fore as a standard setting body as it has done very successfully for IEEE802.11 standards family.

IEEE had already a working group for wireless personal area networks (WPAN) for short-distance communications (in less than 10m range) called IEEE802.15 group. It was formed to create the standards for low power, low cost networks. The aim was to provide only the media-access control (MAC) and physical communication layers while leaving the higher levels to be developed according to the market needs[6] Zigbee is one of the best known

[6]http://www.radio-electronics.com/info/wireless/ieee-802-15-4/wireless-standard-technology.php

examples of the communication protocols which use 802.15.4 .

In response to industry demand and impending FCC regulations for UWB transmissions, IEEE formed a special working group, i.e. the high rate alternative PHY task group (TG3a) to agree on an industry standard for high speed, short-range data communications using UWB technology in November 2001. Throughout the time TG3a working group had been active, the most of the interested parties coalesced around two competing camps with very different underlying technologies:

1. *Multi-band Orthogonal Frequency Division Multiplexing* (MB-OFDM)
2. *Direct-sequence* impulse radio UWB

Unfortunately for the both camps, the TG3a working group could not agree on a common standard with the requisite 75% majority in the two rounds of the voting at the end. This led to a complete split between two industry consortia, *WiMedia Alliance* and *UWB Forum*. Meanwhile, the IEEE802.11 standard groups kept issuing newer and higher throughput versions of the standard such as 802.11n. IEEE 802.11n allowed the increase in the maximum data-rate from 54 Mbit/s to 600 Mbit/s using four spatial streams with each channel occupying 40 MHz bandwidh. Furthermore, 802.11n compliant devices would also be fully backward compatible with the older 802.11a/b/g standard compliant transceivers. These developments obviated the advantage of UWB technology for high-data rate applications over the WiFi technology.

Eventually, many of the companies who attempted to utilize the UWB technology for high data rate, short-range applications either failed due to low customer uptake, long development times and the lack of unifying standards or shifted their focus to more traditional narrow-band RF communication technologies.

LOW DATA RATE COMMUNICATIONS

On the other hand, IEEE 802.15.4a task group was more successful in creating a comprehensive standard for lower data-rate UWB communications with added benefit of the precise location finding and ranging capability included in the standard. The task group chose direct-sequence impulse radio implementation of the UWB as an alternate physical communications option for so-called IEEE 802.15.4a standard, which was finally ratified in May 2007. The standard also included chirp-FM proposal by Nanotron GmbH as another alternate physical layer technology.

UWB MARKETS AND TARGET APPLICATIONS

UWB communication technology has been considered for various applications depending on the trade-off between the range and the data rate. In this section, we will evaluate the various markets the UWB technology has been targeted since early 2000s.

CABLE REPLACEMENT

As mentioned above, one of the first applications targeted by UWB communication systems was the high data rate (up to 480Mbit/s) but short-range communications (less than 10m). It was thought that the devices using UWB technology could replace various high data rate cables used in home entertainment systems such as HDMI. WiMedia alliance created a protocol called *Wireless USB* capable of sending 480Mbit/s at distances up to 3 metres and 110Mbit/s at up to 10 metres. Subsequently, a number of companies brought Wireless USB products including dongles for laptops and TV sets to the market. The uptake of the wireless USB technology was hampered by the fact that the real-life throughput of the Wireless USB devices had never approached the promised numbers. For example, OctoScope, a test company located in Massachusetts, reported that the highest performing Wireless-USB device could not exceed 50Mbps at distances closer than 1m [9] severely comprising the value proposition of the technology.

Another possible use of WiMedia's MB-OFDM UWB technology was considered by *Bluetooth Special Interest Group* as a possible high data rate extension for the Bluetooth 3.0 standard. In 2009, Bluetooth SIG reportedly dropped WiMedia's technology from consideration as an extension of Bluetooth specification as some members of WiMedia alliance would not agree to the necessary agreements for the transfer of the intellectual property to the Bluetooth SIG.

REAL-TIME LOCATION FINDING AND RANGING

IEEE802.15.4 standards have included direct-sequence impulse radio based UWB radio technology as one of its alternate physical communication layer technologies [10] since 2009. One of the more interesting aspects of the standard was the inclusion of the precision ranging capability to the moderate data rate communications. It was the real time location finding and ranging capability that proved to be an advantage for the impulse radio communication systems that could not be replicated by the traditional narrow-band communication systems.

Decawave's IEEE802.15.4-2011 standards compliant transceiver chip, DW1000, allows real-time location finding with a precision of 10cm indoors while allowing communications between the transceivers with a data rate between 110 kbit/s to 6.8 Mb/s[7]. The reported range of communication is up to 300 m. The reported current consuption of the chip is between 31mA in the transmit mode and 64mA in the receive mode from a supply voltage between 2.8V to 3.6V. Although the company claims that the DW1000's low power consumption "reduces the need to replace batteries and lowers system lifetime costs", there are no figures for typical battery operated transceiver's expected lifetime.

ACTIVE RFID TAGS

IEEE802.15.4f standard devised under the umbrella of IEEE802.15.4 WPAN standards group, includes an impulse radio UWB technology based active RFID specification. Although the standard was approved in 2012, there has been very few announcements for RFID tags compliant with IEEE 802.15.4f except from Zebra Technologies.

The UWB air interface described in 802.15.4f standard specifies:

1. 1 MHz base pulse repetition rate,
2. On-off-keying (OOK) modulation,
3. Three symbol mapping modes:
    - Base mode: one chip per symbol
    - Enhanced mode: 4 chips per symbol
    - Long Range mode: 64 chips per symbol
4. Three frequency bands for global use:
    (a) Band 0: Centered at 6.4899 GHz.
    (b) Band 1: Centered at 7.4888 GHz.
    (c) Band 2: Centered at 8.9856 GHz.

According Zebra Technologies DART UWB Technology datasheet[8], the UWB tags can be located with an accuracy better than 30cm line of sight and could run up to 7 years with 1 Hz blink rate without needing to change tag batteries. Real-time location of the tags can be determined up to 200 meters at the line of the sight. Zebra Technologies also offers so-called Dart Sensors, that can be configured as presence readers.

[7] http://www.decawave.com/sites/default/files/product-pdf/dw1000-product-brief.pdf
[8] https://www.zebra.com/content/dam/zebra/product-information/en-us/brochures-datasheets/location-solutions/dartuwb-tech-datasheet-en-us.pdf

WIRELESS SENSOR NETWORKS

IEEE802.15.4 standards were developed for low-data-rate monitoring and control applications where the extended battery life for the nodes were of a primary concern. Combined with IEEE802.15.4a standard including a impulse radio UWB physical layer allowing precise real-time location finding and ranging capabilities [11], a significant uptake of the UWB enabled wireless sensor nodes should have happened by now. Except Decawave's DW1000 transceiver chip and Zebra's UWB RFID tags, the actual product products have been thin on the ground.

CONCLUSIONS

In this introduction chapter, we briefly described UWB signals from the perspective of their bandwidth and power spectral density specifications. As UWB is in many cases is underlying the narrow-band radio frequency channels, the strict limits are placed on UWB signal emissions, limiting their use to either high-speed and very short-range applications or mid-range, but much-lower data rate applications.

Bibliography

[1] Faranak Nekoogar. *Ultra-Wideband Communications: Fundamentals and Applications*. Prentice Hall, 2005. ISBN: 0-13-146326-8. URL: https://www.amazon.com/Ultra-Wideband-Communications-Fundamentals-Faranak-Nekoogar/dp/0131463268?SubscriptionId=0JYN1NVW651KCA56C102%5C&tag=techkie-20%5C&linkCode=xm2%5C&camp=2025%5C&creative=165953%5C&creativeASIN=0131463268.

[2] Robert J. Fontana. "Recent system applications of short-pulse ultra-wideband (UWB) technology". In: *IEEE Transactions on Microwave Theory and Techniques* 52.9 I (Sept. 2004), pp. 2087–2104. ISSN: 00189480. DOI: 10.1109/TMTT.2004.834186. URL: http://ieeexplore.ieee.org/xpls/abs%7B%5C_%7Dall.jsp?arnumber=1327870%20http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1327870.

[3] Terence Barrett. "History of UltraWideBand (UWB) Radar & Communications: Pioneers and Innovators". In: *Progress In Electromagnetics Symposium 2000*. 2000, p. 42. URL: http://www.ntia.doc.gov/legacy/osmhome/uwbtestplan/barret%7B%5C_%7Dhistory%7B%5C_%7D%7B%5C%%7D28piersw-figs%7B%5C%%7D29.pdf%7B%5C%%7D5Cnhttp://www.ntia.doc.gov/legacy/osmhome/uwbtestplan/barret%7B%5C_%7Dhistory%7B%5C_%7D(piersw-figs).pdf.

[4] Shahriar Emami. *UWB Communication Systems: Conventional and 60 GHz*. Springer-Verlag GmbH, May 31, 2013. ISBN: 1461467527. URL: http://www.ebook.de/de/product/20178673/shahriar_emami_uwb_communication_systems_conventional_and_60_ghz.html.

[5] Robert J. Fontana et al. "An ultra wideband radar for micro air vehicle applications". In: *2002 IEEE Conference on Ultra Wideband Systems and Technologies*. Baltimore: IEEE, 2002, pp. 1–6. ISBN: 0-7803-7496-7. DOI: 10.1109/UWBST.2002.1006344. URL: http://ieeexplore.ieee.org/xpls/abs%7B%5C_%7Dall.jsp?arnumber=1006344.

[6] Nuno Paulino, João Goes, and Adolfo Steiger Garção. *Low Power UWB CMOS Radar Sensors*. Springer, May 2, 2008. ISBN: 978-1-4020-8409-6. URL: http://www.ebook.de/de/product/7297398/nuno_paulino_joao_goes_adolfo_steiger_garcao_low_power_uwb_cmos_radar_sensors.html.

[7] Emmanuel Faussurier. "Spectrum management and Ultra-Wideband (UWB)". 2007.

[8] John McCorkle. "Ultra Wide Bandwidth (UWB): Gigabit wireless communications for battery operated consumer applications". In: *IEEE Symposium on VLSI Circuits, Digest of Technical Papers*. Vol. 2005. 2005, pp. 6–9. ISBN: 4-900784-01-X. DOI: 10.1109/VLSIC.2005.1469321. URL: http://ieeexplore.ieee.org/xpls/abs%7B%5C_%7Dall.jsp?arnumber=1469321.

[9] Fanny Mlinarsky. "Wireless HD Video : Raising the Throughput Bar". Bolton, MA, 2008.

[10] Chunjie Duan, Philip V. Orlik, and Zafer Sahinoglu. "A non-coherent 802.15. 4a UWB impulse radio". In: *Ultra-Wideband, 2007.* (2007).

[11] Jinyun Zhang et al. "UWB systems for wireless sensor networks". In: *Proceedings of the IEEE* 97.2 (2009), pp. 313–331. ISSN: 00189219. DOI: 10.1109/JPROC.2008.2008786.