Ultra-Wideband: Past, Present and Future

White Paper

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Foreword

This White Paper represents the outcome of EUWB, a major research project supported by the European Commission dedicated to exploring the enormous economic potential of ultra-wideband (UWB) radio technology for key European industrial sectors.

The objective of this document is to offer a comprehensive yet concise account of the innovative and disruptive potential of UWB. Specifically, it will address the history, unique legal framework and fundamental challenges of UWB, as well as the difficulties that it has faced from the technical regulatory and standardisation perspectives. Finally, the driving forces and future applications that will bring UWB to the wider market, including the latest product developments and market trends, will be described.

Traditional radio communications system designs are based on the assumption that the received signal is an attenuated replica of the transmitted signal mainly degraded by the radio channel characteristics and thermal noise in the receiver. This holds true while the number of radio services and transmitting devices remains limited, which was the case for a relatively long period of time during the last century. System separation was realised using non-adaptive traditional analogue filters with their inherently low degree of flexibility. Consequently, frequency spectrum regulatory policy favoured the granting of exclusive frequency rights to dedicated radio services valid for long periods of time. Following on from this precedent, current radio frequency regulation is still based on frequency separations which are allocated for long periods (tens of years).

With the introduction of bi-directional cellular radio systems into the mass market the system design situation has changed significantly. The system design paradigm now takes additional signals, including interference into account. Interference from adjacent channels allocated to nearby users (due to non-ideal filters) and neighbouring fixed transmitters (due to frequency re-use in cellular systems) is considered in general to be inevitable and is taken into account in system design and rollout. This so called intra-system interference is accepted by the radio service provider (operator) mainly due to the fact, that he can strictly control this interference by means of network planning, intelligent resource allocation and traffic load control. Therefore, it is relatively easy for the operator to guarantee a desired link quality and thus a certain quality of service (QoS) for the customer. Determination of the appropriate link margin during network planning is the major technique used to achieve the required QoS.

Today's modern digital radio services such as digital audio and video broadcasting or wireless local area networks can accept a certain (higher) level of interference without noticeably degrading the perceived system performance. Advanced error correction coding techniques either mask or reconstruct degraded received signals by means of complex digital signal processing. ISM (industrial, scientific and medical) band operation in the 2.4 GHz range is a good example of radio systems designed to operate in environments with a higher level of interference. However, quality of service is still not guaranteed in such a "resource sharing" case.

Even if it is basically not allowed for primary radio services to share radio spectrum (except for ISM bands) each radio system operator has to accept by law that unintentional out-of-band emissions are generated by other radio systems and he has to cope with such interference.

This is where UWB enters the stage to establish services as a secondary user of large bandwidth, coexisting with a lot of primary radio spectrum users. From the start of the UWB regulatory process in Europe, Asia and at the ITU level, it became obvious that there are a number of challenges associated with regulating such spectrum-sharing technology. Modern radio technology is able to operate based on coexistence and cognitive radio principles and is required to do so. Besides the technical challenges, there are also administrative obstacles to be overcome, e.g. to convince stakeholders in the European regulatory process that this approach will provide more efficient spectrum use from an overall economic point of view and that it will open up a new market for applications enabled by modern "intelligent" radio technologies, such as UWB.

It is expected that for the majority of UWB devices, operation in the "upper band" from 6 GHz to 9 GHz is a good choice due to advances in the semiconductor technology and the relaxed range requirements of certain applications, such as Bluetooth. Furthermore, it is expected that for a number of applications the "lower band", targeting 3.1–4.8 GHz, will be still available. Current developments in R&D and standardisation show that future UWB systems will cover the bands below 10 GHz as well as the bands around 60 GHz. The 60 GHz band allows higher transmit power enabling even higher data rates, e.g. 3–5 Gbit/s and the transmission of uncompressed HD video, at the cost of higher energy consumption. Therefore, it will probably be used in stationary devices with a mains power connection instead of portable/mobile devices, which may operate with UWB below 10 GHz only, where it is much more power efficient.

The UWB market follows two major trends: very high data rate applications (about 1–5 Gbit/s physical layer burst data rate) and the low energy consumption sensor and location tracking applications enabling the wireless connection of sensors and/or real-time accurate positioning of terminal equipment. Furthermore, UWB is used for some niche applications enabled by the imaging and radar features of UWB such as material analysis, ground penetration radar, monitoring of vital functions and other sensor applications.

UWB technologies, particularly those based on Wireless USB, allow industry to develop products which have several attractive features suitable for the consumer electronics marketplace. They allow the robust, high speed transfer and streaming of media local to the user within a personal area network and consume far less power than traditional wireless communication technologies. They free the user from connector compatibility issues, and do this in a simple and easy manner requiring nothing more than a single antenna.

Low power devices with a modest range of up to 10 metres permit a high degree of coexistence which is well-suited to multi-occupancy dwellings. The high density of devices in modern dwellings coupled with high data rates makes UWB ideal for the major global market growth area of wireless multimedia applications.

In consumer applications UWB does not share spectrum with other radio technologies in traditional manner and thus does not have to contend for bandwidth, and provides a more predictable and reliable user experience. This is most noticeable in domestic situations where Wi-Fi is prevalent and often already saturated. Mature low-cost single-chip UWB sub-system solutions are now available. Multimedia consumer electronics (CE) products are on sale today based on Wireless USB with the potential to evolve into a wireless CE ecosystem populated with a diverse range of attractive products that offer consumers a fast, seamless, simple and consistent means of sharing the ever-increasing amounts of personal media and entertainment content. The latest product trends are presented in this paper.

Besides investigating high data rate UWB systems, EUWB has advanced research on UWB technology, and can nowadays offer know-how in location tracking (LT) systems to both small and large industrial enterprises. Highly efficient low-power LT platforms, ranging techniques, scheduling mechanisms and positioning algorithms have been developed, prototyped and integrated into real and ready to use UWB platforms.

Two main types of LT systems have been addressed by the EUWB partners, namely, active and passive positioning both of which are addressed in this paper.

An overview of the LT technologies developed by the project is presented in this document in a condensed form. It shows how high accuracy location can be achieved, together with the requirements and fundamental limits of UWB-LT technology. The focus is on the key aspects of ranging and positioning algorithms and a description of the fundaments of the EUWB LT technology is presented. The use of such systems is also discussed within the context of innovative location-based services and emerging LT applications developed through cooperation between leading European enterprises in electronics, automotive, transport, security and mobile services.

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List of Abbreviations

3G	3rd generation
A/C	Aircraft
ADC	Analogue-to-digital converter
ADSL	Asymmetric digital subscriber line
AoA	Angle-of-arrival
AP	Access point
APT	Asian Pacific Telecommunity
AV	Audio and video
AWGN	Additive white Gaussian noise
BER	Bit error rate
BG	Band group
BI	Beacon interval
BPF	Band-pass filter
CAP	Contention access period
CE	Consumer electronics
CEPT	European Conference of Postal and Telecommunications Administrations
CFP	Contention-free period
CITEL	Inter-American Telecommunication Commission
CIR	Channel impulse response
CMOS	Complementary Metal Oxide Semiconductor
CMS	Cabin management system
CR	Cognitive radio
CRB	Cramér-Rao bound
CSS	Chirp spread spectrum
CUWBR	Cognitive UWB radio
DAA	Detect-and-avoid
DAC	Digital-to-analogue converter
DBO	Differentially bi-orthogonal
DBPSK	Differential binary phase shift keying
DC-P/N	Distance contraction positive/negative
DCM	Dual carrier modulation
DEC	Decision
DLNA	Digital Living Network Alliance
DoD	Department of Defense

DOF	Degrees of freedom
DP	Direct path
DRP	Distributed reservation protocol
DSA	Dynamic spectrum access
DTV	Digital television
DVI	Digital visual interface
DWA	Device wire adapter
EC	European Commission
ECC	Electronic Communications Committee
ECMA	European Computer Manufacturers Association
ED	Energy detection
EIRP	Equivalent isotropically radiated power
EKF	Extended Kalman filter
EN	European Norm
ETSI	European Telecommunications Standards Institute
EU	European Union
EUWB	Coexisting Short Range Radio by Advanced Ultra-Wideband Radio Technology
FCC	Federal Communications Commission
FDS	Frequency-domain spreading
FFC	Fixed frequency code
FFT	Fast Fourier transform
FG	Factor graph
FH	Frequency hopping
FP7	7th European Framework Programme for RTD and Demonstration Activities
GDC	Global distance continuation
GPS	Global Positioning System
GTS	Guaranteed timeslot
GUI	Graphical user interface
HD	Hard disk
HDMI	High-definition multimedia interface
HDR	High data rate
HDTV	High-definition television
HMAC	Hardware MAC
HSDPA	High speed downlink packet access
HSPA	High speed packet access

HWA	Host wire adapter
ICT	Information and communication technology
IDC	International Data Corporation
IEEE	Institute of Electrical and Electronics Engineers
IF	Interface
IFE	In-flight entertainment
IMU	Inertial measurement unit
INS	Inertial navigation system
IP	Internet protocol
IPTV	Internet protocol television
IR	Impulse radio
IT	Information technology
ITU	International Telecommunication Union
JBSF	Jump back and search forward
L-GDC	Linear global distance continuation
LAES	Localisation application for emergency services
LCD	Liquid crystal display
LDC	Low duty cycle
LDPC	Low-density parity-check
LDR	Low data rate
LLS	Linear least squares
LMAC	Lower MAC
LOS	Line-of-sight
LP	Linear programming
LS	Least squares
LT	Location (and) tracking
LTE	Long term evolution
LTI	Linear time-invariant
MAC	Medium access control
MAS	Multiple antenna systems
MB-OFDM	Multiband orthogonal frequency division multiplex
MDCM	Modified dual carrier modulation
MDS	Multidimensional scaling
MEMS	Micro-electro-mechanical systems
MF	Matched filter

MIC	Ministry of Internal Affairs and Communication
MIMO	Multiple input/multiple output
ML	Maximum likelihood
NLOS	Non-line-of-sight
NLS	Non-linear least squares
NWI	New work item
ODM	Original design manufacturer
OEM	Original equipment manufacturer
OFDM	Orthogonal frequency division multiplex
PA	Power amplifier
PAN	Personal area network
PAX	Passenger
PC	Personal computer
PCA	Prioritised contention access
PCI	Peripheral component interconnect
PHY	Physical layer (system)
PLCP	PHY convergence protocol
PN	Pseudo (random) noise
PNC	Piconet coordinator
PPM	Pulse position modulation
PRP	Pulse repetition period
PSDU	PHY service data unit
PU	Primary user
PULSERS	Pervasive Ultra-Wideband Low Spectral Energy Radio Systems
QoS	Quality of service(s)
QPSK	Quaternary phase shift keying
R&D	Research and development
REM	Radio environment map
RF	Radio frequency
RMSE	Root mean square error
RSS	Received signal strength
RTD	Research and technological development
RTOS	Real-time operating system
RWGH	Residual weighting algorithm
RX	Reception; receiver

SA	Simulated annealing
SAP	Service access point
SBS	Serial backward search
SBSMC	Serial backward search for multiple clusters
SD	Spatial diversity
SDP	Semi-definite programming
SDP-M	Semi-definite programming over mutlihop
SF	Superframe
SIG	Special Interest Group
SM	Spatial multiplexing
SMACOF	Scaling by majorising a complex function
SME	Small and medium-sized enterprise
SNR	Signal-to-noise ratio
SRD	Short range device
SRDoc	System Reference Document
ST	Simple thresholding
SU	Secondary user
SUE	Spectrum utilisation efficiency
STL	Tree level
TDMA	Time division multiple access
TDoA	Time-difference-of-arrival
TDS	Time-domain spreading
TFC	Time frequency code
TFT	Thin-film transistor
ToA	Time-of-arrival
TR	Technical Report
TV	Television
TX	Transmission; transmitter
UMAC	Upper MAC
UMTS	Universal Mobile Telecommunication System
USB	Universal Serial Bus
USB-IF	USB Implementers Forum
UWB	Ultra-wideband
UWB-RT	UWB radio technology
VGA	Video graphics array

VHDL	Very high speed integrated circuit hardware description language
VHDR	Very high data rate
VPN	Virtual private network
WHCI	Wireless host controller interface
WI	Work item
Wi-Fi	Wireless Fidelity
WiMAX	World-wide interoperability for microwave access
WiMedia	WiMedia Alliance; WiMedia UWB PHY/MAC specification
WiNet	WiMedia network *(formerly WiNET)*
WLAN	Wireless local area network
WLP	WiMedia logical link layer control protocol
WPAN	Wireless personal area network
WUSB	Wireless USB

Contents

1. The Evolution of Ultra-Wideband Technology at a Glance

Ultra-wideband (UWB) refers to radio systems for measurement or communications purposes. UWB has been considered a revolutionary technology for transmitting large amounts of digital data over a broad frequency spectrum using short-pulse, low powered radio signals. The term UWB was introduced by the US Department of Defense (DoD) around 1989 [1] and commonly refers to a signal or system that either has a bandwidth that exceeds twenty percent of the centre frequency or a large absolute bandwidth of more than 500 MHz. Such radio systems have been authorised by the US Federal Communications Commission (FCC) for unlicensed use in the range 3.1–10.6 GHz. In February 2002, the FCC approved the first Report and Order for the commercial use of UWB technology under strict power emission limits. For UWB systems the transmitted power is of the order of 0.5 mW. Moreover, due to the huge bandwidth of UWB systems (3.1–10.6 GHz allotted by FCC), the power spectral density is even less than other wireless communication systems or devices, typically 6.7×10^{-8} W/MHz [1]. The huge bandwidth coupled with a very low power level makes UWB signals appear more or less like background noise to other wireless communication systems. This allows them to coexist with other radio communication devices as well and make them immune to detection and interception by other narrowband wireless communication receivers. UWB facilitates the efficient use of relatively scarce radio bandwidth, while enabling high data rate personal area network (PAN) wireless connectivity and longer-range, low data rate applications as well as radar and imaging systems [1].

UWB-enabled sensors are non-destructive and non-invasive measurement devices, collecting information across a much wider frequency range than non-UWB systems and so can get more detailed knowledge about the structure or behaviour of the devices under test. In the context of communications, UWB is often called carrier-less because it does not concentrate signal energy around a dedicated frequency. The data are not modulated on a continuous waveform with a specific carrier frequency as is in the case of narrowband and wideband technologies. Furthermore, UWB can be used for localisation purposes, where the large bandwidth facilitates an impressive accuracy which benefits both short range localisation and the realisation of autonomous moving devices.

As early as 1901, Marconi employed very large bandwidths to transmit Morse Code sequences across the Atlantic Ocean using spark gap radio transmitters [1]. Nevertheless, the benefit of a large bandwidth and the capacity to implement multi-user systems was never considered at that time.

In the 1950s, pulse based transmission gained momentum in military applications in the form of impulse radars [1]. As a matter of fact, many communications technologies have been investigated and used in the military domain, sometimes for decades prior to their public commercialisation. UWB is certainly no exception here. From the 1960s to the 1990s, UWB technology was restricted to military applications under classified DoD programs in the US, aimed at highly secure communication.

Looking at UWB development from a scientific rather than a political perspective, it took until the 1960s when ground-breaking research in time-domain electromagnetic waves started to pave the way for modern UWB technology. The idea was to characterise linear time-invariant (LTI) systems by their output response to an impulse excitation, known as the impulse response of an LTI system, instead of the more conventional means of swept frequency response [1]. Until the development of impulse excitation and measurement techniques it was not possible to measure the impulse response directly. However, once these techniques became available, it was obvious that they could be used for short pulse radar and communication systems. In 1978, Ross and Bennet applied these techniques in radar and communication applications [2].

Although UWB is no new technology, its application for communication is quite new. Recent advances in microelectronics have made UWB ready for use in commercial applications. Therefore, it is more appropriate to consider UWB to be a new name for a long-existing technology.

Most UWB communication systems are either pulse-based or multicarrier-based. Pulse-based systems have been demonstrated at channel pulse rates in excess of 1.3 giga-pulses per second, supporting forward error correction encoded data rates in excess of 675 Mbit/s. A pulse-based method using bursts of pulses is also the basis of the low-data rate IEEE 802.15.4a [3] standard which proposes UWB as an alternative physical layer (PHY). Carrier-less transmission has the benefit of requiring fewer radio frequency (RF) components than carrier based techniques, permitting the realisation of simple and inexpensive transceiver architectures. For instance, the transmission of low-powered pulses often eliminates the need for a power amplifier (PA) in UWB transmitters. Also, there is no need for mixers and local oscillators to convert the carrier frequency to another required frequency. Consequently, there is no need for a carrier recovery stage at the receiver. This simplicity makes the all-CMOS (Complementary Metal Oxide Semiconductor) implementation of UWB transceivers possible and translates into smaller form factors and lower production costs [1].

In multicarrier-based UWB systems, orthogonal frequency-division multiplexing (OFDM) is usually employed. In multiband UWB systems, instead of using the whole 7.5 GHz of UWB spectrum as a single band, it is divided into 15 sub-bands of 528 MHz [1]. One obvious advantage of a multiband scheme is to avoid sending signals on frequencies where other radio communication devices are present, with the corresponding dis-advantage that this requires sophisticated signal processing techniques and thus more complex transceivers. However, considerable data rates can be achieved. The ECMA-386 (European Computer Manufacturers Association) and ECMA-369 documents introduced a successful OFDM-based UWB concept [4],[5]; a standard promoted by the WiMedia Alliance and therefore often referred to as the WiMedia MAC and PHY. The WiMedia Alliance has subsequently published an updated version 1.5 of its specification [6],[7].

In EUWB all commercially attractive system architectures were considered including the IEEE 802.15.4a and ECMA standards. In this White Paper we will also describe the benefits of UWB technology and demonstrate its superiority in many application areas.

The majority of the UWB industry players that became suppliers of WiMedia and Wireless USB solutions are fabless semiconductor manufacturers. A need for simple, high speed wireless connectivity and the increasing relevance of transmitting and synchronising stored data could be translated into direct benefits for the consumer. This made the technology very attractive to the finance community and fuelled multiple venture capital backed start-up organisations as well as investments from several of the larger, well-established companies in the semi-conductor arena.

The initial target markets were consumer electronics, such as digital video and still cameras, with plans for UWB to be highly integrated into the core of the product, and to some extent business equipment such as overhead projectors. Around 2005, a broad range of product prototypes was being considered. Most of these prototypes were focused on video and still camera needs while on the personal computer (PC) host side, two types of Wireless USB (Universal Serial Bus) sub-systems were being promoted, one designed for aftermarket retrofitting and another deeply integrated into the PC to offer higher performance. In addition, there were prototypes for printers, mass storage devices, overhead projectors and in the longer term all eyes were on the holy grail of integration into mobile handsets. In short, pretty much any kind of product available in wired USB form was being considered as a candidate for a wireless equivalent. Manufacturers of such products all required reference designs tuned to their target application and their preferred platforms, which would typically include Linux, WinCE and a variety of real-time operating systems (RTOS).

The standards picture has been equally varied. In the early days large corporations took up opposing positions to back competing standards based on pulse modulation and OFDM. The majority of small and medium-sized enterprises (SME) eventually settled on OFDM and the WiMedia MAC and PHY. Wireless USB (WUSB), WiNet/WLP (IP over WiMedia), Bluetooth and the Digital Living Network Alliance (DLNA) all incorporated or created some variant or enhancement of WiMedia and used differing sub-sets of the functionality described in its specification. As one might expect all these standards were heavily influenced by large companies, for some of whom participation was interesting but not necessarily strategic and their commitment to the standards varied accordingly. As part of Bluetooth 3.0 the Special Interest Group (SIG) took a neutral position with respect to UWB. It regarded both WiMedia and Wi-Fi as potential high speed data transport channels to operate in tandem with standard Bluetooth via an abstraction layer. In the end Bluetooth decided to wait for a critical mass of UWB peripheral devices to appear and adopted Wi-Fi as the initial transport layer. Wireless USB became a dominant standard and brought the benefit of clear end-user brand recognition.

Today two or three UWB silicon vendors remain active in the market compared to more than ten as recently as three years ago. The majority of the survivors are European. The reasons for this rapid shrinkage can be divided into a number of themes.

The variety of standardisation bodies with a UWB component (Bluetooth, WUSB, WiMedia, WiNet/WLP) and applications, presented the smaller original equipment manufacturers (OEM) and silicon vendors alike with the difficult challenge of accurately predicting where they should focus their modest resources. Furthermore, potentially synergistic standards such as DLNA and Bluetooth fluctuated in their commitment to adopting the WiMedia UWB platform. This forced the SME silicon vendors to either spread their resources thinly or risk backing the wrong horse.

The major corporate customers for UWB were themselves unclear about what the market for UWB products would look like and did not display the corporate vision needed to shape and build the markets. This lack of clear direction from large OEMs emphasised the imbalance between SMEs developing the underlying technologies and the large companies. The large OEMs looked to the SMEs to provide packaged solutions ready to integrate into applications that they themselves found it difficult to define. The exploratory approach drained SME resources developing demonstrators and reference designs for a wide variety of platforms and markets. It is now a typical obstacle for any SME in today's market and doubtless contributes to the increasing difficulty of raising funding for fabless semiconductor ventures, leaving the future of silicon technology development solely in the hands of large corporations. A further restraint on UWB ecosystem growth was the natural inertia among PC manufacturers when presented with new communications standards and, having just come to grips with the rising popularity of Bluetooth and Wi-Fi, an increased reticence to lead the market with the integration of a non-ubiquitous system. Many manufacturers considered and some even prototyped and certified such PCs, but did not take them into production as they waited for a critical mass of peripheral devices to appear and so created a bootstrapping problem for the marketplace.

The financial crisis in the autumn of 2008 crippled the traditional maturing funding rounds (e.g. round C, D, etc.) for many of the silicon vendors, forcing them to cease trading. The reduction in vendors contributed to a collapse of confidence in the technology, further damaging growth potential for the ecosystem.

The surviving silicon vendors appear to have concluded that they would have to bootstrap the market themselves by proving that the technology had a viable application that would generate high volume demand. For the most part they stopped trying to sell chips and sub-systems to large OEMs and instead identified wireless multimedia as their best target and have defined and developed complete products based on WUSB that are now in a position to act as a basis for growing a UWB ecosystem. This has had the advantage of eliminating costly inter-company support and product definition activities with their associated iterations and provided a channel for more direct end user feedback into product development.

2. Essential Features of UWB Technology

Since by definition a signal or system is called UWB if it has either a bandwidth that exceeds twenty percent of the centre frequency or a large absolute bandwidth of more than 500 MHz, several physical layers are considered as UWB. The two major physical layers (PHY) that have been standardised are the multiband (MB-)OFDM waveform and the impulse radio waveform. However, other equipment exists using less conventional waveforms, namely chirp and frequency hopping (FH) waveforms.

2.1. Impulse Radio

2.1.1. History and Motivation

Impulse radio (IR) technology and its opportunities have been known about for decades. The technique uses very short pulses for the transmitted radio signal instead of modulated continuous sine waves. Due to the time/frequency duality, IR naturally falls within the scope of UWB technologies as defined by the regulators. Early implementations were developed by the US army around 1960, in particular for radar applications and electro-magnetic weapons. Similar implementations followed later in the public domain in the imaging, medical and construction fields, and more recently, IR has been considered for communication purposes. Although the communication potential of impulse radio has been apparent for a long time, the technical requirements for implementing an efficient impulse radio transceiver only became achievable over the last ten years. On the other hand, carrier-based radio technologies have continued to improve their performance and still meet market requirements, meaning that there has been little reason for spending time and money on developing IR technology.

During the last ten years, a combination of factors has changed the situation, leading to a renewed interest for impulse radio techniques:

- Several high-throughput applications appeared which proved to be difficult to address with existing radio technologies and low power requirements from the embedded market did not help to improve the situation. Moreover, the radio frequency (RF) spectrum was intensively used, making it difficult to get a usable broad bandwidth that would allow a reduction in the power consumption budget. The 60 GHz band usage for consumer applications is still a long-term goal.
- Wide adoption of location-based services based on GPS stimulated the demand to extend them into indoor environments.
- Emerging applications based on sensors networks, in particular in the industrial sector, created a need for ultra-low power RF communication links which have to be robust in harsh environments.
- Silicon technology was not a blocking point anymore.

Due to its obvious market impact the high data rate aspect was considered first. In 2003, Freescale demonstrated a working IR, low power and high data rate video streaming application. More recently, Nokia demonstrated an IR-based ultra-low power, high data rate download application for embedded devices, too. Nevertheless, these implementations have remained in the proof-of-concept state up to now and the vast majority of key chip vendors involved in UWB preferred an alternative implementation based a combination of OFDM and frequency hopping. This second approach is discussed in the following section.

As mentioned before, one of the earliest applications of impulse radio was radar. The use of very short pulses allowed detailed analysis of the channel impulse response which made the resolution of small size objects possible without suffering fading effects. A simplified application of this capability is the detection of the received RF wave leading edge. Combined with an accurate time base, this allows RF wave time of flight estimation, and consequently distance measurement, between the transmitter and the receiver. Compared to approaches based on signal strength in traditional RF systems like Wi-Fi or ZigBee, this technique proves to be more accurate and easier to deploy. In addition, existing integrated implementations of pulse generators proved to have lower power consumption than their carrier-based counterparts for a similar data rate. Last but not least, the huge bandwidth of IR transceivers makes them more immune to fading effects in harsh environments.

All these considerations led to the adoption of the IEEE 802.15.4a standard in 2007 [3]. This standard proposes use of IR for distance measurement and data transmission. Proprietary solutions were also proposed by "historical" companies in the field of IR.

2.1.2. Implementation Considerations

The use of pulses for carrying transmitted information opens the door to several modulation options. The first one is pulse polarity modulation, as depicted on Figure 1. Amplitude modulations other than binary ones are generally not used due to the low associated performance/complexity trade-off.

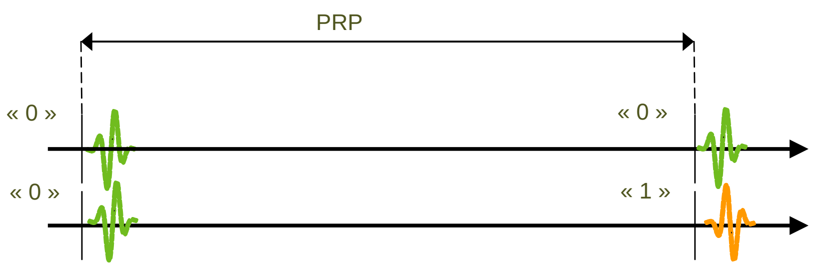


Figure 1: Polarity modulation

Another commonly considered modulation scheme is on/off keying, as depicted in Figure 2. This is commonly used for very low complexity transceivers which are unable to control the transmitted pulse shape on the transmitter side and/or detect the received signal polarity on the receiver side.

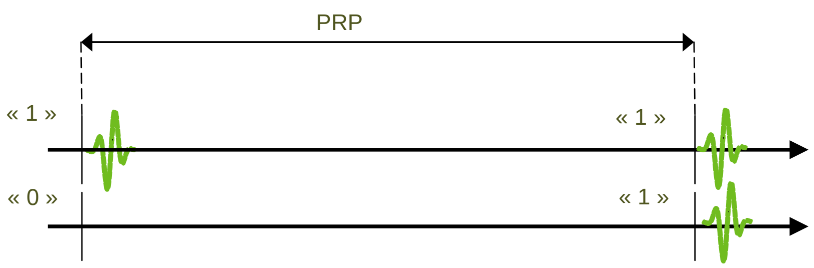


Figure 2: On/off modulation

Thanks to the temporal locality of the transmitted pulse, a specific modulation scheme can be used with impulse radio transceivers: pulse position modulation. As depicted in Figure 3, information can be carried by the temporal position of the transmitted pulse. Binary modulations are generally preferred since higher order modulation would lead to unattractive signal-to-noise ratio (SNR) requirements.

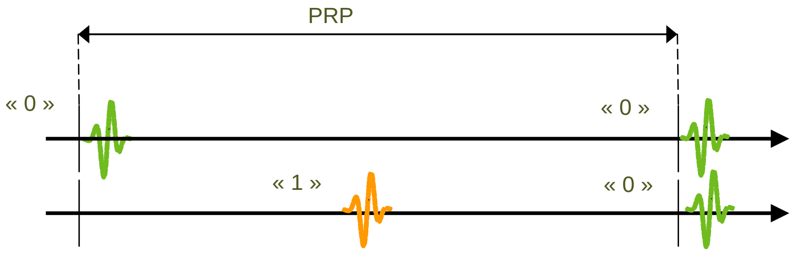


Figure 3: Position modulation

Depending on the performance/complexity trade-off, several classes of transceivers can be considered. The most efficient implementation is the coherent one (Figure 4). This implementation is also the most complex one. On the transmitter side, the pulse generator has to control the transmitted pulse shape finely and is generally able to handle its polarity. On the other side, the receiver is able to estimate the composite channel impulse response (the resulting waveform of the transmitted pulse shape affected by its interaction with the propagation channel). This estimation is then used as a comparison pattern to demodulate the received signal and all modulation schemes can be used. Correct operation of the transceiver is ensured by a good quality time base on both the transmitter and receiver sides.

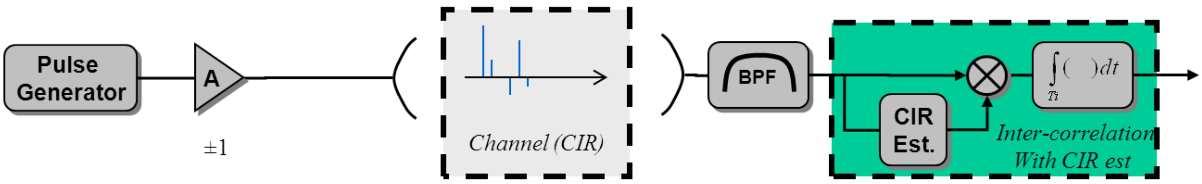


Figure 4: Coherent receiver transmission scheme

A less complex implementation is the non-coherent approach. It is generally less efficient but more attractive if cost or power consumption are crucial requirements for the envisioned application. Signal detection is based on energy detection performed on the incoming signal. This class of receiver is unable to handle pulse shape or polarity detection, and the associated pulse generator implementation is generally simplified. Time base requirements are generally relaxed, allowing the use of low cost oscillators.

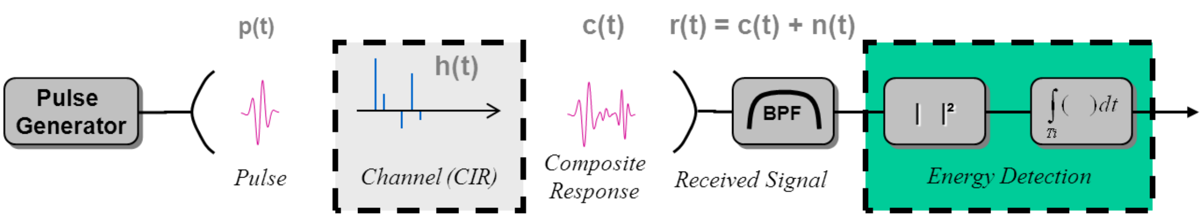


Figure 5: Non-coherent receiver transmission scheme

A third class of transceivers is also generally considered (Figure 6). This approach, called a "differentially coherent" transceiver, is based on the ability of the receiver to keep a delayed version of the incoming signal and use it as reference to be compared with the current signal. On the transmit side, a differential modulation scheme is used in order to resolve the resulting bit ambiguity. This approach is less complex than the coherent one and can generally work with low cost oscillators. This class of transceivers offers an intermediate performance/complexity/power consumption trade-off between the two previous ones.

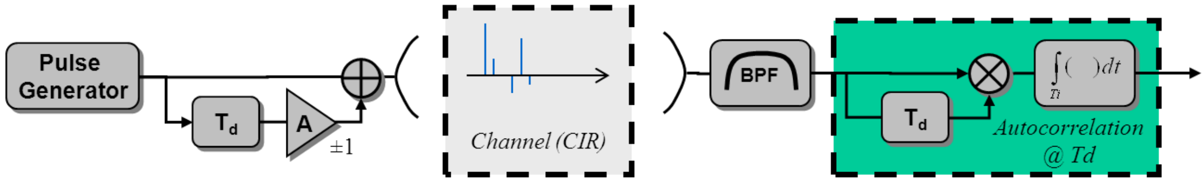


Figure 6: Differentially coherent transmission scheme

2.2. Multiband OFDM

The high data rate (HDR) MB-OFDM PHY has been defined by the WiMedia Alliance and standardised within the ECMA framework [4]. This standard has two versions, mainly differing in the supported aggregate data rates and the techniques used to achieve those rates: modulation and channel coding and the maximal allowed packet size. The following sub-sections describe some of the major PHY characteristics.

2.2.1. Transmitted Power

The UWB transmitted power level is limited under all regulations according to the maximum power density of the signal (see also Section 5 on UWB regulation). Put simply, the limitation level according to the European regulation is –41.3 dBm/MHz. Accordingly, the total transmitted power is approximately –14 dBm for a single sub-band (see Table 1 for the power level changes depending on the used time frequency codes). This regulatory limitation also forces the UWB HDR to strive for a spectrally flat transmission with minimal periodical elements which may create a stronger spectral imprint at some frequencies forcing a decrease of the total power.

2.2.2. Supported Frequencies

The HDR PHY is modulated by OFDM symbols spanning 528 MHz of contiguous bandwidth. Each allocation of 528 MHz is called a band. Every two or three bands are grouped into a band group, in which devices may access in the same transmission, according to the TFC in use (see Section 2.2.3). The WiMedia frequency plan is constructed of five orthogonal band groups (BG) and one additional overlapping band group. Most band groups are composed of three separate bands except for BG#5 which has only two bands. Figure 7 gives an explicit description of the WiMedia frequency plan including bandwidth and centre frequencies.

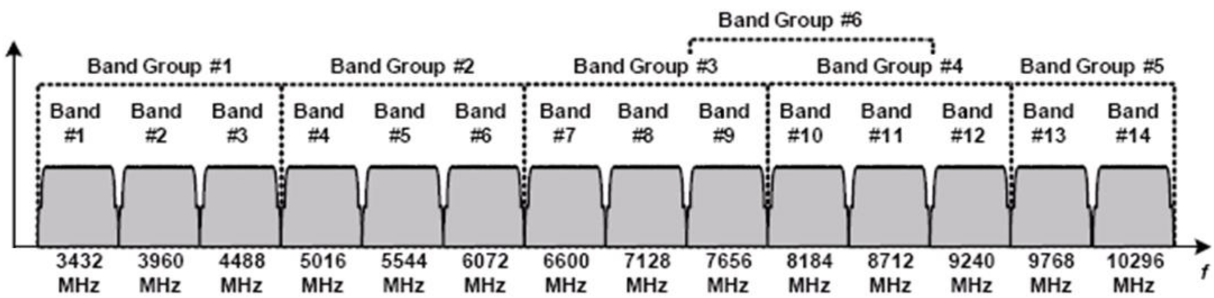


Figure 7: WiMedia frequency plan

Not all bands are permitted by the world-wide regulatory bodies (see also Section 5). Particular attention has been given to BG#1 which may only be utilised in Europe for a limited time, except for utilising band #3 with detect-and-avoid (DAA, see Section 2.5). Furthermore, most manufacturers and regulators seem to agree not to utilise BG#2 due to the high density of wireless services in that spectral band.

2.2.3. Time Frequency Codes (TFC)

The WiMedia standard allows access to a channel according to logical channels, which are defined by the band group and the time frequency code. The TFC defines the band frequency of each symbol in a repetitive group of 6 symbols, hence the multiband description of the HDR PHY and the ability to span up to 1.5 GHz of bandwidth in a single transmission. The TFCs defined by the standard are described in Table 1.

TFC	Bands used	Max. relative power	Orthogonal in group	Comments
1, 2	3	+5 dB	No	
3, 4	3	+5 dB	No	Not recommended for usage.
5, 6, 7	1	0 dB	Yes	Also called FFC (fixed frequency code).
8, 9, 10	2	+3 dB	No	Each is orthogonal to one FFC.

Table 1: WiMedia TFC

Note that Table 1 only describes the TFCs for BG#1–#4 and BG#6. Furthermore, some TFCs were defined later on (TFC 8, 9, 10) whereas others have been defined previously.

2.2.4. Data Rates: Coding and Modulation

The first version of the standard for the HDR UWB PHY supported rates of up to 480 Mbit/s achieved by using convolutional (Viterbi) channel coding. Recently, a new standard version has been released which supports additional data rates up to 1024 Mbit/s as well as an additional operational mode to some of the pre-existing data rates. All existing MB-OFDM UWB chips (including the EUWB "open platform") support only rates up to 480 Mbit/s conforming to the first version of the standard. Table 2 lists the data rates supported by both standards, their associated modulation, coding type and data rate.

Data rate (Mbit/s)	Modulation	Coding rate (R)	Code type	FDS	TDS
53.3	QPSK	1/3	Viterbi	Yes	Yes
80	QPSK	1/2	Viterbi	Yes	Yes
106.7	QPSK	1/3	Viterbi	No	Yes
160	QPSK	1/2	Viterbi/LDPC	No	Yes
200	QPSK	5/8	Viterbi/LDPC	No	Yes
320	DCM	1/2	Viterbi/LDPC	No	No
400	DCM	5/8	Viterbi/LDPC	No	No
480	DCM	3/4	Viterbi/LDPC	No	No
640	MDCM	5/8	LDPC	No	Yes
800	MDCM	1/2	LDPC	No	No
960	MDCM	5/8	LDPC	No	No
1024	MDCM	3/4	LDPC	No	No

Table 2: WiMedia data rates

The UWB tones modulation for rates above 320 Mbit/s utilises either dual carrier modulation (DCM) or modified DCM (MDCM). These modulations take advantage of the large frequency diversity provided by UWB for improved performance over multipath channels. For this purpose the same data is modulated over two tones separated by approximately 220 MHz (which means an order of magnitude above the channel coherence). The MDCM/DCM doubles the effective constellation of each tone and changes the order of the bits between the tones in a technique that prevents the same constellation points from being adjacent on both tones.

2.2.5. OFDM Symbol Mapping

The ECMA standard [4] defines the OFDM symbol mapping based on the parameters listed in Table 3. All sub-carriers have a fixed position in the OFDM modulation. Unlike most OFDM standards, the UWB standard is based on zero padding to ensure the orthogonality of the symbol tone. This technique is better in terms of maximal power density since it is not periodic compared to padding a cyclic prefix.

Parameter	Description	Value
f_S	Sampling frequency	528 MHz
N_{FFT}	Total number of sub-carriers (FFT size)	128
N_D	Number of data sub-carriers	100
N_P	Number of pilot sub-carriers	12
N_G	Number of guard sub-carriers	10
N_T	Total number of sub-carriers used	122 (= $N_D + N_P + N_G$)
Δf	Sub-carrier frequency spacing	4.125 MHz (= f_s/N_{FFT})
T_{FFT}	IFFT and FFT period	242.42 ns (Δf–1)
N_{ZPS}	Number of samples in zero-padded suffix	37
T_{ZPS}	Zero-padded suffix duration in time	70.08 ns (= N_{ZPS}/f_s)
T_{Sym}	Symbol interval	312.5 ns (= $T_{FFT} + T_{ZPS}$)
F_{Sym}	Symbol rate	3.2 MHz (= T_{Sym} – 1)
N_{Sym}	Total number of samples per symbol	165 (= $N_{FFT} + N_{ZPS}$)

Table 3: OFDM symbol mapping

2.2.6. Frame Structure

The MB-OFDM specification defines the frame structure as listed in Table 4. Two preambles are defined: a standard and a burst preamble. The burst preamble shall only be used in burst mode when a burst of packets is transmitted, which are separated by a minimum inter-frame separation time:

- For data rates up to 200 Mbit/s all the packets in the burst shall use the standard preamble;
- For data rates above 200 Mbit/s the first packet shall use the standard preamble whereas the remaining packets may use either the standard preamble or the burst preamble.

Parameter	Description	Value
N_{pf}	Number of symbols in the packet/frame synchronisation sequence	Standard preamble: 24 Burst preamble: 12
T_{pf}	Duration of the packet/frame synchronisation sequence	Standard preamble: 7.5 µs Burst preamble: 3.75 µs
N_{ce}	Number of symbols in the channel estimation sequence	6
T_{ce}	Duration of the channel estimation sequence	1.875 µs
N_{sync}	Number of symbols in the preamble	Standard preamble: 30, Burst preamble: 18
T_{sync}	Duration of the preamble	Standard preamble: 9.375 µs Burst preamble: 5.625 µs
N_{hdr}	Number of symbols in the PLCP header	12
T_{hdr}	Duration of the PLCP header	3.75 µs
N_{frame}	Number of symbols in the PSDU	$6 \cdot \left\lceil \frac{8 \cdot \text{Information\_Lenght} + 38}{N_{IBP6S}} \right\rceil$
T_{frame}	Duration for the PSDU	$6 \cdot \left\lceil \frac{8 \cdot \text{Information\_Lenght} + 38}{N_{IBP6S}} \right\rceil \cdot T_{Sym}$
N_{packet}	Total number of symbols in the packet	$N_{sync} + N_{hdr} + N_{frame}$
T_{packet}	Duration of the packet	$(N_{sync} + N_{hdr} + N_{frame}) \cdot T_{Sym}$

Table 4: OFDM frame parameters

2.2.7. Ranging and Location Awareness

The WiMedia PHY specifications [4],[5] define an optional measurement for ranging and location awareness based on propagation delay measurements that are intended to achieve an accuracy of ±60 cm in line-of-sight (LOS) conditions. The timing reference point is defined as the beginning of the first channel estimation symbol in the PHY convergence protocol (PLCP) preamble.

Support for range measurement in the PHY is based on counting the arrival time and storing it in a register (see Section 3.3). Such a counter may be clocked by a frequency source of 528 MHz to achieve a 56.8 cm ranging uncertainty. To provide increased precision, optional implementations may clock bit 2 at 1056 MHz (28.4 cm), bit 1 at 2112 MHz (14.2 cm), or clock bit 0 at 4224 MHz (7.1 cm).

2.3. Un-conventional UWB

According to the definition of UWB, several physical layers are considered to be UWB. The two major physical layers that have been standardised are the MB-OFDM waveform and the impulse radio waveform. However, other equipment exists which is using less conventional waveforms like chirp and frequency hopping waveforms.

The principle of a frequency hopping UWB (FH-UWB) waveform is to transmit fixed frequency hops across a very broad frequency band. One existing implementation consists of frequency hops of 20 MHz over a 1.25 GHz bandwidth. The FH-UWB solution, as a hopping narrow-band receiver, will only suffer interference from one source of moderate bandwidth in two or three adjacent hop bands out of 124.

Another un-conventional waveform called UWB-CSS (chirp spread spectrum) has been defined in IEEE 802.15.4a standard. The CSS waveform is authorised in the 2.45 GHz ISM band with 80 MHz of bandwidth and a maximum transmit power of 100 mW. The data to be transmitted are modulated on the slope (the chirp) according to a differentially bi-orthogonal (DBO) 8 M-ary modulation (8 states). The maximum capacity is 2 Mbit/s. The chirps can be sent sequentially, but can also be superimposed due to the orthogonal properties of the successive slopes in order to increase aggregate rates. Distance measurement between two CSS nodes is achieved by common methods of two-way ranging or symmetrical double sided two-way-ranging. The advantage of this technique is that it is easily adapted to the available frequency bandwidth from a minimum of 20 MHz to several hundreds of megahertz.

2.4. MIMO-UWB Systems

Multiple-input multiple-output (MIMO) systems are widely recognised as viable solution to provide enhanced quality of service and highest peak data rates of emerging UWB applications for short-range wireless communications. The deployment of multiple antennas on both sides of the link is a promising technique to extend the link reliability or coverage of UWB systems via spatial diversity as well as to increase throughput, which is limited by the channel excess delay, via spatial multiplexing [8]. In this section MIMO-UWB approaches to obtain spatial diversity (SD) and spatial multiplexing (SM) gains are shortly presented with applications to UWB communications.

By opening independent spatial pipes, SM approaches let the data rate grow linearly with a slope equal to the minimum number of transmit and receive antennas without occupying additional bandwidth resources. Full-rate multiplexing allows for linear increase in spectral efficiency that has motivated the adoption of MIMO in various mobile, WLAN and WPAN standards, e.g. HSDPA, LTE, IEEE 802.11n and high rate modes of IEEE 802.16. The success of a practical SM technique for UWB wireless communications depends on the realisations of the specific MIMO-UWB channel matrices that have some unique features [9], whereas SD is usually deployed when the receiver must operate under low signal-to-noise ratios.

The SD methods for UWB can be roughly divided into two categories, namely real and complex SD coding approaches. The real SD coding methods are used in pulsed UWB transceivers [10],[11] whereas complex SD coding approaches are used in carrier-based orthogonal frequency division multiplexing UWB systems [12],[13]. An important advantage of the real SD coding methods with pulsed UWB systems is the resulting low complexity while still being able of achieving high data rates. One motivation is to allow for non-coherent receiver processing typically used in single antenna systems to avoid complicated phase recovery and energy capture from numerous resolvable multipaths [10],[14]. However, the interference mitigation with complex SD combined with OFDM can be more efficient in case of severe intersymbol or multi-user interference. Further, if real non-coherent SD techniques with pulsed UWB are deployed, it becomes crucial to avoid any type of non-white interference by signal design. The SD coding approaches can be further divided into block and trellis coding methods. A significant design aspect with SD approaches for extending the coverage of UWB applications is being able to exploit the available gains from soft-decision SD decoding [15].

In EUWB a hybrid system concept was developed featuring a MATLAB data path simulator and an experimental offline MIMO-UWB test-bed that enables the evaluation and verification of various multiplexing and diversity schemes under realistic propagation constraints. Due to the induced higher complexity of the applied MIMO signal processing at the transmitter and/or receiver, major challenge is the design of low-complexity MIMO diversity and SM decoding schemes and the development of corresponding architectures being able to support the harsh throughput, latency and power requirements of UWB applications. Finding the trade-offs between achievable performance gains and complexity of the detection schemes is a prerequisite for future implementation of the proposed solutions. Therefore, the design of MIMO-UWB systems implementing SD or SM is different and requires intensive research on topics like signalling trade-offs (diversity versus multiplexing gains), joint interference mitigation and link optimisation, suitable architectures and UWB antenna arrays.

2.5. Cognitive UWB

Nowadays, the UWB technology provides perfect opportunities for broadband wireless communications. In fact, the frequency band for UWB has been already fixed by the regulatory and licensing bodies. It was approved, however, that the current spectrum capabilities are not efficiently utilised in time and space dimensions [16], especially at frequencies beyond 3 GHz. This results in the appearance of “white spaces”, i.e. fixed frequencies which are not used at the moment but which, however, could be accessed by unlicensed users. The problem of efficient spectrum utilisation therefore appears to be of vital importance.

Cognitive radio (CR), a concept proposed by Mitola [17], seems to be the most encouraging paradigm to address the spectrum underutilisation issue. CR supports intelligent interaction between a wireless communication system and the environment in which it operates [18]. This interaction is performed by adopting spectrum sensing, spectrum management and spectrum access mechanisms. The spectrum sensing mechanism [19],[20] is one of the crucial functionalities of the CR to learn the radio environment which performs periodical scanning of a targeted frequency band to determine its occupancy by licensed (primary) users. Besides, CR needs to sense the nearby bands which can be potentially used if the current band is being requested by a primary user (PU). Moreover, regulatory bodies expect CR nodes to detect the PU in the environment with a very high probability which becomes a hard task considering the temporal behaviour of the PU [21]. Spectrum management performs the analysis of spectrum sensing information and evaluates the system parameters to determine whether they can be adjusted for spectrum access or not. Besides, the final decision on spectrum access can be made upon statistical experience gained by the system through the use of self-education capability hence giving rise to dynamic spectrum access (DSA) systems [22], [23]. DSA using CR technology are developed using various game theoretical approaches and power controlling mechanisms [22]. The spectrum access efficiency is further enhanced when CR nodes localise the PU in the radio environment and hence create a radio environment map (REM) of its vicinity. Localisation and REM creation therefore are also considered to be enabling technologies of CR for DSA [24].

From the above one can define that cognitive UWB radio (CUWBR) is an intelligent wireless communication system based on UWB technology with self-adaptation to environment capability [25],[26]. Due to its unique MB-OFDM-based architecture, UWB radios are considered to be a potential candidate for the application of CR technology.

Due to its large frequency span, UWB devices (also referred to as secondary users (SU)) can interfere with other wireless communication technologies or services, e.g. UMTS, GPS, WiMAX, satellite DTV [27],[28],[29]. Basically, CR uses two approaches which provide coexistence among these communication technologies and services [30]. Therefore, in order to perform DSA, DAA mechanisms [31] are utilised to ensure no interference is caused to the PU. The DAA mechanism is a CR technique which provides spectrum sharing capabilities for PUs and SUs by allowing a SU to occupy the spectral band while a PU does not use it. However, in the case of detecting the transmitting PU, the SU must avoid interference to PU, e.g. by stopping its transmission, decreasing the transmitted power or changing the frequency band.

It is expected that CR technology will play a key role in spectrum sharing for the next generation wireless communications systems. Using its intelligent capability, a mobile device which supports various communications technologies (UWB, WiMAX, TV) can easily indentify the status of the wireless access networks and make a proper decision which network to connect to. The service provider will be able to optimise radio resources for a given number of mobile devices and to satisfy their requirements.

However, there are a number of issues associated to CR which have to be addressed in the future. For instance, coordinated and cooperative spectrum sensing is required in a multi-user network to address the problem of the multiple licensed and unlicensed networks' coexistence. Learning algorithms from artificial intelligence can improve the quality of spectrum analysis by characterising it with performance metrics, e.g. bit error rate (BER), signal-to-noise ratio (SNR), spectrum utilisation efficiency (SUE) and spatio-temporal availability of "white spaces". The game theory paradigm is typically applied to tackle the spectrum access decision problem. Based on the utility obtained during the game, a user in multi-user/multiple networks environment makes a proper decision on spectrum access. In fact, the game model becomes complicated if a secondary user has multiple objectives.

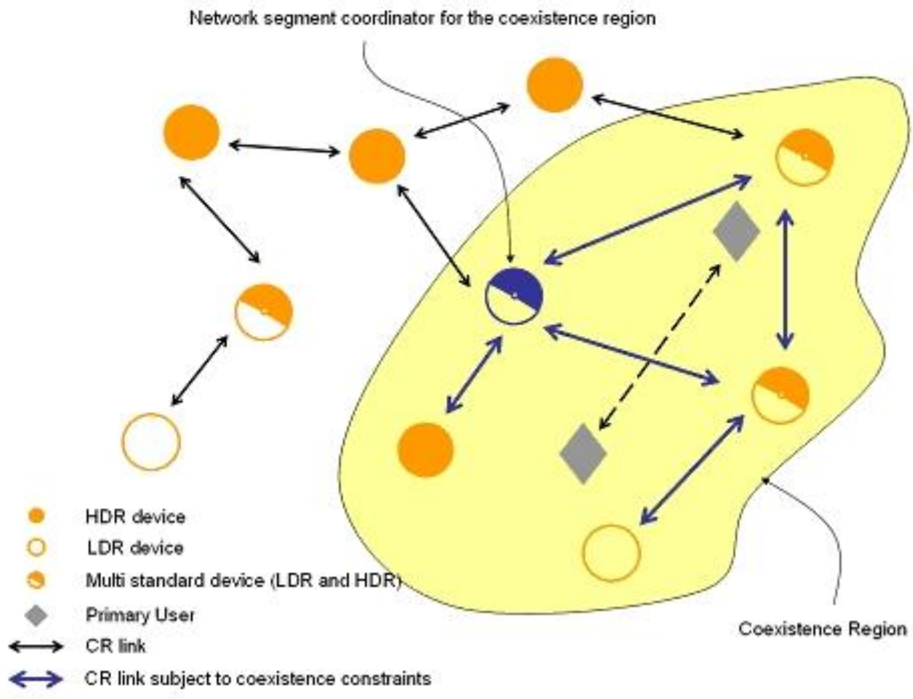


Figure 8: Example of a network using CR

3. UWB Technology Platforms

3.1. EUWB Low Data Rate Platform

3.1.1. Features of the EUWB LDR Physical Layer (PHY)

The PHY layer of the EUWB LDR platform is an impulse radio transceiver based on the differentially coherent approach discussed in the previous section. A DBPSK modulation combined with spectrum spreading using PN sequences was chosen to allow very simple signal processing on the receiver side. The framing scheme was inspired by IEEE 802.15.4a [3].

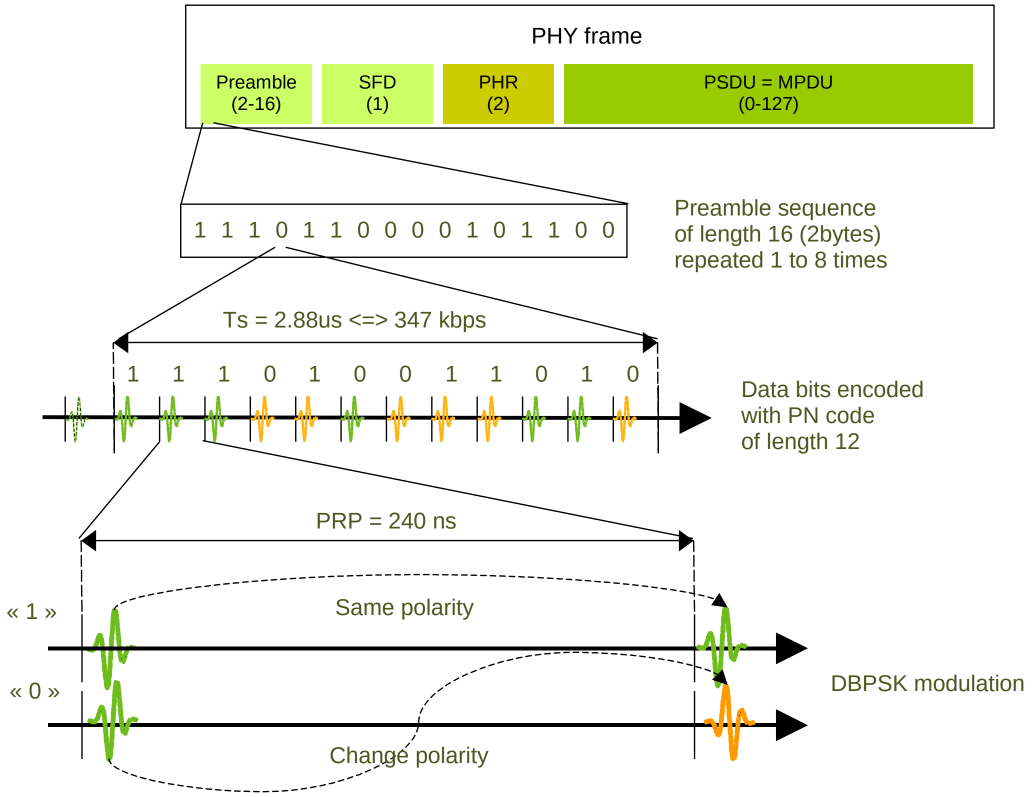


Figure 9: LDR platform framing and modulation scheme

Demodulation is performed using differential correlation between the incoming signal corresponding to the current data symbol and the previous one. Signal processing tasks are split into a set of independent “contexts” computed sequentially. Each context is related to a particular chunk of incoming samples and processed as independently as possible. Depending on the kind of data processing, the size of the signal chunk and the number of accumulations is adapted:

- For preamble detection, a chunk of about 8 ns of incoming signal combined with a long PN sequence (hundreds of pulses) is used.
- For demodulation, the same chunk size is used, however with a shorter PN sequence (typically between 10 and 30 pulses).
- For the fine resolution ranging, shorter chunks are used, typically 1 ns, and a huge number of pulses is required in order to extract the first path from noise, typically some thousands of pulses.

It can be noticed that the preamble detection is performed on chunks of 8 ns of the incoming signal. Demodulation is then performed only on signal chunks for which a detection event occurred, acting like a RAKE receiver.

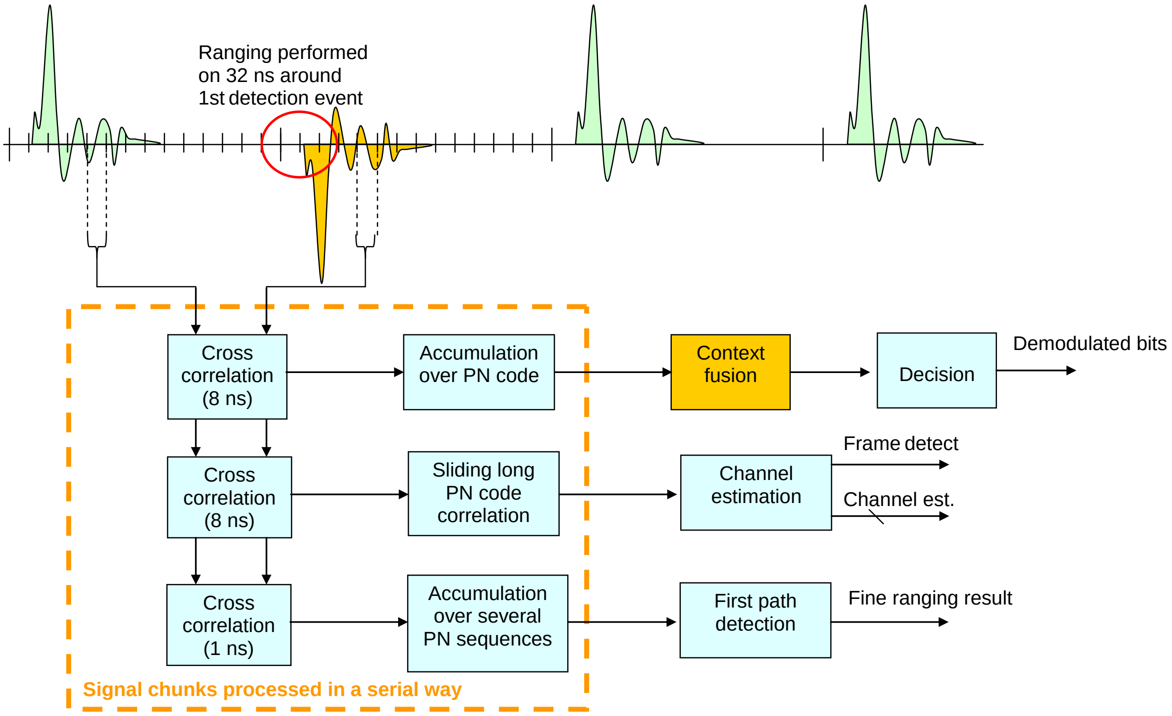


Figure 10: Received signal processing overview

The RF part on the receiver is simply composed of an amplification chain followed by a high speed analogue-to-digital converter (ADC). The proposed approach consists in sampling the incoming signal on 1.5 bit to reduce the power consumption and to use the UWB channel diversity to compensate the loss of amplitude information. It was shown that considering the operating conditions envisioned for UWB signals, in particular SNR, the loss on the link budget is asymptotically marginal.

The presence of signal information (called “energy bit”) is added to the already available polarity information. We obtain a 3-level signal {-1; 0; 1}, also called “1.5 bit” signal. The first assumption driving this idea is that the main contribution to the noise comes from the electronics itself instead of the channel. Thus, the objective was to design a circuit as immune as possible to its own noise. The principle is to consider that if the same signal goes through the circuit following separate paths, then they will be affected by uncorrelated noises.

The gain required to sample UWB signals using energy detection techniques is so high that it would be very difficult to design stable linear amplification chains. Thus, the idea here relies on performing energy detection on signals extremely distorted by the amplification chain. The principle is to perform the first part of the amplification using an analogue amplification chain thanks to the use of low noise amplifiers; and the remaining gain is obtained by saturating the signal over one bit using cascaded digital inverters. Energy detection is simply obtained by a digital comparison between the two chains performed by a XNOR gate. After remapping and multiplication of one branch output with the XNOR output, we obtain the 1.5 bit signal.

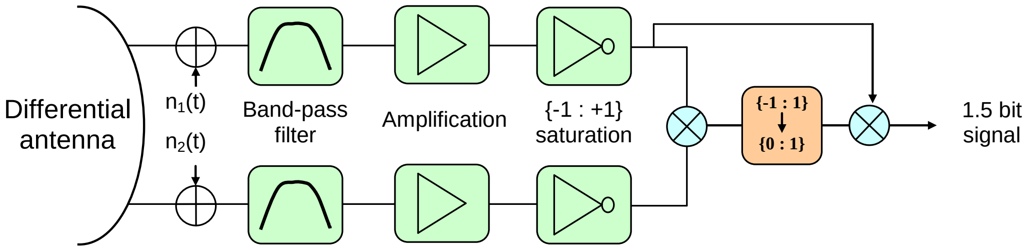


Figure 11: 1.5 bit conversion principle

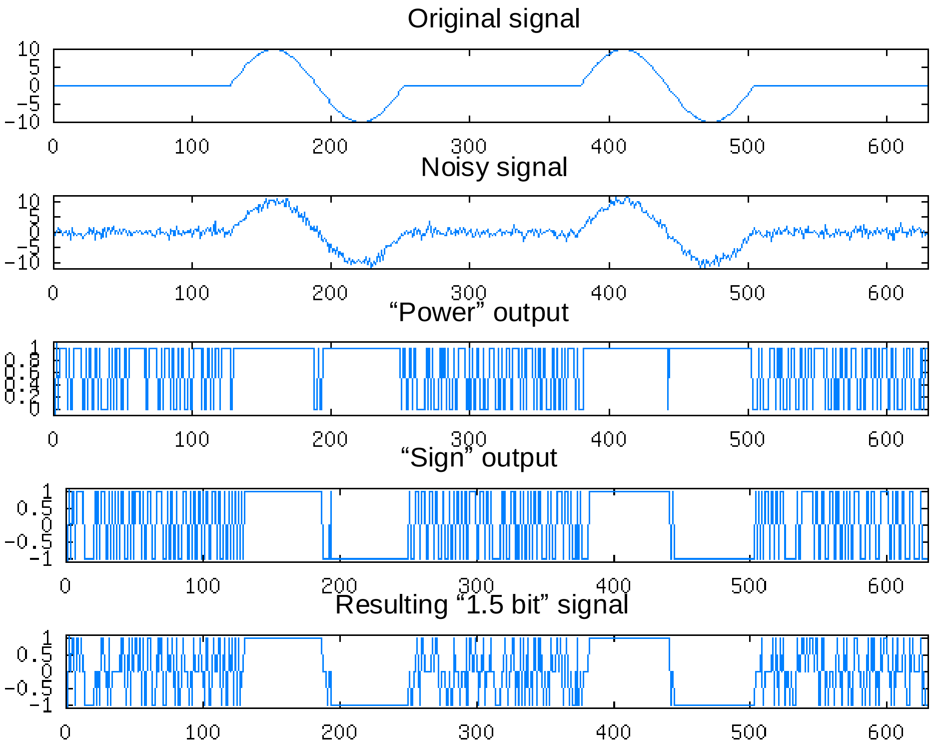


Figure 12: 1.5 bit conversion principle (corresponding waveforms)

This 3-level signal allows handling several kinds of modulation:

- On/off keying based on "energy" output;
- Pulse position modulation (PPM) based on energy output;
- Polarity-based modulations based on the complete 1.5 bit output.

In the proposed transceiver, DBPSK and 2-PPM were implemented for performance comparison.

On the transmission side, the operating principle of the pulse generator is based on a samples memory coupled with a fast digital-to-analogue converter (DAC) running at 9 gigasamples per second. When triggered, the DAC runs during 128 cycles. For IEEE 802.15.4a compliance, a set of 15 predefined pulse shapes can be stored in the memory, allowing burst scrambling.

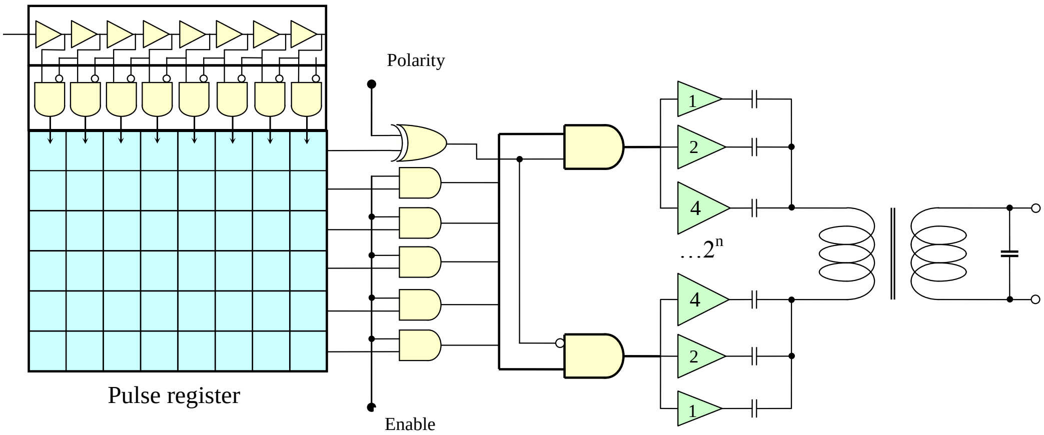


Figure 13: Pulse generator architecture

3.1.2. Features of the EUWB LDR Media Access Control (MAC) Layer

The MAC layer developed for the EUWB low data rate location tracking (LDR-LT) platform is based on a time division multiple access (TDMA) access scheme. This MAC layer is different from the MAC layer proposed in IEEE 802.15.4a [3]. Indeed, IEEE 802.15.4a MAC layer is based on Aloha and can have two modes: one which is a beacon-enabled and a second which is a non-beacon mode.

The EUWB MAC layer is based on the IEEE 802.15.4 MAC layer with some modifications in order to allow relaying and to guarantee latency. It has only one mode which uses beacons and has a contention-free access period and a contention access period. It allows to have various network topologies and to have a TDMA access scheme. The MAC layer has been designed in order to allow distance measurement between all nodes (also in an anchor free mode) and to allow data transmission if not all slots are used for localisation depending on the distance measurement rate.

The beacons allow to synchronise the network and to give a temporal reference. The IEEE 802.15.4 super frame has been modified in order to have a contention-free period for data and distance measurement exchanges. In order to increase the range of the whole network, a mesh network has been defined. After simulation studies carried out in PULSERS, it has been demonstrated that the centralised mesh network architecture was suitable for most applications.

The MAC layer is a centralised mesh network in which a node (the piconet coordinator), is responsible for the radio resources allocation and for the network synchronisation. For this kind of network the following functions are needed:

- The mesh network discovery: A node is elected as a coordinator. All nodes in the network have to be associated to the coordinator or to their parent node.
- Relaying: The relaying function has to relay beacons and data.
- Resources allocation: The resource allocation has to take into account all links in the network as well as relaying.

Additionally, the MAC supports two-way and three-way ranging procedures.

Mesh Network Discovery

In the scope of EUWB, two modes have been defined for the coordinator:

- In the first mode, the coordinator is fixed and associated to the GUI which is embedded on a PC. All information are collected in the coordinator and displayed on the PC.
- In the second mode, the coordinator is dynamically chosen. When a node does not receive any beacons after a time out, it is declared as the coordinator of the network. The time out value is an important parameter in order to have two coordinators for the same network.

In the mesh network tree, the coordinator is on the top of the tree. All other nodes in the network are defined by their tree level (STL). In order to avoid delays the maximum number of tree levels is set to five. Figure 14 provides an example of a mesh network with three relays for node K.

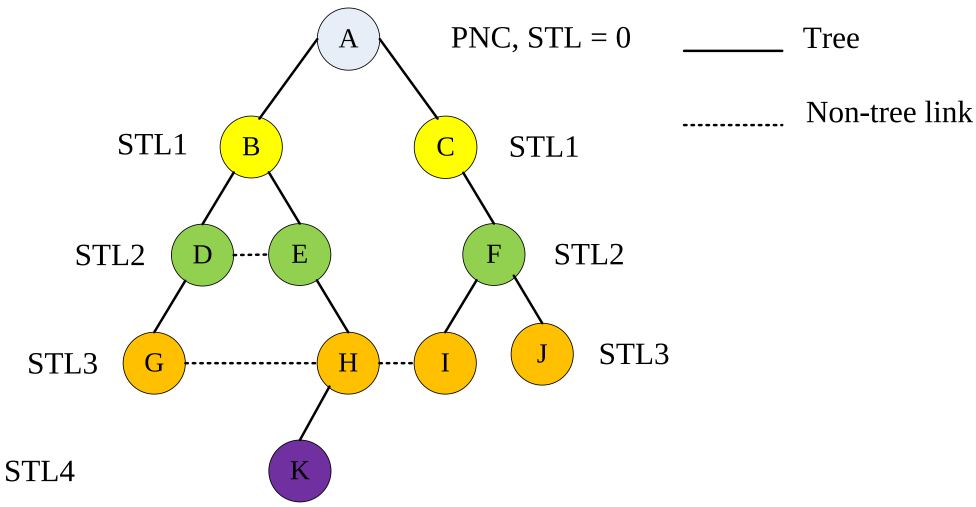


Figure 14: Example of a mesh network

Relaying Functionality

As stated before, all nodes have to be associated to the coordinator. If the node is not on STL1, it cannot receive the beacons sent by the PNC. For that reason, the beacons are relayed over the whole network. Some provisions have been taken in the super frame structure in order to relay the beacons.

Figure 15 provides an example of the MAC layer super frame with the beacon period, the topology management period (for hello frames) and the CFP slot which is used for data and ranging and the GTS request period. The GTS request period is used by nodes in order to request resources from the coordinator depending on their traffic and ranging rates. The contention access period (CAP) is used only during the association process. The beacon period is composed of several beacon slots. Indeed, the first slot corresponds to the beacon sent by the coordinator of the network. The following beacon slots correspond to beacon slots sent by other nodes in the network which are relaying the beacons.

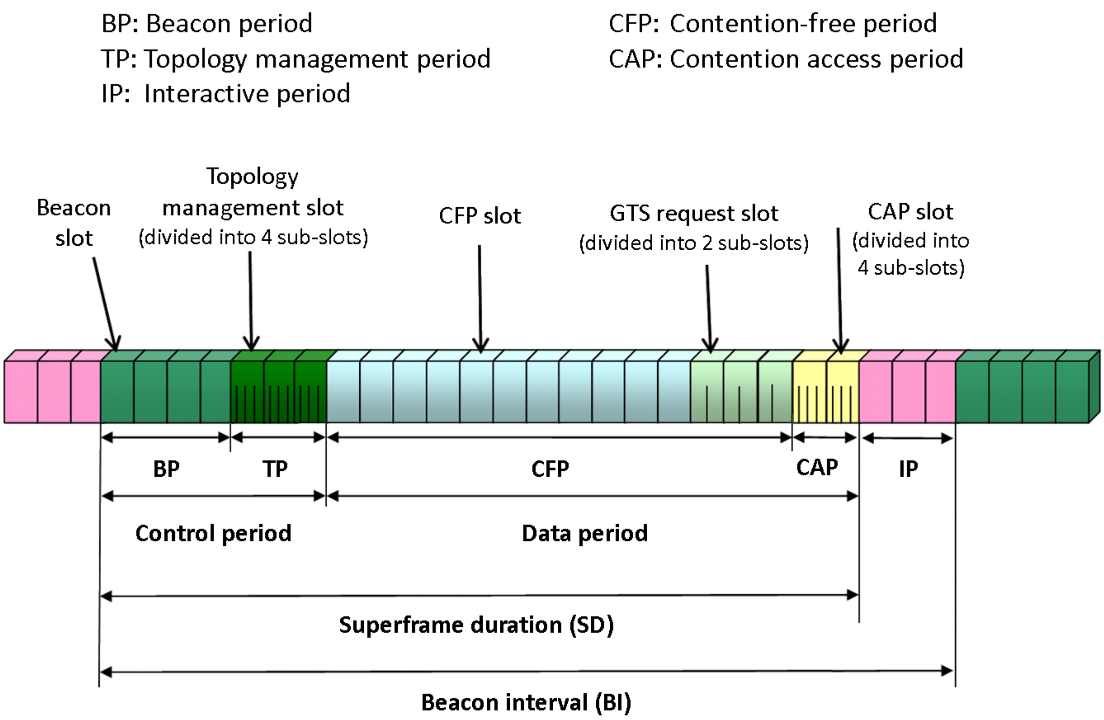


Figure 15: Super frame structure of the EUWB MAC

It has to be noticed that the relaying procedure is performed at the MAC level. Indeed, when the relaying is performed at the MAC level it is more efficient for data that have been fragmented as only the missing fragment is retransmitted in case of failure. This mechanism is necessary to reduce the transmission delay.

Resource Allocation

The resource allocations are made for the whole route for data transfer. When a node has data to transfer, it requests resources from the coordinator through GTS request indicating the source address and the destination address. The coordinator allocates resources for each link between the source and the destination. The piconet coordinator (PNC) has the knowledge of the whole topology and routing. The PNC will verify in the global routing table if there are relays between the source and the destination. As there are some relays it will allocate the resources for each link. Indeed, the relaying nodes do not make any resource request for the data they have to relay. For ranging slots, the allocation is made only with the one hop neighbours as the distance measurements are performed only with direct neighbours.

Distance Measurement Procedure

Distance measurement between two nodes can be obtained through two modes: a two way ranging mode for which only two messages are exchanged between the nodes performing the ranging and a three way ranging mode for which three messages are exchanged between nodes. The three way ranging mode is used in order to avoid clock drifts between the devices. However, tests performed in the scope of EUWB showed that two way ranging provided good results as the clocks are really stable. A two way ranging procedure seems so sufficient. In the implemented version of the MAC layer, one slot is needed to send a ranging request and another slot is needed for the ranging response. However, some studies have shown that it would be possible to perform the ranging request and the ranging response in one slot. This would allow to increase the ranging rate in the network and thus to provide more confidence to the localisation results depending on the velocity.

3.2. EUWB High Data Rate Platform

3.2.1. Features of the EUWB HDR Physical Layer (PHY)

The PHY of the EUWB “open HDR platform” consists of a development kit based on the WISAIR WSR602 chip (Figure 16), Wisair’s 2nd generation CMOS WUSB single chip. The WSR602 chip provides a full WUSB system solution on a single CMOS chip, including the RF, the PHY, the WiMedia MAC, the WUSB MAC and connectivity through multiple interfaces (USB, PCI Express/WHCI, etc.). The PHY of the open platform interfaces with the PHY of the WSR602 at the MAC/PHY IF and is controlled by the HDR MAC developed within EUWB.

The PHY of the WSR602 is WiMedia-certified and covers the frequency range of the WiMedia band groups BG#1, BG#3, BG#4 and BG#6 upper bands (3.1 GHz to 9.5 GHz). According to the first version of the ECMA specification [4], a data rate of up to 480 Mbit/s with convolutional (Viterbi) channel coding is supported (Table 2). The PHY also supports a ranging feature beyond the standard, with extended MAC interface as defined within the EUWB project.

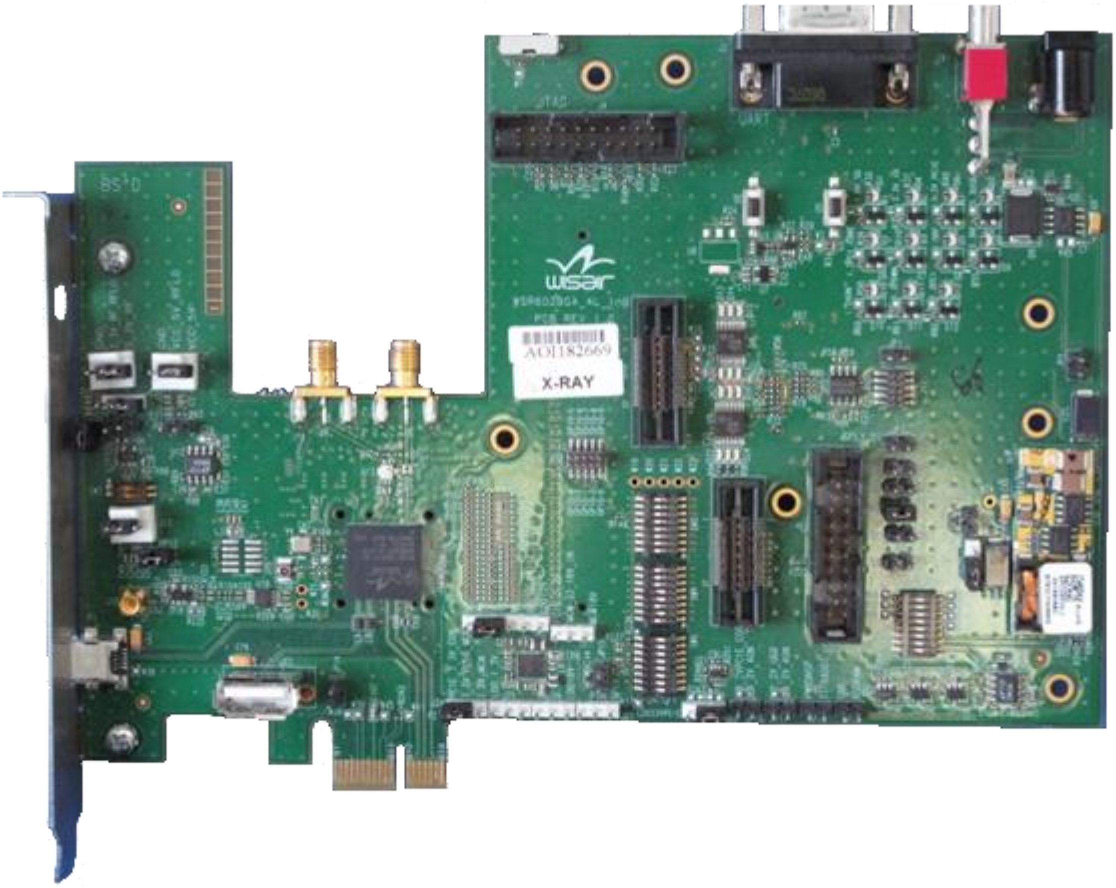


Figure 16: The WISAIR 612 development board

3.2.2. Features of the EUWB HDR Media Access Control Layer (MAC)

MAC Introduction

The MAC core has been designed and implemented with an architectural focus on functional completeness and performance. The MAC sub-layer requires the following features provided by the PHY:

- Frame transmission in both single frame and burst mode;
- Frame reception for both single frame and burst mode transmission;
- PLCP header error indication for both PHY and MAC header structures;
- Clear channel assessment for estimation of medium activity;
- Range measurement timestamps if MAC range measurement is supported.

The exchange of parameters between the MAC sub-layer and the PHY makes the frame transmission and reception possible. In single frame transmission the MAC sub-layer fully controls the frame timing, while in burst mode transmission the MAC sub-layer has only the control of the first frame timing and the PHY provides accurate timing for the remaining frames in the burst.

High Level MAC Architecture and Partitioning

The MAC is divided into three parts:

- The hardware MAC (HMAC) which provides procedures to manage small-scale transactions on the medium;
- The lower MAC (LMAC) which manages multiple streams of frames to be sent to and received from the medium, together with immediate control of the HMAC;
- The upper MAC (UMAC) which manages protocol exchanges with peer MAC entities.

The UMAC exposes the MLME-SAP and the MAC-SAP. The functionality is specified in reference [4] with some exceptions.

The natural interface between the UMAC and the LMAC is internal, in the sense that they require access to common data structures. This is necessary for efficient communication and in order to avoid duplication. Moreover, they share access to common helper functions, for example for access to hardware registers.

MAC Digital Hardware

The MAC hardware sub-system is described in Figure 17. This block diagram identifies all core hardware components and peripherals in the MAC hardware design.

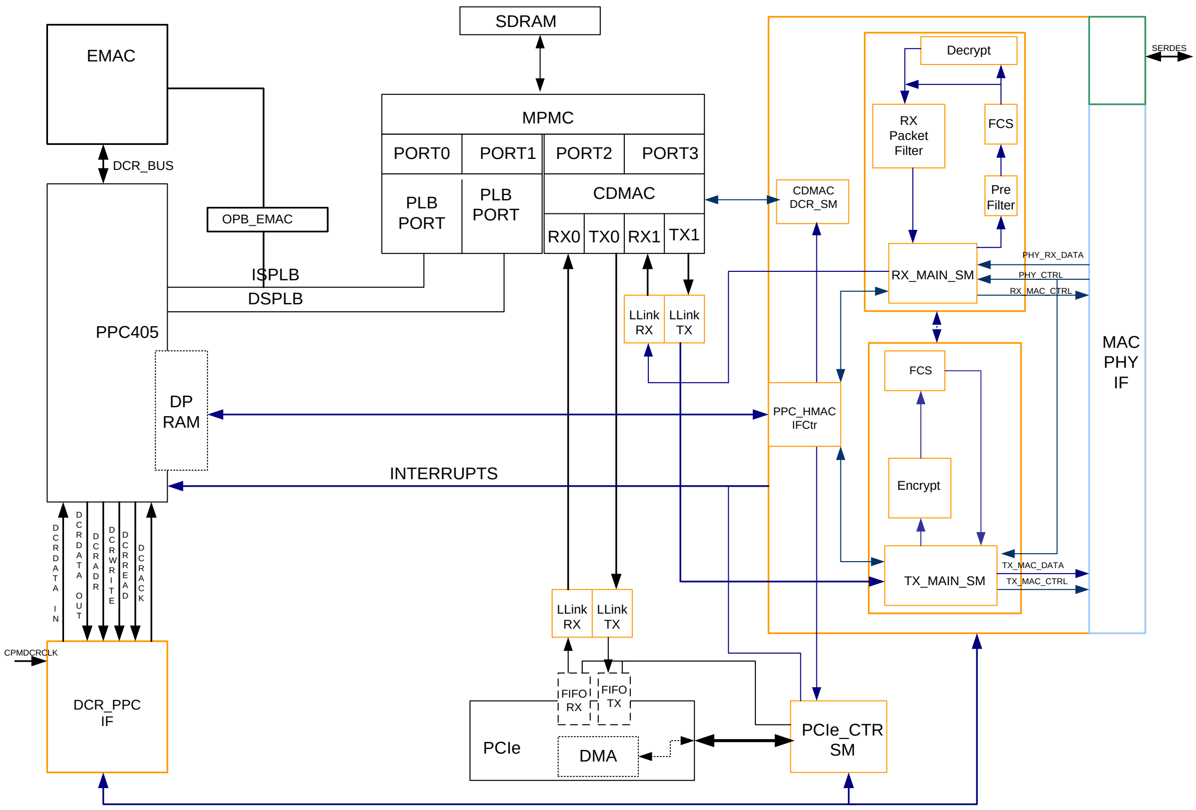


Figure 17: HDR MAC digital hardware block diagram

The HMAC is a VHDL design that provides the hardware sub-system that compliments an embedded software design. The HMAC and software sub-system implement a WiMedia MAC that supports an ECMA-369 MAC/PHY interface [5]. Figure 18 provides a simplified overview on the HMAC sub-system.

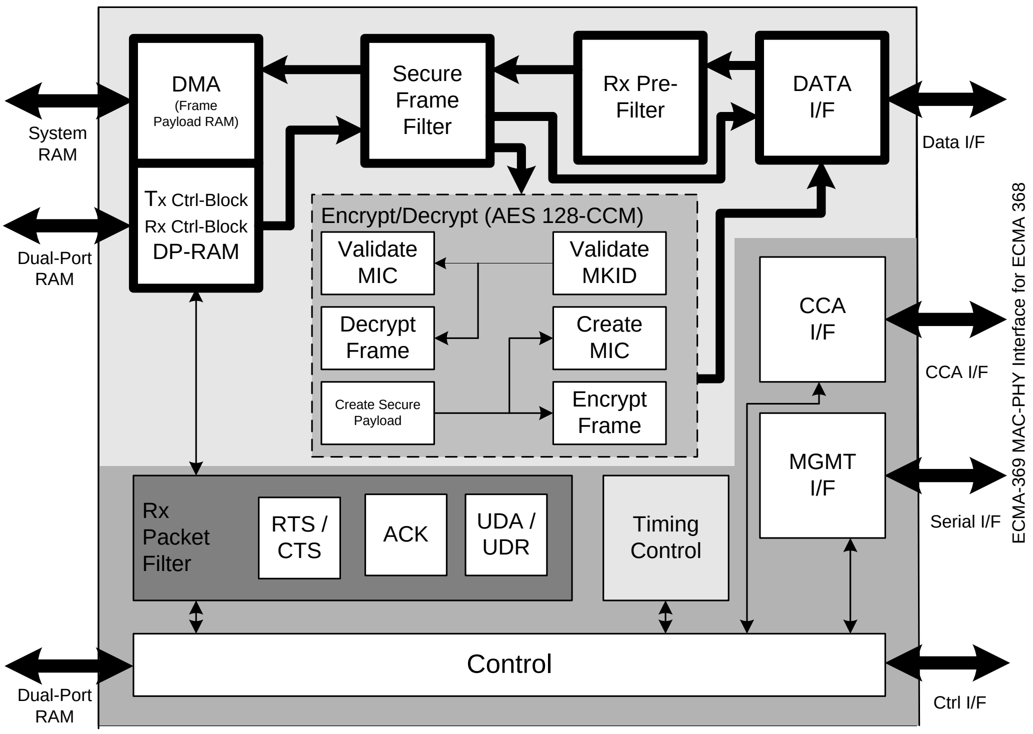


Figure 18: Overview of the HDR HMAC core

The HMAC core performs real-time processing of transmitting and receiving data and controls interfaces between the software sub-system and the physical interface.

High-level Features

The key capabilities of the MAC core that will be available on the HDR open platform are listed in Table 5.

Attribute	Supported (Yes/No)
PCA	No
Hard DRP	Yes
Soft DRP	Yes
Block ack.	No
Explicit DRP negotiation	Yes
Hibernation anchor	No
Probe	No
Link feedback	Yes
Range measurement	Yes
Security levels M0	Yes
Security levels M1	No
Security levels M2	No

Table 5: MAC core high-level features supported by HDR open platform

3.3. Radio Ranging with UWB

UWB technology offers the potential of achieving high ranging accuracy through signal time-of-arrival (ToA) measurements even in harsh environments due to its ability to resolve multipath and penetrate obstacles [32],[33]. It is expected that the advantages of UWB-based localisation will be exploited in future high-definition situation-aware systems that utilise coexisting networks of sensors, controllers and peripheral devices. The IEEE 802.15.4a is the first UWB-based standard for low-rate WPAN with localisation capability [3]; ranging accuracy is expected to be one meter or sub-meter at least 90% of the time.

3.3.1. Theoretical Limits in Ideal Propagation Conditions

In order to better understand why UWB signals are of particular interest for accurate ranging through the estimation of signal ToA, it is worthwhile to identify which fundamental signal parameters dominate ranging accuracy under ideal conditions. If a scenario is considered in which a pulse $p(t)$ is transmitted in an AWGN channel (in the absence of other error sources) then the received signal can be written as

$$r(t) = \sqrt{E_p}p(t-\tau) + n(t) \tag{3.1}$$

where $n(t)$ is the AWGN with power spectral density N_0 and τ is the delay (ToA) we want to estimate based on the noisy observation of the received signal. Under this model, ToA estimation is a classical non-linear parameter estimation problem where the performance of any unbiased estimator is bounded by the Cramér-Rao bound (CRB) given by

$$CRB = \frac{N_0/2}{(2\pi)^2 E_p \beta^2} = \frac{1}{8\pi^2\beta^2 SNR} \tag{3.2}$$

where $SNR = E_p/N_0$ and the parameter β^2 represents the second moment of the spectrum $P(f)$ of $p(t)$, also often referred to as effective bandwidth, that is

$$\beta = \frac{\int_{-\infty}^{\infty} f^2 |P(f)|^2 df}{\int_{-\infty}^{\infty} |P(f)|^2 df}. \tag{3.3}$$

Thus, the best achievable accuracy of a range estimate $\hat{d}$ derived from ToA estimation satisfies the following inequality

$$\vee\{\hat{d}\} \geq \frac{c^2}{8\pi^2 \beta^2 SNR} \tag{3.4}$$

with c the speed of light. Notice that the lower bound in (3.4) decreases with both SNR and the constant β^2 which depends on the shape of the pulse. This reveals that signals with high power and broad transmission bandwidth (and hence UWB) are beneficial for ranging.

3.3.2. Sources of Errors in Ranging

Ranging techniques based on ToA estimation of the first arriving signal path are mainly affected by noise, multipath components, obstacles, interference and clock drift [32]. In particular, non-line-of-sight (NLOS) channel conditions represent the most critical situation. For example, with reference to Figure 19, RX_2 is in NLOS condition but the direct path (DP) is not completely obstructed. The propagation time of the signal depends not only upon the travelled distance, but also on the encountered materials. Since the propagation of electromagnetic waves is slower in some materials compared to air the signal arrives with excess delay, thereby introducing a positive bias in the range estimate even in the presence of perfect ToA estimation. An important observation is that the effect of DP blockage (RX_3) and DP excess delay is the same: They both add a positive bias to the range estimate. In dense multipath channels the first path is often not the strongest, making estimation of the ToA challenging. Several ToA estimators as well as ranging/localisation schemes have been proposed in the literature to deal with these challenges [32].

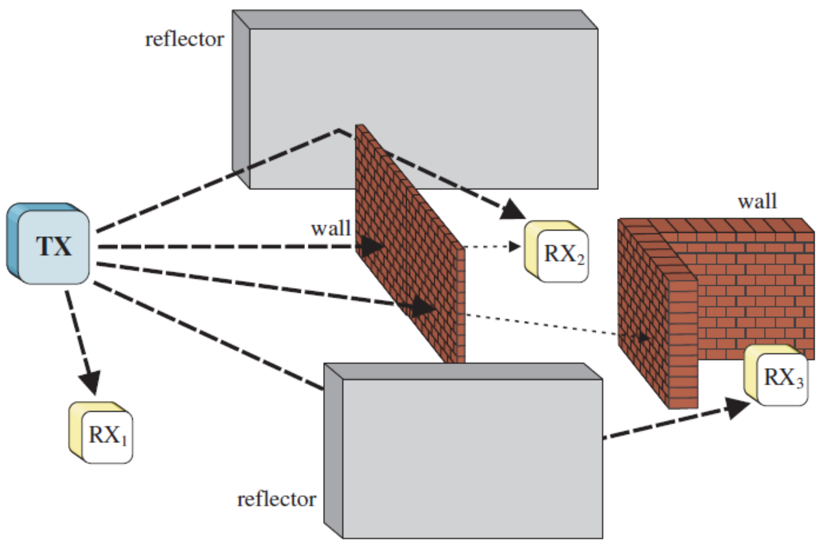


Figure 19: Possible LOS and NLOS conditions from transmitter TX to various receivers. RX1 is in LOS condition, RX2 is in NLOS condition without DP blockage, RX3 is in NLOS condition with DP blockage.

3.3.3. Practical ToA Estimators

The performance of any ToA estimator can be bounded by using theoretical bounds described in the previous section. Maximum likelihood (ML) estimators are known to be asymptotically efficient, that is, their performance achieves the CRB in high SNR regions. A ToA estimate can be obtained by using a matched filter (MF) or equivalently a correlator matched to the received signal; the ToA estimate is equal to the time delay that maximises the MF output. Note that in the presence of multipath the template in the receiver (also known as the locally generated reference) should be proportional to the channel response instead of $p(t)$ in the case of an AWGN channel. However, it is difficult to implement such estimator since the received waveform must be estimated. In addition, each received pulse (echo) may have a different shape than the transmitted pulse due to varying antenna characteristics and materials for different propagation paths. When channel parameters are unknown, ToA estimation in multipath environments is closely related to channel estimation. In this case, path amplitudes and ToA are jointly estimated using, for example, the ML approach [33]. Unfortunately, the computational complexity of ML estimators for multipath channels limits their implementation. To alleviate this problem several practical sub-optimal ToA estimators have been proposed in the literature [34],[35]. Another primary barrier to the implementation of ML estimators is that they usually require implementation at the Nyquist sampling rate or higher, but these sampling rates can be impractical due to the large bandwidth of UWB signals. As an alternative, sub-sampling ToA estimation schemes based on energy detection (ED) have recently received significant attention [36]. These ToA estimation techniques rely on the energy collected at sub-Nyquist rates over several time slots.

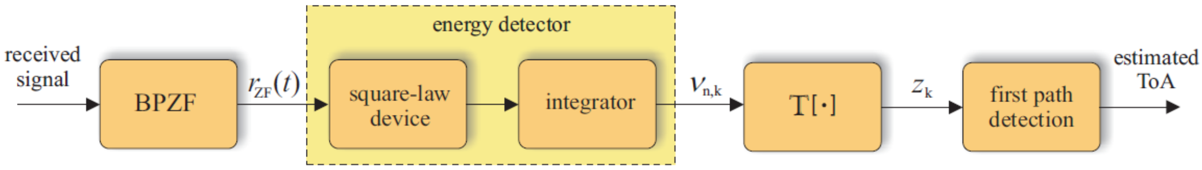


Figure 20: The generic ED ToA estimator scheme

A typical ED-based ToA estimator scheme is shown in Figure 20. The received signal is first passed through a bandpass zonal filter to eliminate the out-of-band noise. The observed signal forms the input to the ED whose output is sampled at every T_{int} seconds (the integration time of the ED), thus $K = \lfloor T_{ob}/T_{int} \rfloor$ energy samples are collected in each sub-interval (with indexes $[0.1, \dots, K-1]$ corresponding to K time slots). The true ToA τ is contained in the time slot $n_{TOA} = \lfloor \tau/T_{int} \rfloor$. Note that the first n_{TOA} samples contain noise and possible interference (called the *noise region*), followed by the $(n_{TOA}+1)$th sample containing the first path, and the remaining $K - n_{TOA} - 1$ samples possibly containing the echoes of the useful signal (*multipath region*), in addition to noise and interference. The integration time T_{int} of the ED determines the resolution in estimating the ToA and thus the minimum achievable root mean square error (RMSE) for ToA estimation is given by $T_{int}/\sqrt{12}$.

Prior to the ToA estimation, the collected samples can be pre-processed or filtered in order to reduce the interference effects and to improve the detection of the first path. The output of the filter T[·] is a vector $\mathbf{z} = \{z_k\}$ to be used by the ToA estimator. With reference to Figure 21, some recently proposed techniques to detect the first path from $\mathbf{z}$ are briefly described. For more details please refer to [32].

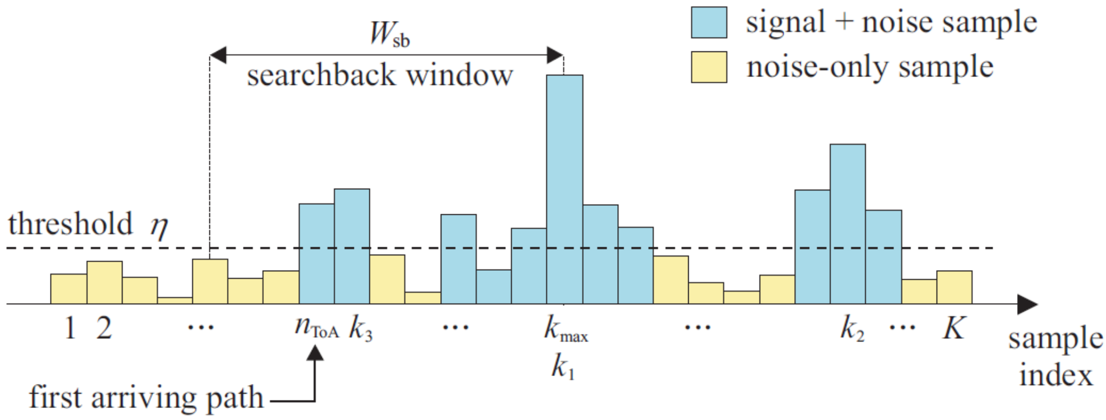


Figure 21: Illustration of the Max, P-Max, ST, JBSF, SBS and SBSMC algorithms

Max

The Max criterion is based on the selection of the largest sample in **z**. This criterion has the advantage of not requiring extra parameters to be optimised accordingly to the received signal (channel, interference and noise levels). However, it suffers performance degradation when the first path is not the strongest. This typically occurs in NLOS propagation.

P-Max

The P-Max criterion is based on the selection of the earliest sample among the P largest in **z**. ToA estimation performance depends on the parameter P, where P can be optimised according to received signal characteristics.

Simple Thresholding (ST)

The ST criteria is based on estimate of n_{TOA}, and hence τ, by comparing each element of **z** within the observation interval to a fixed threshold η. In particular, the ToA estimate is taken as the first threshold crossing event (Figure 21). The design of the threshold depends on the received signal characteristics, operating conditions and channel statistics. The choice of the threshold η strongly influences the performance of ST ToA estimation. When η is small, a high probability of early detection prior to the first path due to noise and interference is expect. On the other hand, if η is large, a low probability of detecting the first path and a high probability of detecting an erroneous path is expected due to fading.

Jump Back and Search Forward (JBSF)

The JBSF criterion is based on the detection of the strongest sample and a forward search procedure. It assumes that the receiver is synchronised to the strongest path and the leading edge of the signal is searched element-by-element in a window of length $W_{sb} + 1$ containing W_{sb} samples preceding the strongest one. The search begins from the sample in **z**, with index $k_{max} - W_{sb}$, and proceeds forward until the sample-under-test crosses the threshold η (Figure 21). Note that the optimal selection of W_{sb} and η depends on the received signal characteristics.

Serial Backward Search (SBS)

The SBS criterion is based on the detection of the largest sample and a search-back procedure. The search begins from the largest sample in **z**, with index k_{max}, and proceeds element by element backward in a window of length W_{sb} until the sample-under-test goes below the threshold η (Figure 21).

Serial Backward Search for Multiple Clusters (SBSMC)

In typical UWB channels, multipath components arrive at the receiver in multiple clusters that are separated by noise-only samples. In this case, the SBS algorithm may choose a sample that arrives later than the leading edge. This clustering problem can be alleviated by continuing the backward search until more than D consecutive noise samples are encountered. This is referred to as SBSMC.

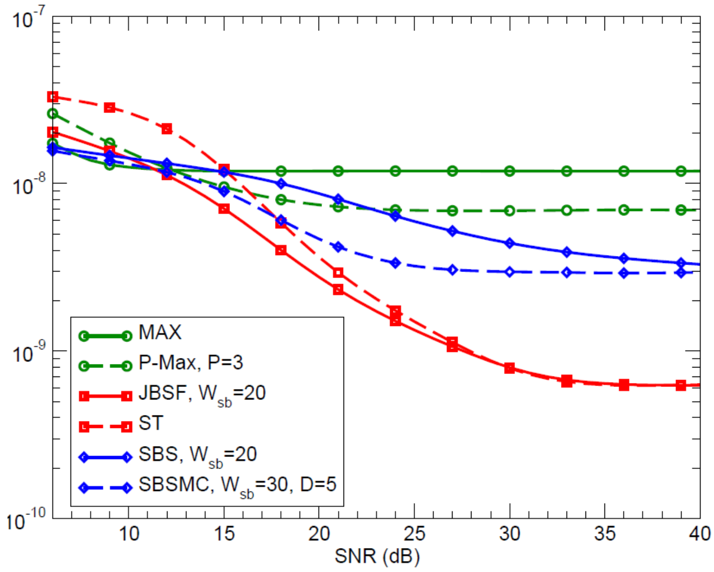


Figure 22: RMSE as a function of the SNR for various ED-based ToA estimators. The IEEE 802.15.4a CM4 channel characterising NLOS indoor propagation in large office environments is used. The band-pass pulse has a centre frequency of 4 GHz and bandwidth of 1.6 GHz. T_{int} is 2 ns and 400 pulses are considered.

In Figure 22 a comparison in terms of RMSE in ToA estimation for different ED-based schemes is shown. Recall that all these schemes, except Max, require an optimal selection of parameters (specifically η, W_{sb}, D or P) depending on received signal characteristics. The best scheme for ToA estimation depends on operating SNR. However, one can compare them at high SNRs since all schemes exhibit error floors. Note that the ST and JBSF schemes achieve the minimum attainable error floor of ED-based ToA estimators, that is $T_{int}/\sqrt{12} = 0.57\ ns$, which corresponds to about 15 cm of ranging error. The SBS and SBSMC schemes exhibit an increased error floor due to the search back procedure that can stop after the first path in a clustered channel. The Max and P-Max schemes result in even higher error floor due to the fact that they identify the strongest paths instead of the first path which often is not the strongest one.

3.3.4. Further Research Directions

Ranging in UWB channels has experienced a flurry of research in recent years. However, there still remain multiple areas of open research that will help systems to meet the requirements of high-definition situation-aware applications. The rapid deployment of location-based networks, for which accurate ranging is likely pivotal, will be aided by the development of the following techniques as example:

- *Interference mitigation:* Narrowband and wideband interference are inevitably present in typical environments due to the nature of UWB transmissions. To date however, the majority of research effort ignores the effects of interference on ToA estimation accuracy. There are opportunities for further research in robust interefence-resistant ranging, such as the design of jam-resistant schemes.

- *Secure ranging*: Ranging can be subjected to hostile attacks in certain environments. In order to make impostor and snooper attacks more difficult the IEEE 802.15.4a standard includes an optional *private ranging* mode: After a preliminary authentication step nodes exchange information via a secure communication protocol, on both the sequences to be used in the next ranging cycle and their timestamp reports [3].
- *Cognitive ranging*: There are opportunities for further research in *cognitive positioning systems* where the localisation accuracy can be varied according to bandwidth availability.

3.4. Motion Sensors

Motion sensors comprise accelerometers, gyroscopes and magnetometers do provide accurate position tracking for short periods of time, but they are drift prone during longer time periods. Hence, when the sensors are added to an UWB system one can expect to obtain a more robust solution, capable of detecting and rejecting multipath effects and NLOS situations. Thus, the integrated combination of the inertial system (motion sensors) and UWB device provides position estimates updated at a higher rate and with a smaller position error when compared to a standalone UWB receiver. Additionally, sensors will deliver improved tracking results, especially for dynamic quantities like velocity. Overall, the result of such integration is a system with 6 degrees of freedom (DOF) and general purpose tracking capability for indoor localisation applications.

The complementary characteristics of both sub-systems, radio and inertial, are summarised in Table 6. Inertial navigation system (INS) has unbounded error growth, but provides autonomous and robust estimation of all the navigational states (as attitude) and is further capable of handling high dynamics. On the other hand, the UWB ranging does not provide attitude information, has poor dynamic range and poor robustness to external disturbances, but has bounded errors. A combination of these two systems compensates for the shortcomings of each and yields a better performance when compared to individual sub-system.

	Autonomy (self-contained)	Stand-alone error	Dynamic range	Navigation states
INS	Yes	Unbounded growth	High	Yes
UWB	No	Bounded	Low	No

Table 6: INS and UWB complementary characteristics

If UWB localisation quality drops below the desired threshold, then the trajectory reconstruction is performed only by inertial navigation.

There are three coupling strategies of UWB with external inertial data sources – *loose, tight and deep coupling*. A *loosely coupled* approach is a solution where the measurements from IMU and UWB are pre-processed before they are used to compute a final result. A *tightly coupled* approach refers to a strategy in which all the measurements are used directly to compute the final result. The d*eep coupling* assumes integration of navigation solution as one element of the UWB receiver tracking loop. Generally, tighter coupling increases both the algorithm complexity and the final performance.

Since both sensor and UWB errors can be modelled as Gaussian variables optimal sensor fusion algorithms are commonly based on the extended Kalman filter (EKF). It is an optimal recursive mathematical algorithm for state estimation of dynamic system with noisy measurements and state variables.

In contrast to the data from inertial sensors (INS), the availability of UWB measurements is particularly irregular in time and a measurement appears at slow rate, in order of a second. The INS data are available at 100 Hz, which is illustrated in Figure 23.

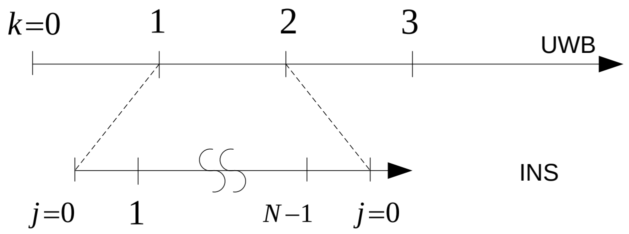


Figure 23: Availability of UWB supplied and INS supplied position fixes in time

When UWB measurements are not available or some of the measurements are of low confidence because of multipath radio propagation, the inertial measurements are used for the position calculus. The calculus is performed based on a previously determined kinematics model of the motion. The position calculations based on the INS are confident only for short time periods because of the biases and sensor errors that are being accumulated during longer integration periods.

Before the INS data can be fed into the system it needs to be pre-processed. For every specific system it is necessary to properly calibrate the sensors. The calibration procedure is an opportunity to trade system costs for improved accuracy. The result of the calibration procedure are compensation matrices for the sensor data obtained. Compensation matrices contain biases, scale-factors, cross-axis misalignment corrections, linearity error, etc. However, micro-electro-mechanical systems (MEMS)-based sensors, such as those used in the current prototype, can have different biases and scale factors after every switch-on. Furthermore, the biases and scale factors can change during the calibration process and certainly do with a change in temperature. Moreover, one characteristic of gyroscopes is the so-called “random-walk” bias component that cannot be calibrated by using standard methods. This limits the impact of an extensive lab calibration. As a complement, field calibration methods using onboard sensor fusion algorithms should be employed to increase the accuracy.

In the integrated UWB + INS system, a position error is calculated from the difference in the position estimation from both systems. This error signal is then used to drive an extended Kalman filter which contains a model for the error dynamics. These error states are then used to compensate the INS states which results in a closed loop system, depicted in Figure 24.

The most essential contribution of INS to UWB positioning is the attitude. In pure UWB systems it is impossible to determine the attitude; it is only possible to calculate the heading by subsequent position fixes. This heading can be quite inaccurate if the environment is changing fast and the position fixes are noisy. With the inclusion of inertial sensors the attitude can be determined independently of external disturbances.

This, in overall, will allow for construction of location/attitude/orientation-aware systems which are much needed in various applications. As a major market, a wireless gaming console or unit can be constructed where a user interface can be implemented by a UWB + INS system. Less location constraints when compared with today's gaming experiences can be achieved especially in the light of 3D technology. Similarly, various robotic applications might benefit from the integrated system. On the other hand, more demanding markets, such as rescue or firemen teams might benefit from the full trajectory reconstruction and localisation of their team members during risky operations.

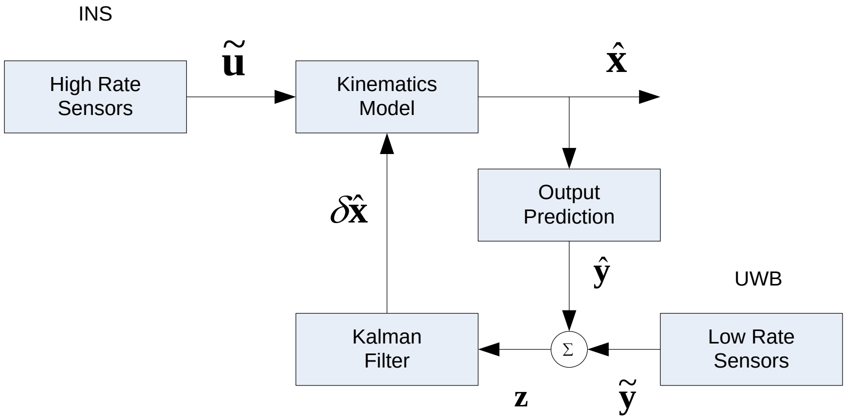


Figure 24: UWB INS integration building blocks

4. UWB Applications

4.1. HDR Short Range Communications

The major market of the HDR UWB devices follows the ECMA-368 [4] standard and the Wireless USB (WUSB) standard aimed for WPAN applications. These devices are aimed for use in personal area networks, providing throughput reaching above 200 Mbit/s for indoor ranges based on PHY data rates from 53.3 Mbit/s to 480 Mbit/s.

It should be noted that ECMA-368 devices may also exploit additional markets in the future, such as IP over UWB, but currently Wireless USB is the main interest of the various companies manufacturing HDR UWB.

4.1.1. The WUSB Market Potential

With many billions of USB devices sold to date, the USB standard offers connectivity in almost any device. Besides usage for the PC and its peripherals, e.g. mouse, keyboard, (external) hard disk, printer, scanner, USB connectivity now exists in multitude of additional consumer devices as well such as common TVs, mobile phones, cameras, camcorders, audio and video players, tablet PCs, netbooks and many more. For most of those, the desire to remove the cables and switch from the line connected to the wireless, is most natural. Wireless USB builds upon the consumer awareness of USB and its ease of use. Similar to the impact on networking and the freedom that Wi-Fi brought to mobile internet access in the last decade, Wireless USB promises a user experience with fewer cables. This means consumer electronics without the typical rat's nest of wires, easier installation and set-up for devices in the digital home, and revolutionary new products such as wireless monitors and displays.

WUSB is a standard of the USB Implementers Forum (USB-IF), the same organisation which is responsible for the USB standard. As such, WUSB promises very high compatibility with the legacy USB devices that significantly simplifies the replacement and combination of WUSB to a USB-connected device, internally, as part of manufacturer model upgrade. Additionally, WUSB has introduced standardisation for intermediate WUSB connectivity, utilising a dongle connected to the USB port, in a form called HWA/DWA.

WUSB allows a Wireless USB connectivity and new applications across a variety of USB cable replacements, such as a connection between a laptop and HDTV for viewing Internet content on TV or computer, wireless computer docking cables that replaces a number of cables (video, audio, keyboard, mouse) and more. The main relevant market segments of WUSB are:

- *Display products*: Projectors, televisions, flat computer monitors and other related products can be sold or merged into display devices. HD televisions are becoming commonly available, both in the home and business markets. In 2012, the expectation for sales is 241 million units world-wide [37]. One of the attractive features many new devices offer is to easily link the laptop to the HDTV, and WUSB connection is proposing one of the best solutions for this.
- *Laptop computers*: The laptop market is expected to reach about 200 million in 2011. Multiple new configurations have entered the market in the last few years, e.g. tablets and netbooks, both having shown the potential for new smaller, lightweight portable computers. The WUSB market entry is expected to increase

significantly due to the trend of reducing the size of a portable computer to 10" or 11" (mini notebook, netbook and tablet PC) and the abstraction of the mobile computer peripherals such as its optical drive. The significant minimisation of the number of connectors in the body of the computer because of the reduction in size and in particular the reduction in thickness (thin devices like the MacBook Air and various tablets) increases the need for wireless connectivity of products and peripherals, including large displays, hard drives and optical drives with high data rate requirements.

- Other *portable devices* with Internet connectivity and the ability to store content such as iPhones and other *smart phones*. According to IDC, in 2009 about 1.1 billion mobile phones have been sold world-wide [38]. The trend in this market is high rate connectivity to the Internet and a strong requirement to create and store personalised content (for example Sony Ericsson announced a plan for the introduction of HD quality camera in a coming model). The number of low cost (below US$200) smart phones was about 30% in 2009 [39] and this number is expected to dramatically grow as these devices become more and more common. These trends increase the demand for wireless connectivity of your mobile phone to television or other display devices and to other peripherals that will allow more convenient use of mobile equipment at home or office.
- *Peripherals*: Peripheral equipment manufacturers offer the product in their marketing channels (retail). Markets include both the business sector with meeting rooms where the projector is hanging from the ceiling or a large flat-screen display far from the conference table and the domestic sector where the screening of the living room television content or Internet viewing on TV screen is of importance. For example the projector market alone is expected to grow from 12.6 million in 2010 to 15 million in 2011.

4.1.2. Existing WUSB Products and Applications in the Consumer Market

Currently, a number of attractive products is available on the market which are briefly presented.

Display Video and Audio Adaptor Kits

WUSB video and audio products take advantage of the relatively high throughput of WUSB and the existence of USB connectors on almost any laptop, to easily link the laptop to HDTV. The A/V set provides full room coverage, is easy to set up and use and is an ideal solution for home and office users alike. In a conference room scenario, the USB A/V set enables users to display content from their notebooks using a projector, commonly mounted on the room's ceiling, without cable length limitation and without the need to route dedicated wiring through the walls and the ceiling.

The A/V products consist of a WUSB dongle that connects to the laptop and a receiver that connects to the HDTV or projector and speakers. The small PC adapter connects to a USB port available in all notebooks and PCs, while the A/V adapter connects to an HDMI port (available in screen TVs) or VGA port (available in projectors and monitors) and supports stereo audio.

Figure 25: TV adapter concept

Current products exist and are currently sold under multiple brands at price ranges about 100–150 Euro, depending on supported features such as different resolutions.

Figure 26: WISAIR Wireless USB adapter set (PC adapter, AV adapter with device)

Wireless Docking Stations

A Wireless USB docking station allows users to wirelessly connect from their notebook PCs to their desktop environment, consisting of a monitor, speakers, keyboard, mouse and other USB devices, without having to connect any cables. The set includes a PC adapter and a pre-paired display dock comprised of a device adapter and a dock base, enabling a quick, hassle-free set-up and immediate operation. The Wireless USB docking stations provides full room coverage, making it ideal for using with a large screen and listening to music from the laptop without cable length limitations. Plug and play functionality provides users with the freedom of walking away with the notebook PC and immediately getting connected when re-entering the room.

Figure 27: Docking station concept

Products are currently sold under multiple brands at price ranges about 150–200 Euro.

Figure 28: WISAIR wireless DisplayDock device side (PC device adapter)

Dongles and Hubs for Legacy USB Connectivity

A Wireless USB adapter set allows users to ‘upgrade’ any existing USB device to Wireless USB. Consisting of a pair of Wireless USB adapters, one for the device and one for the PC, the solution brings Wireless USB connectivity to a range of devices, such as hard disk drives, printers and hubs. Wireless USB connectivity is enabled by attaching the PC adapter to the PC or notebook and the device adapter to the USB port of the device. The device adapter receives power from an external power supply. A similar solution replaces the device with a USB hub enabling the connection of multiple USB devices to it.

Although these products are mostly designed for the existing legacy devices and therefore typically suffer from lower throughputs and other limitations, these products can often solve office arrangement situations in ways that are impractical using wired USB, e.g. putting the printer at the other end of the room in a position that requires too long cables to reach.

Products are currently sold under multiple brands at price ranges about 70–90 Euro.

Figure 29: WISAIR Wireless USB adapter set (PC adapter, device adapter, table adapter)

4.1.3. Existing Main Manufacturers

Currently (2011), after the last financial crisis there are very few UWB/WUSB solution manufacturers. The first three companies: Wisair, Veebeam and Alereon are relatively small UWB dedicated companies, yet each of them supports several multiple brands. The fourth and the fifth – Samsung and CSR – are much larger, yet so far only announced existing chips and have yet to announce incorporation of their chips into any products.

Wisair

Wisair Ltd. is a fabless semiconductor company providing UWB and Wireless USB solutions based on its CMOS single chip. Recognised for their superior coverage and throughput, Wisair's solutions offer the best combination of performance, price and power consumption for Wireless USB. For more information, please visit http://www.wisair.com.

Based on industry standards, Wisair's products are designed to serve a range of customers, including:

- PC and PC peripherals brand vendors;
- Manufacturers of consumer electronics products such as digital cameras, video recorders, set-top boxes and projectors;
- ODM/OEM module manufacturers.

With several decades of combined experience in the wireless industry, Wisair provides unmatched technical excellence and expertise which results in best-in-class Wireless USB solutions with superior performance and low cost. These solutions have received world-wide regulation and have been adopted by leading brands and retailers.

Wisair is headquartered in Israel, with offices in the USA and Japan, and representatives in Korea, Taiwan, Germany and Singapore.

Veebeam

Veebeam is the consumer electronics refocus of the fabless semi-conductor start-ups Artimi and Staccato Communications.

Today, Veebeam uses its highly cost and power efficient, single chip, 65 nm CMOS UWB solution as part of a wireless PC to TV streaming product (also named Veebeam). Veebeam is the easiest, most affordable way to wirelessly stream anything from a laptop to a TV. It makes it possible to easily share the best of the Internet with the whole family from the comfort of your living room.

The Veebeam team includes an impressive group of veterans with experience bringing to market a wide array of consumer hardware, mobile phones, Bluetooth and Wi-Fi products. The team has a track record of building successful products and services at such companies as Virata, Texas Instruments, SiGe, IBM, Best Buy, Logitech, VUDU and AOL.

Veebeam is a privately held, venture-backed corporation and maintains offices in Burlingame (CA), Cambridge (UK) and Bangalore (IN). For more information, please visit http://www.veebeam.com.

Alereon

Alereon, Inc. is a fabless semiconductor company using UWB radio technology to develop high bandwidth, low-power, low-cost ECMA standard and WiMedia UWB chipsets that are ideal for today's personal computer, HDTVs and portable products, like cell phones, digital cameras and mp3 players. Our mission is to replace the complex tangle of wires that interconnect today's electronic devices with wireless links. For more information, please visit http://www.alereon.com.

Samsung Electronics

Samsung Electronics Co., Ltd. is a global leader in semiconductor, telecommunication, digital media and digital convergence technologies with consolidated sales of US$116.8 billion in 2009. Employing approximately 188,000 people in 185 offices across 65 countries, the company consists of eight independently operated business units: Visual Display, Mobile Communications, Telecommunication Systems, Digital Appliances, IT Solutions, Digital Imaging, Semiconductor and LCD. Recognised as one of the fastest growing global brands, Samsung Electronics is a leading producer of digital TVs, memory chips, mobile phones and TFT-LCDs. For more information, please visit http://www.samsung.com.

CSR

CSR plc was formed in 1999 and floated on the London Stock Exchange in 2004. It is headquartered in Cambridge, UK, and has over 1500 employees working in offices in the UK, the US, Taiwan, Japan, China, Korea, India, Denmark and France. CSR operates a fabless business model, focusing on its core competency – the design and sale of its components and platforms – and outsourcing manufacturing for cost and technology benefits. For more information, please visit http://www.csr.com.

4.2. Localisation and Tracking

4.2.1. Algorithmic Considerations

Thanks to recent developments of short/medium-range wireless technologies, a multitude of services for indoor application scenarios has been designed for any need and purpose. Amongst the many location-based services are the most popular and they span onto a large variety of application scenarios, such as surveillance, rescuing, logistics, remote health-care, home-office, entertainment, military, public transport, etc.

Depending on the application scenario, location information can be given with different levels of accuracy. For instance, in home and office environments it is sufficient to identify in which room the target node is. For indoor/outdoor navigation as well as in warehouse, industrial, hospital and entertainment, application scenarios, a meter of accuracy is sufficient to track assets and persons. And for military and rescuing applications a precision of half of a meter is required to locate troopers.

Thank to their high temporal resolution, UWB and CSS technologies are considered as two promising solutions for indoor location tracking (LT) systems. In fact, these technologies are able to provide high ranging accuracy with low-complexity and low-energy algorithms and electronics. However, the big challenge is to achieve location errors with few centimetres of accuracy also in non-ideal conditions, i.e. when the ranging measurements are affected by large errors (1–3 metres).

To this end, a large number of researches and projects, e.g. EUWB and WHERE, have been devoted to the development of robust LT algorithms that can provide accurate location estimates despite the large error affecting the distance measurements.

When starting with the description of an LT system, we first distinguish two types of devices and functionalities. For instance, the wireless network depicted in Figure 30 consists of NA radio access points NT terminal devices. The access points, which will be referred to as anchor nodes, are typically fixed, wire interconnected and their location is known a priori. The mobile terminals, instead, are the objects to be localised; therefore they will be considered as the nodes (targets) with unknown locations. For each pair of connected nodes, it is assumed that a set of distance measurements can be obtained via the estimation of physical parameters such as time-of-arrival (ToA) or time-difference-of-arrival (TDoA). The set of measurements are collected by the anchors and forwarded to a server (localisation engine), in which the location algorithm runs and computes estimates of the targets' positions.

An LT system has three essential functional blocks namely, the data acquisition, the data processing and the location estimation as illustrated in Figure 31. Specifically, the data acquisition block deals with the problem of extracting physical parameters such ToA, TDoA, received-signal-strength (RSS) or angle-of-arrival (AoA) from the radios. The second block in Figure 31 deals with the processing of the observed data. In this block, a time-series filter is typically conceived to improve the signal to noise ratio of the measurements. The choice of the technique, however, depends on the dynamic and noise models assumed in the scenarios. For instance, in the case of quasi-static target nodes and a stationary zero mean Gaussian noise affecting the observations even a simple moving average filter can substantially improve the location accuracy of that LT system. Finally, the third block concerns with the LT algorithm.

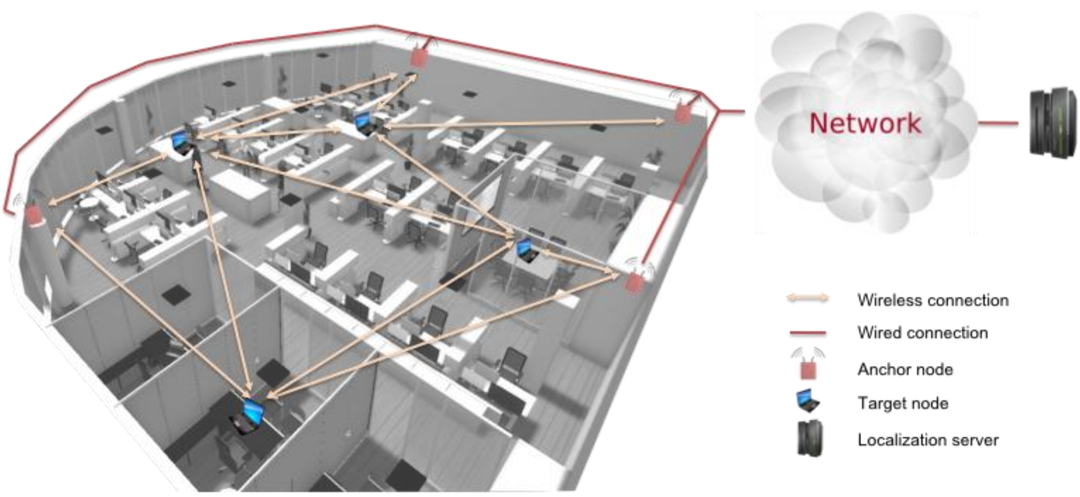


Figure 30: Network set-up for home/office LT application scenario

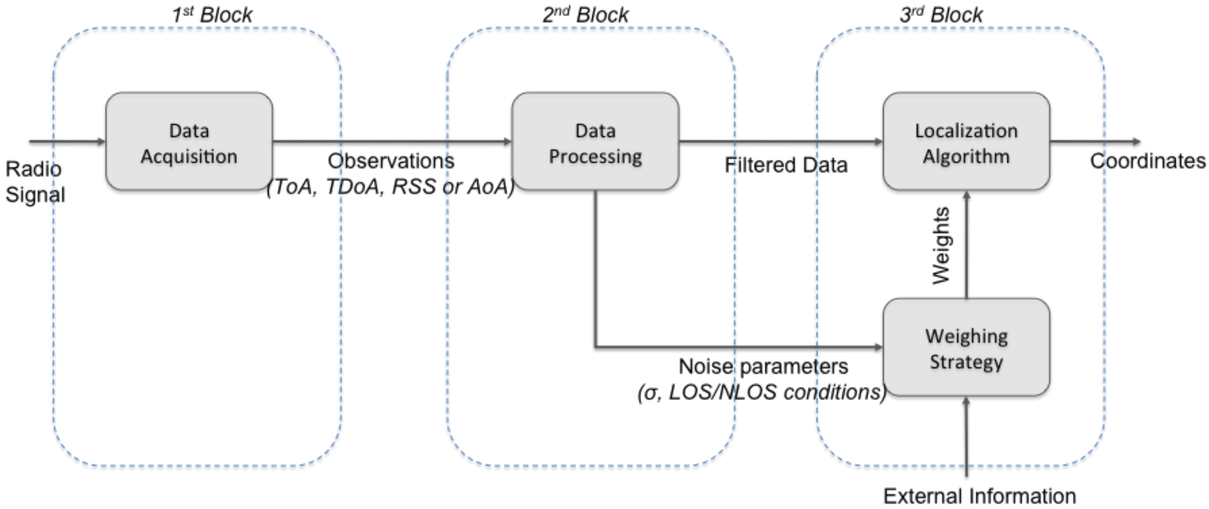


Figure 31: Functional blocks of an LT system

EUWB, as a follow-up of the European research projects PULSER and PULSER Phase II, focused on the development of localisation and tracking algorithms. Several strategies have been investigated and developed, however, all based on a least-square (LS) formulation of the problem and specifically, on the minimisation of the following LS function

$$f_{\mathrm{R}}(\hat{\mathbf{Z}}) \triangleq \sum_{ij\in\mathcal{H}} w_{ij}\left(\tilde{d}_{ij}-\hat{d}_{ij}\right)^2 = \sum_{ij\in\mathcal{H}} w_{ij}\left(\tilde{d}_{ij}-\|\mathbf{a}_i-\hat{\mathbf{z}}_j\|_{\mathrm{F}}\right)^2 + \sum_{ij\in\mathcal{H}} w_{ij}\left(\tilde{d}_{ij}-\|\hat{\mathbf{z}}_i-\hat{\mathbf{z}}_j\|_{\mathrm{F}}\right)^2, \tag{4.1}$$

where wij are weights, $\tilde{d}_{ij}$ and $\hat{d}_{ij}$ are the measured and estimated distances between the i-th and the j-th nodes.

Due to the non-convexity of the objective function this minimisation problem is generally difficult to solve and special optimisation algorithms are required in order to minimise the probability of finding a local minimum.

In the literature several mechanisms can be found offering solutions that can be either very accurate but computational complex or of low-complexity but with poor performance. EUWB developed novel algorithms that prove a good trade-off between accuracy and computational complexity, for instance, the global distance continuation (GDC) method is very accurate in LOS conditions and easy to implement, while the distance-contraction (DC) method requires a slightly higher computational complexity but it is very effective in the presence of NLOS channel conditions.

Table 7 provides an overview on existing localisation techniques classified per assumption (LOS and LOS/NLOS) and optimisation method (local or global).

Channel condition	Method	Technique	Characteristic	One target	Multiple targets	Com-plexity
LOS	LOCAL OPTIMISATION METHODS	Non-linear LS (NLS) [40][41]	Minimisation performed using Newton's method	Yes	Yes	Medium
		Linearised LS (LLS) [42]	Close-form solution based on the linearisation of the objective function	Yes	No	Low
		SMACOF [43],[44]	Minimisation of a LS majorising objective function	Yes	Yes	Low
	GLOBAL OPTIMISATION METHODS	Closed-form squared-LS (S-LS) [45]	Exact solution	Yes	No	Low
		Classical-MDS [43],[46]	Algebraic method	Yes	Yes	Low
		Linear-global distance continuation (L-GDC) [47]	Minimisation of the LS objective via iterative smoothing technique (EUWB)	Yes	Yes	Low
		Simulated annealing (SA) [48]	Minimisation of the LS objective via simulated annealing	Yes	Yes	High
		Factor graph (FG) [49]	Optimisation based on the decomposition of the *a posteriori* probability	Yes	Yes	Medium
		Semi-definite programming (SDP) [50],[51],[52]	Reformulation as matrix proximity problem and optimisation via interior-point	Yes	Yes	High
LOS/NLOS	LOCAL OPTIMISATION METHODS	Linear programming (LP) [53]	Optimisation of the LS objective function built from the LOS information; NLOS states are used to define constraints	Yes	Yes	Low
		Residual weighting algorithm (RWGH) [54],[55]	Solution found from a combinatorial search of the minimum residual LS error	Yes	No	High
		Constrained LS [56],[57],[58],[59]	Constrained LS optimisation solved via Interior point method	Yes	No	Medium
		Constrained LS with bias estimation [60],[61]	Constrained LS optimisation with bias estimation	Yes	No	Medium
	GLOBAL OPTIMISATION METHODS	SDP over multihop (SDP-M) [62]	Multi-hop strategy positioning (EUWB)	Yes	Yes	Medium
		Distance contraction – positive (DC-P) [63]	LS optimisation with contracted and positive distances (EUWB)	Yes	No	Low
		Distance contraction – negative (DC-N) [64]	LS optimisation with contracted and negative distances (EUWB)	Yes	No	Low

Table 7: Localisation techniques

UWB technology allows even non-cooperative localisation of objects that do not carry any tag. This type of localisation is usually referred to as passive or tag-free localisation. In this case targets are detected and localised just by exploiting electromagnetic waves scattered from them. Although there are many articles reporting on tag-free detection and localisation of a single target by means of UWB technology [65],[66],[67],[68] UWB-based localisation of multiple targets is still in its infantry. Articles describing multiple target localisation usually rely on computationally more complex algorithms which involve multiple hypothesis tracking [69] or data association [70]. Passive localisation is of major importance for emergency and security applications like surveillance of unknown interiors or regions after a disaster, through wall detection and tracking of persons, etc. In these applications UWB sensors feature high accuracy and robust operation even in multipath-rich propagation environments.

4.2.2. EUWB-LDR Localisation System

Within EUWB, a fully integrated UWB-LDR platform with ranging and positioning functionalities was developed. The platform can be monitored via a graphical user interface in which, for instance, the nodes' locations can be visualised and mapped in the environment as illustrated in Figure 32.

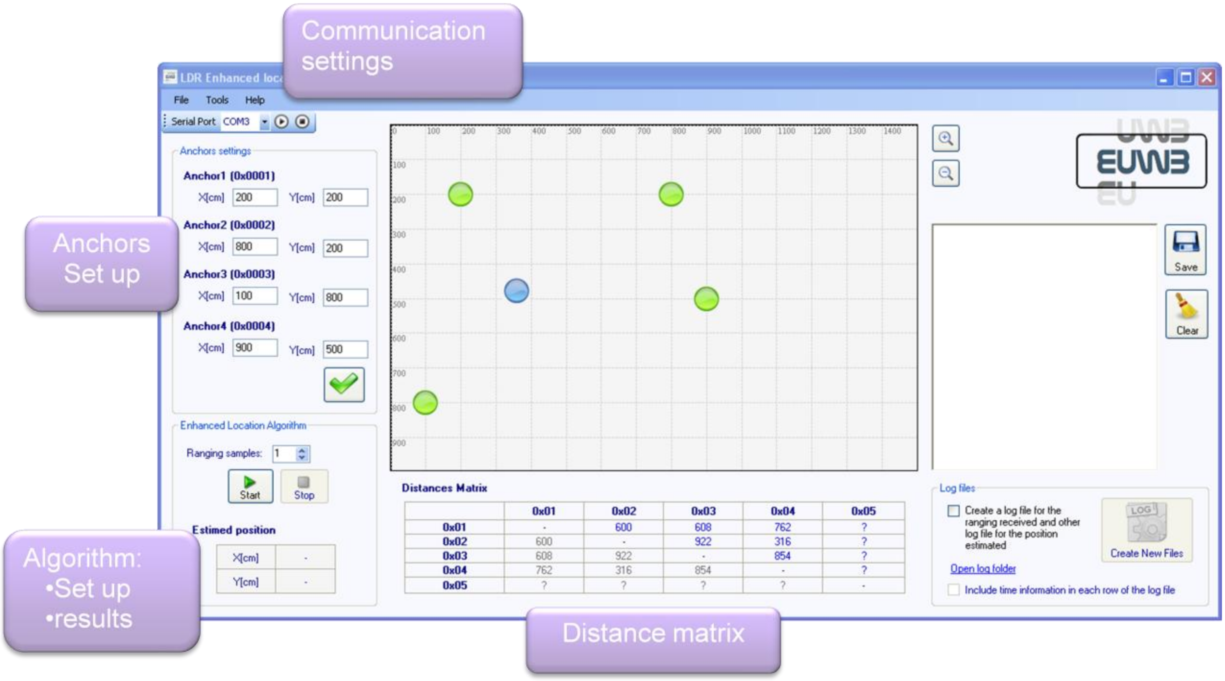
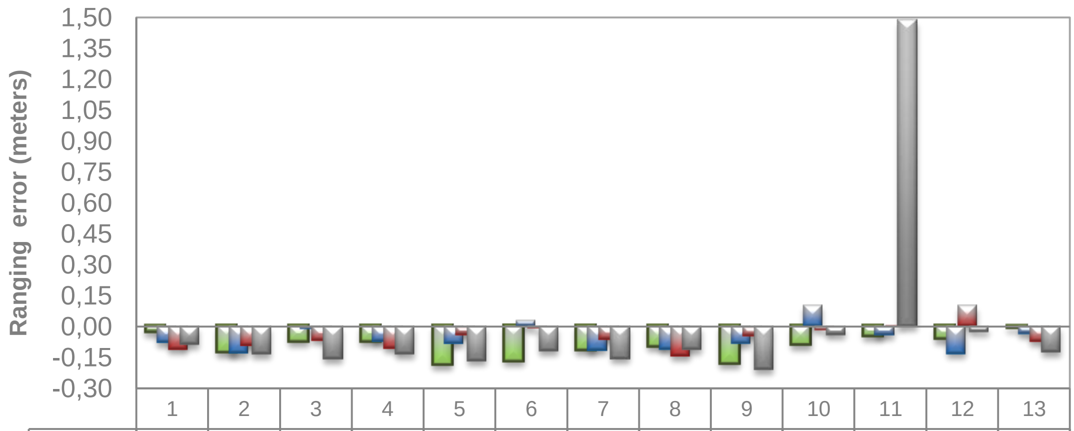


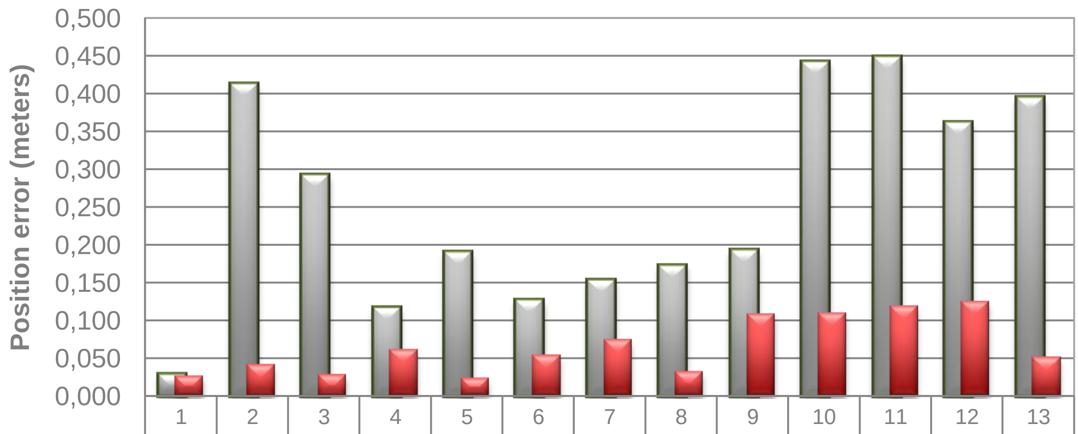
Figure 32: EUWB LDR-LT graphical user interface

The localisation engine that computes the position estimation is based on the DC-algorithm. In an experiment with 1 mobile node (tested in 13 different positions) and 4 anchors deployed in a realistic indoor environment, the EUWB LT solution was proved accurate in both ranging and positioning. The results given in Table 8 and Table 9 show that the EUWB LT solution can provide ranging measurements with a precision of a few tens of centimetres in LOS and approximately a meter in NLOS conditions. However, in terms of positioning accuracy, instead, the average error is about 20 cm with picks of 40 cm in NLOS conditions. For further information about the location engine, please refer to the corresponding EUWB public deliverable [71].



	1	2	3	4	5	6	7	8	9	10	11	12	13
R1 error	-0,03	-0,13	-0,07	-0,07	-0,18	-0,17	-0,11	-0,10	-0,18	-0,09	-0,05	-0,06	-0,01
R2 error	-0,08	-0,13	-0,01	-0,07	-0,09	0,03	-0,12	-0,11	-0,09	0,10	-0,04	-0,13	-0,04
R3 error	-0,11	-0,09	-0,07	-0,11	-0,04	-0,01	-0,06	-0,14	-0,05	-0,02	0,01	0,10	-0,08
R4 error	-0,09	-0,14	-0,16	-0,14	-0,17	-0,12	-0,16	-0,11	-0,21	-0,04	1,49	-0,03	-0,13

Table 8: EUWB-LDR ranging test



	1	2	3	4	5	6	7	8	9	10	11	12	13
Mean Error	0,029	0,413	0,292	0,117	0,190	0,127	0,153	0,173	0,193	0,442	0,448	0,362	0,395
Std Dev	0,026	0,041	0,028	0,061	0,023	0,053	0,073	0,032	0,109	0,110	0,118	0,125	0,051

Table 9: EUWB-LDR localisation test

4.3. Emerging UWB Application Areas

4.3.1. UWB in Public Transport

UWB is a very promising technology for public transport vehicles. In contradistinction to the common view *less range is less good*, its limited range also has its advantages as it opens new deployment schemes and applications, i.e. makes it easier to restrict the network to the interior of the vehicle. Additionally, the security situation becomes eased as the signals are restricted to a smaller area.

Aircrafts (A/C) belong to the most fascinating and complex machines which have ever been created. The harsh operating environment they have to cope with enforces the employment of the safest materials and components, together with a reliable management system to prevent, detect, forecast and eventually remove any kind of failure [72].

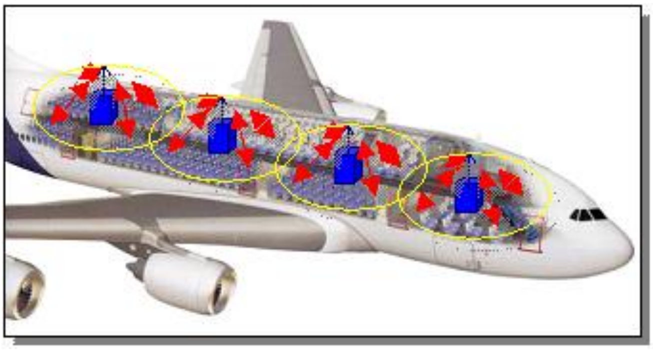


Figure 33: UWB access points and coverage area in an aeroplane

The responsibility for such activities in the cabin area is assigned to the cabin management system (CMS): At the present it has always consisted of a wired network infrastructure, although a wireless realisation has recently drawn attention. Functions handled by this system range from reading lights, passenger calls or speakers to climate control, water waste monitoring or fire and smoke detectors. For a double deck passenger cabin, such as in the A380, the number of deployed wireless nodes can easily be very high. In addition, if an UWB in-flight entertainment (IFE) network is considered, the number of clients and the corresponding aggregated throughput increases further with the number of passengers. Having multiple APs with relatively small ranges instead of few long range APs increases the total number of possible nodes by increasing the local link capacity. Fewer nodes will share an AP and thus more bandwidth per node is possible. Furthermore, the robust signal propagation of UWB and its large frequency spectrum, in addition to the very low power spectral density and support for Internet protocol (IP) communications, makes it a good candidate for difficult environments, and therefore it has been identified as one of the most promising technologies to be assessed for low and high data rates.

The motivation for a wireless CMS or IFE has several reasons. One of them is the weight reduction: With wireless data transmissions the communication network cabling is eliminated. The most important argument, however, is the ease of installation and increase of cabin flexibility. The currently used connectors require a lot of time to connect due to security screws. Furthermore, mistakes can happen and cables would be not connected correctly. All these factors make the installation, maintenance or replacement of a device a time consuming task.

To achieve an UWB network inside an aircraft, several challenges have to be taken into account:

- *Multi-cell network*: The reduced range at high data rate requires multiple access points to cover the entire aircraft.
- *Dense wireless network*: Calculation for the number of nodes in the aircraft showed that 1000 nodes for a full featured wireless cabin are realistic.
- *Resource management*: Decision on the access point positions, UWB channel allocation and media access times should be optimised to provide the best possible reliability.
- *Auto configuration*: Minimal installation, maintenance and configuration effort is a key requirement.

- *Reliability demands* resulting from the necessary certification of devices installed in an aircraft.
- *Mobility and seamless handover* are key factors to enable portable crew equipment like crew intercom or headsets.
- *Interface diversity* to increase the availability and reliability of the wireless communication a second independent interface (i.e. 60 GHz UWB) should be foreseen.

In addition to the high data rate applications, LDR UWB impulse radio or UWB systems with ranging capabilities increase the spectrum of possible applications within the cabin like wireless sensor networks for monitoring of crucial events and parameters in an A/C and other location-aware services. Currently, what differentiates an airline from its competitors is the service. With help of some location-aware mobile devices it would be very easy for a stewardess to offer a personalised care to each passenger (PAX). One example would be, knowing the name and the meal preference by the time the meals are served. That could be achieved by tracking the row where the catering trolley is and matching the location data with the passenger wish list. In addition, when the PAX call button is pressed, one would also directly know the seat (or seat row) and the passenger's name. Furthermore, ranging allows providing partial solutions to the challenges previously mentioned, specially related to auto configuration.

4.3.2. UWB in Automotive Applications

In the automotive area, there is a variety of emerging applications for UWB technology. Until now wireless technologies have only been introduced as an accessory, communicating with a fixed infrastructure. Prominent examples are mobile telephones, radio reception and navigation. Only recently, generic automotive applications like car-to-car and car-to-infrastructure communication gained some attraction. Additionally, applications like keyless entry or tire pressure measurement employ only very simple proprietary wireless data transmission techniques. Such narrowband solutions achieve only limited reliability in dense environments.

Typically, the in-car environment is very tough for any wireless application. The metal shielding of the car body as well as changing occupation with passengers and load lead to complex propagation characteristics. UWB technology is capable of handling these challenges, in order to achieve reliable functionality for wireless applications. With this knowledge and UWB as basic technology a novel technical approach to wireless data communication and location tracking inside and around a car is possible.

Three basic automotive application areas for UWB emerge.

At first, wireless connection of a sensor in the engine compartment to its electronic control unit might be possible, thereby replacing the complex and therefore expensive automotive cable harness. Locations hard to reach can be easily connected to the car's infrastructure.

Secondly, tracking the position of a small portable low-power tag inside and in close proximity of a car is possible with high spatial resolution (Figure 34).

Figure 34: Automotive localisation system based on UWB

UWB location tracking technology enables passenger-aware interaction of the car's human-machine interface. Novel comfort applications arise such as smart car access, driver authentication and personalised user settings, e.g. for the seat positioning or the climate control. That means the car recognises the driver and adjusts the personal settings according to the driver's position.

At last, regarding non-cooperative scenarios like car burglars, passive localisation systems based on UWB technology can be realised (Figure 35).

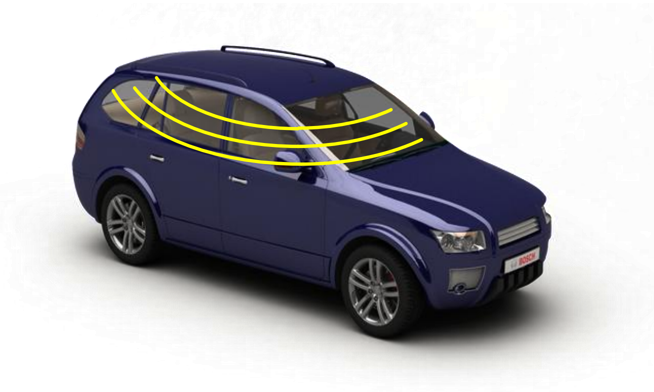


Figure 35: Passive UWB localisation system

Through the reflection of the UWB signal at the object, the car determines the position and tracks the movement of objects inside and in close proximity.

Due to the very precise measurement of the object's position even a convertible car is able to distinguish whether the object is inside or outside.

EUWB has successfully demonstrated the possibilities of UWB technology like precise localisation and robust communication. Achieved results will positively influence the automotive product planning and development for the envisaged applications.

4.3.3. UWB in Home Environment

Within the home environment, UWB radios can potentially be suitable candidates to enable diverse applications. Two examples of these use cases investigated within EUWB include i) multiband/multi-mode HDR/VHDR UWB platforms offering connections among a multitude of multimedia capable devices to share high quality audio/video content and ii) location tracking UWB platforms providing location information that allows design of smart entertainment devices to enhance user immersion experience.

Multiband/Multi-mode HDR and VHDR UWB Applications

Consumers increasingly find themselves using different classes of devices that can serve and/or consume large range of multimedia content. In general, these devices may be divided into three categories.

- Portable/mobile consumer electronics (CE) devices such as smart phones, media players, portable game consoles, which serve their users' needs for communication, infotainment as well as capturing and sharing of experiences on the go: These devices are capable of storing modest amount of data and are also increasingly used for mobile video viewing, download of content and social networking purposes. Power consumption is a key parameter to the user.
- Personal computer devices such as notebooks, netbooks and tablets which offer very diverse functionalities to the user: Within the living room these devices are used for access to both online multimedia content as well as general browsing. These devices have more processing power than the first category, offer more storage capability and are used for downloading, streaming and displaying real HD content as well as for more demanding types of PC gaming. Power consumption is also an important feature of these devices but less critical than the mobile devices category.
- Multimedia CE such as HDTVs, game consoles, set-top boxes, DVD/BD players and digital video recorders: These devices aim for the best possible user experience with support for the highest quality content. These devices are becoming increasingly better connected, more powerful and are also taking on tasks not normally associated with their original function. For example, TVs are also providing access to online services, the same applies for Blu-ray players. These devices are mains powered and power consumption although important, is not a critical performance parameter.

In this landscape, for consumption of video content within the home environment, the TV is well placed to provide the ultimate user experience. It has the largest display of all devices, gives the user the best audio and video experience and is on its way to become the central control point for sharing a wide range of contents.

However, it can be seen from the above classification that providing inter-connectivity among these devices and the TV poses several challenges:

- Large diversity of processing power, available memory, power consumption limitations and display resolution (and hence content handling capabilities);
- Different device categories use different connectivity options (HDMI, USB, VGA, DVI, etc. depending on PC, TV or portable device platforms).

It becomes obvious that no single wireless connectivity solution will be able to adequately meet all these challenges. Hence, wireless TV requires deployment of multi-mode radio principles. Such approach allows an intelligent TV platform to discover devices within its eco system, list available content and select the best connectivity depending on the application scenario and source device capability.

Using a dual mode/dual band UWB HDR/VHDR system operating at UWB and 60 GHz frequencies can offer HDTV and other classes of devices such a connectivity platform. On one hand, the UWB HDR platform can allow power efficient, high bandwidth data transfer, e.g. for the transfer of a large video file from a battery operated portable device to a local hard drive, while on the other side 60 GHz VHDR radio provides unparalleled bandwidth for streaming of high quality HD content to the display.

Equally important, both radios offer very good interference/coexistence properties often lacking in competing wireless technologies.

Location Tracking UWB Platforms

The second application considered for UWB within the home environment involves use of its localisation and tracking capabilities for smart in-room surround sound applications. Two distinct use cases are investigated:

- User location information for optimisation of audio experience in sound bar systems;
- Speaker location information for 5.1/7.1 surround sound systems.

Figure 36: Home cinema speaker system

Using this location information, advanced audio tuning algorithms are developed to optimise the directivity of audio signals in order to provide improved listening experience regardless of the position of the user or placement of speakers within the living room environment. Figure 37 and Figure 38 depict the application of re-routing of audio signals for the individual surround systems described.

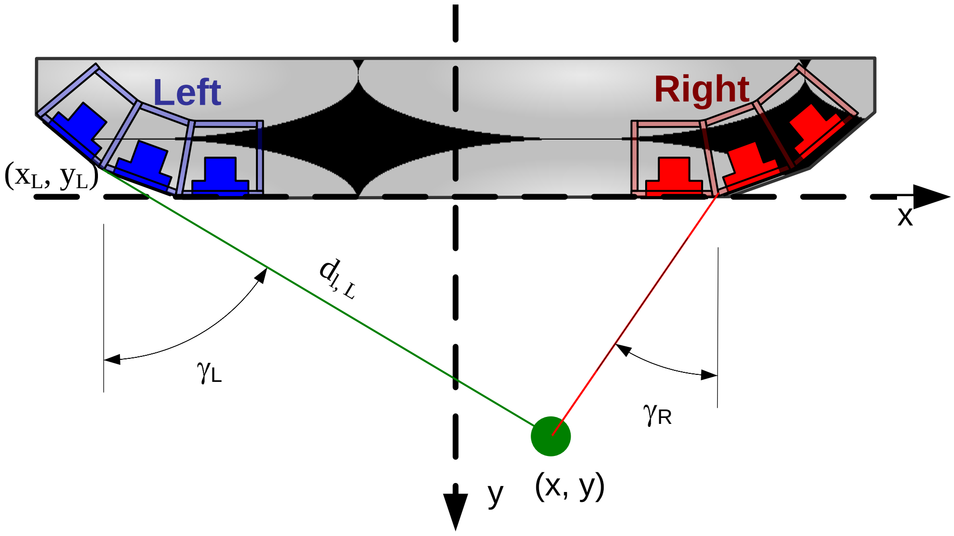


Figure 37: Calculation of wanted notch angle γ_L

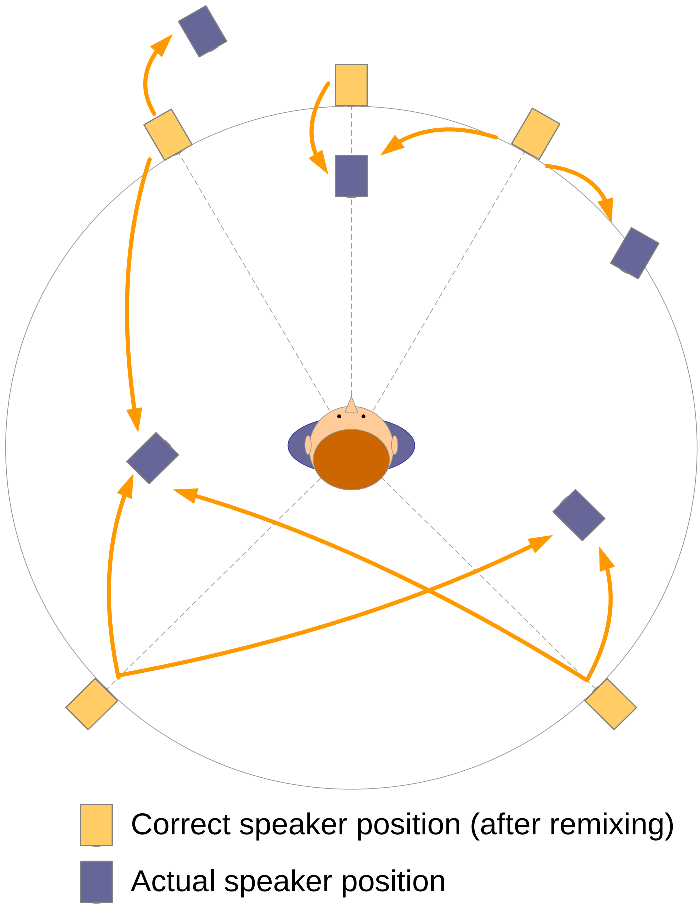


Figure 38: Complex rerouting/remixing in a multi-speaker home theatre system

4.3.4. UWB in Heterogeneous Access Networks

During the last decade, the idea of making the diverse networks converge has been broadly discussed. Convergence can be explained from two main points of view: services (voice, data, media …) and network architecture (mobile, wireless, fixed …), but a unique target is pursued: enabling a ubiquitous network access to a pervasive service infrastructure.

It can be stated that the roadmap for future converged networks goes through homogeneity in the core and platform services and heterogeneity in the access. In that way, the technologies enabling network access also interoperate among them and with other complementary technologies (3G with Bluetooth, ADSL with Wi-Fi), but their performance is still far from the aim of providing a true mobile broadband experience, especially due to the low data rates offered and to the effort needed to obtain the required convergence. UWB is a top-candidate technology to play a key role in this convergence process thanks to its low power consumption, very high data rate, low cost and indoor localisation capabilities. Three fields have been identified in EUWB to perform the integration of UWB into current and future heterogeneous networks: user devices, access network equipment and services based on location awareness. Moreover, the world-wide acceptance of UWB is conditioned by coexistence issues that can arise in a heterogeneous environment where multiple wireless technologies are present.

An attractive application scenario for a global operator is presented in Figure 39, which shows a possible configuration to offer Triple-Play service. Triple-Play service is a marketing term for the provision of two broadband services (high speed Internet access and television) and one narrowband service (telephone) over a single broadband connection (ADSL technology in Figure 39).

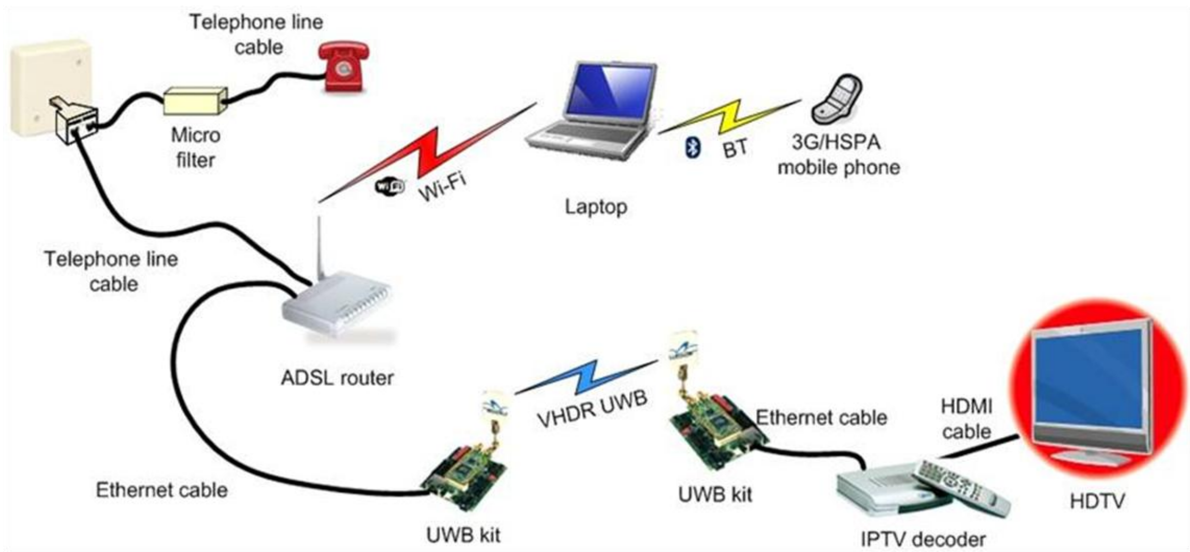


Figure 39: IPTV over UWB scenario

In this case, the high speed Internet access is performed by means of a Wi-Fi link, whereas through a VHDR UWB link, the HD television signal reaches the IPTV (Internet Protocol Television) decoder located next to the TV (up to 10 metres from the ADSL router). UWB-RT is an optimal wireless technology to transport HD signals due to its inherent capability to transmit the information at extremely high data rates, acting as a range extender and avoiding any cable clutter around the screen. In this way, only a short single HDMI cable is used to carry the signal from the decoder to a cutting-edge TV that combines HD technology with an ultra-flat screen design. The inclusion of a Bluetooth transmission, for example a mobile phone downloading some pictures to the laptop as shown in Figure 39, enriches this Triple-Play scenario, but a new interference risk appears, highlighting the importance of studying its impact to ensure a harmless coexistence among all technologies that form a part of the scenario.

The indoor localisation provided by UWB combined with cellular networks such as HSPA or WiMAX will open the door to a large set of novel location-aware services in a heterogeneous environment, increasing the customers' satisfaction as well as the income of operators and service providers. Two particular location-based applications were considered of great interest within the EUWB consortium:

- To provide the users with wireless/cellular access networks with location information in indoor environments, complementing the information provided by GPS outdoors and extending the scope of location-based services to a higher number of potential scenarios, applications and users, as shown in Figure 40. Some possible scenarios include airports, business districts, shopping centres, industrial areas, amusement parks, trade fairs, exhibition centres and sports complexes.

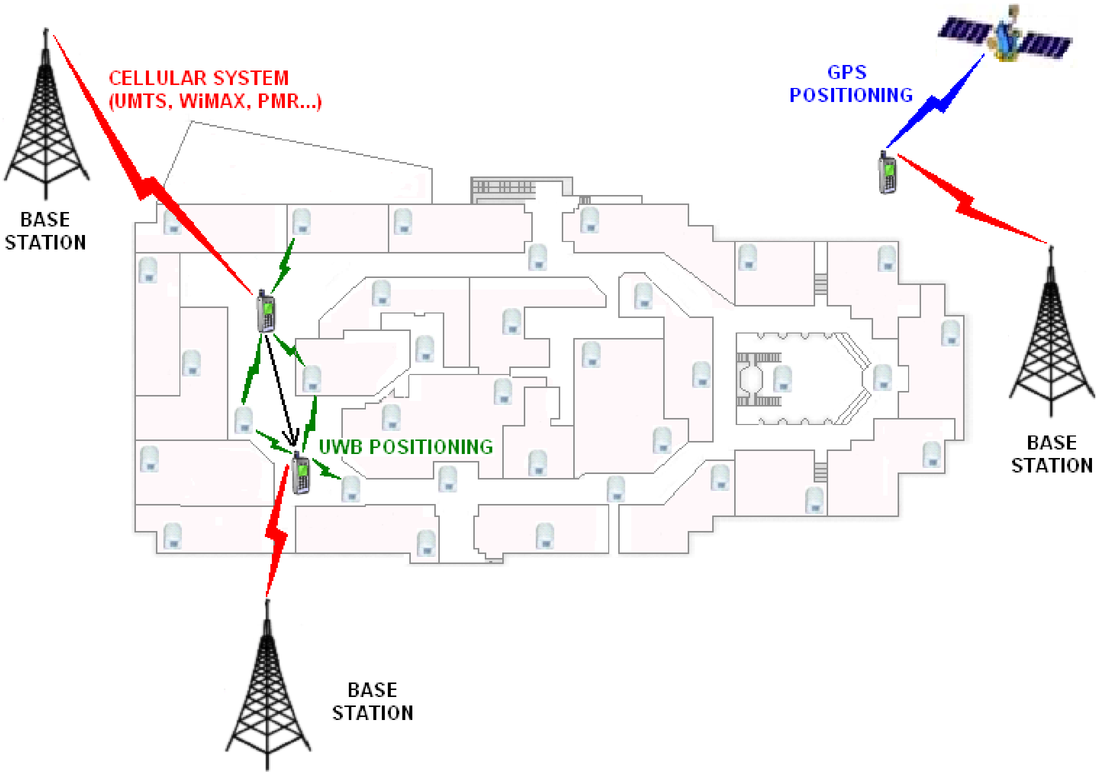


Figure 40: Location-aware services in indoor scenarios

In these scenarios, a wide range of location-based services and applications would be enabled by the integration of LDR-LT UWB into mobile user devices. Indoor navigation service takes the highly successful car navigation systems and Internet map services to indoor scenarios such as a shopping mall or an airport, helping the user find a certain shop or guiding him to the boarding gate. Location-based search provides the user with search results ordered according to proximity, for instance to find the closest restaurant or cash machine. Proximity marketing aims to increase the impact of advertising by sending offer advertisements and discounts to potential nearby customers. Proximity payments combined with mobile payments enable small monetary transactions (e.g. parking, public transport, road tolling, etc.) by placing the mobile phone near a payment station. Other potential applications may include custom multimedia guides that select the narration as the user approaches a work of art in a smart museum or children surveillance wristbands that send a notification to the parents' mobile phone in case they move apart from them in an amusement park.

- Location tracking applications for emergency services, in particular to provide the headquarters with real-time information about the indoor location of fire fighters in an emergency area. Through a unique gateway, equipped with WiMAX and LDR-LT UWB interfaces, the information carried by UWB signals can be transmitted through a WiMAX network without weakening. This integrated LDR-LT UWB/WiMAX device, installed on a truck, allows the interconnection between the fire fighters and the headquarters. It transmits the position of fire fighters, who carries LDR-LT UWB nodes that implement a location system (Figure 41).

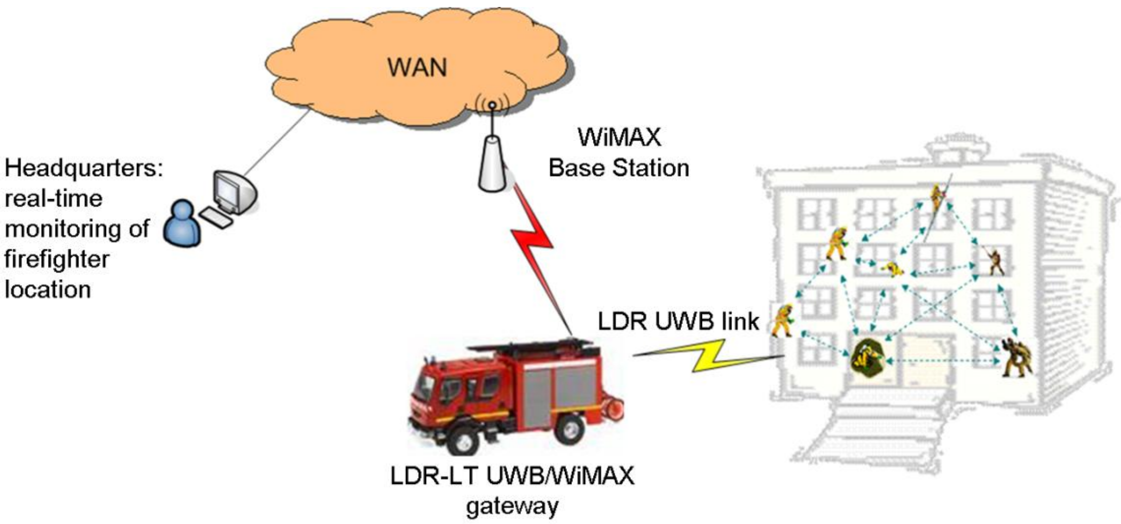


Figure 41: UWB localisation of fire fighters in indoor environment

The headquarters is connected to the Internet and can be physically located anywhere. It is connected to the dual LDR-LT UWB/WiMAX device thanks to a VPN (virtual private network), which secures the link between the headquarters and the dual LDR-LT UWB/WiMAX device. The headquarters will be able to track in real-time each node of the network and will be able to send useful information to the nodes on the field (map of the building, position of the victims).

This scenario requires high accuracy of positioning information and must be independent from classical positioning systems, which are not suitable in indoor environments.

5. European and Global Regulation and Standardisation

At a national level, the radio spectrum is managed by national administrations which adopt a national table of radio spectrum allocations, define a framework for its use and partition it among the different users via licenses or via license-free arrangements.

At the European level, the European Commission (EC), the European Telecommunications Standards Institute (ETSI) and the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) cooperate on matters related to the regulatory environment for radio equipment and spectrum both at the EU level and at the wider intergovernmental level across Europe.

5.1. European Union Radio Spectrum Regulatory Framework

The European Commission embodies and upholds the general interest of the European Union (27 countries). Its four main roles are: to propose legislation to Parliament and Council; to administer and implement Community policies; to enforce Community law; and, to negotiate agreements, mainly those related to trade and cooperation.

EU radio spectrum policy aims to coordinate spectrum management approaches across the Union. The overarching objective is to support the internal market for wireless services and to foster innovation in electronic communications and other sectors. It includes a regulatory framework to harmonise access conditions at EU level to ensure efficient use of radio spectrum and to enable interoperability of radio equipment. EU decisions and regulations take precedence in the EU over ECC decisions, which are non-binding, in cases where both measures exist in relation to the same issue.

CEPT is a cooperative body in Europe comprising 48 national regulatory administrations in the field of posts and telecommunications. The ECC of the CEPT brings together these countries to develop common policies and non-binding regulations in electronic communications and related applications for Europe, and to provide the focal point for information on frequency use. Its primary objective is to harmonise the efficient use of radio spectrum and satellite orbits. It takes an active role at the international level, preparing common European interests in the ITU and other international organisations.

5.2. The Role of ETSI in the European Radio Regulatory Environment

ETSI produces globally applicable standards for information and communications technologies (ICT), including fixed, mobile, radio, converged, broadcast and internet technologies. ETSI is officially recognised by the EU as a European standards organisation and is an independent, not-for-profit association. Its purpose is to produce and maintain the technical standards and other deliverables which are required by its members. ETSI also develops Technical Reports (TR) and System Reference Documents (SRDoc) providing technical, legal and economic background on new radio systems under standardisation and informs the ECC accordingly.

Within the ITU, CEPT in ITU Region 1 (Europe and Africa) is comparable to the Asian Pacific Telecommunity (APT) in Region 3 (Asia Pacific). In Region 2 (North and South America) the US Federal Communications Commission (FCC) is dominant in regulation and the Inter-American Telecommunication Commission (CITEL) for standardisation.

5.3. UWB Technology in the Regulatory and Standardisation Landscape

Any application which intends to use radio spectrum has to be allowed to do so by national administrations which hold the sovereign rights over spectrum usage within their national territories. On a world-wide level these administrations work together in the ITU(-R) to develop a harmonised frequency allocation for these applications, while taking into account that there is a world-wide market for radio-based products. Due to the fact that radio spectrum is a limited resource, industry (equipment manufacturers, service providers ...) and organisations (radio astronomy, military forces, meteorology ...) compete for bandwidth.

Products using UWB technology as described in EUWB, belong to the license-exempt short range device (SRD) category. They may be used on a non-interfering non-protected basis.

UWB devices already in, or expected to enter, the market use frequencies in the range between 2 GHz and 9 GHz which are already allocated to radio services as defined in the International Telecommunication Union (ITU) radio regulations. Therefore, the ITU has performed studies to investigate the coexistence of UWB and existing radio services [73],[74].

European regulations are being considered in several countries as the basis for the future regulation of UWB. The main EU regulatory parameters are depicted in Figure 42.

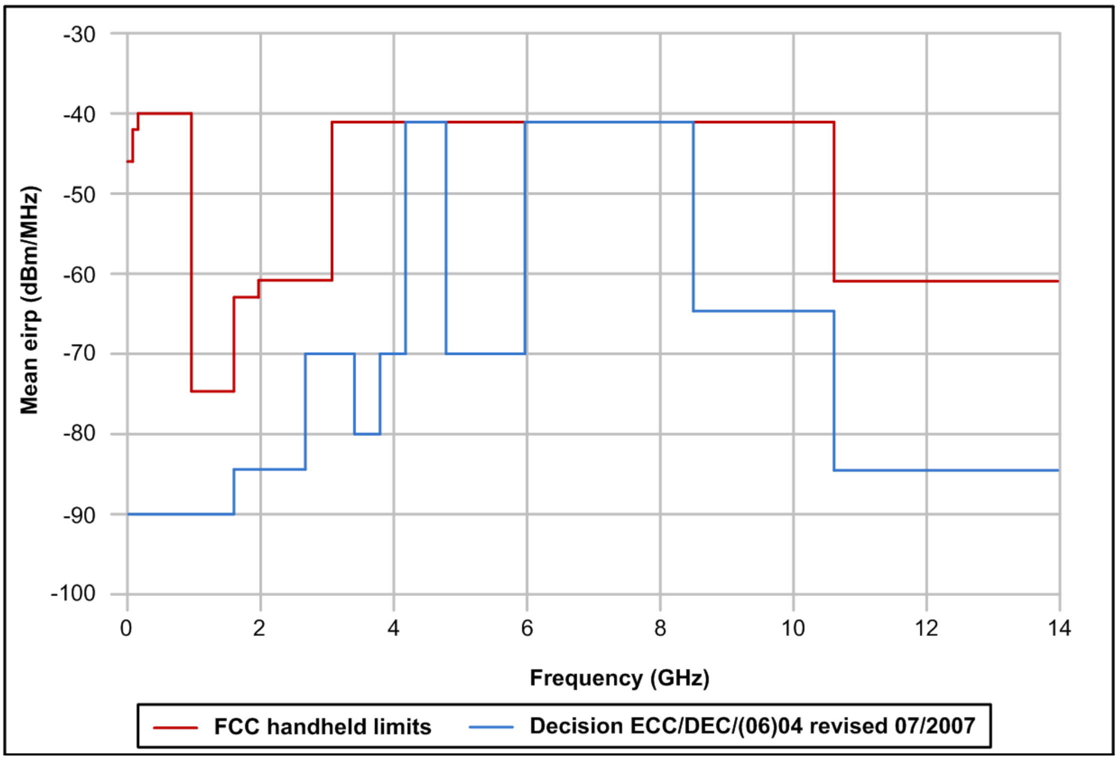


Figure 42: European spectrum mask compared to FCC regulation

Regulation in Japan has been fixed since 2006 and is now in a transition phase to a fully DAA-based approach. New inputs to the Ministry of Internal Affairs and Communication (MIC) can lead to simplification of the existing regulations. An increase of permitted power in the higher bands has already been requested. Further enhancement proposals such as the integration and consideration of specific environments have been agreed by interested UWB parties and will be forwarded to the MIC as soon as initial feedback has been received.

One of the major tasks of EUWB has been to convince the primary frequency user of a frequency range that UWB as an underlay technology neither harms nor interferes with this primary user and to prove this by means of studies and measurements. The outcomes of these EUWB activities are EC decisions, ECC decisions and ETSI standards.

In addition to the first recognised application for this technology of efficient broadband data transmission over short distances, new application areas have been discovered and are on the way to being realised. These are for instance location tracking and material analysis devices which use the physical transmission characteristics of broadband electromagnetic waves. This requires additional regulation and standardisation of frequency ranges and transmission levels compared to pure data transmission.

In EUWB the following regulation and standardisation activities have been carried out by the project partners or are underway and set to continue beyond the end of the project. ETSI classification, the work items (WI) and associated documents regarding UWB are illustrated in Figure 43 and Figure 44.

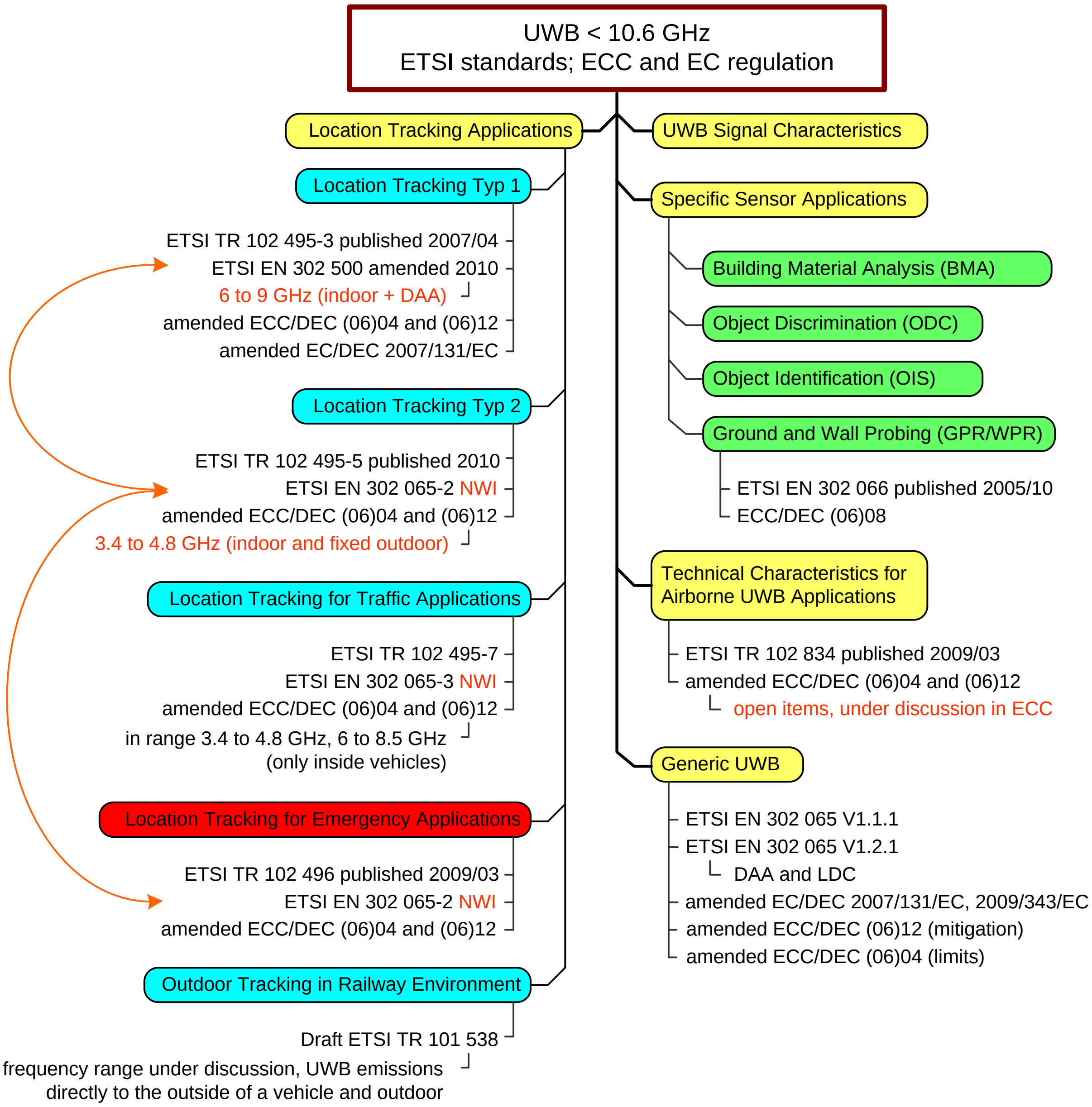


Figure 43: ETSI classification and documents related to UWB technology and applications

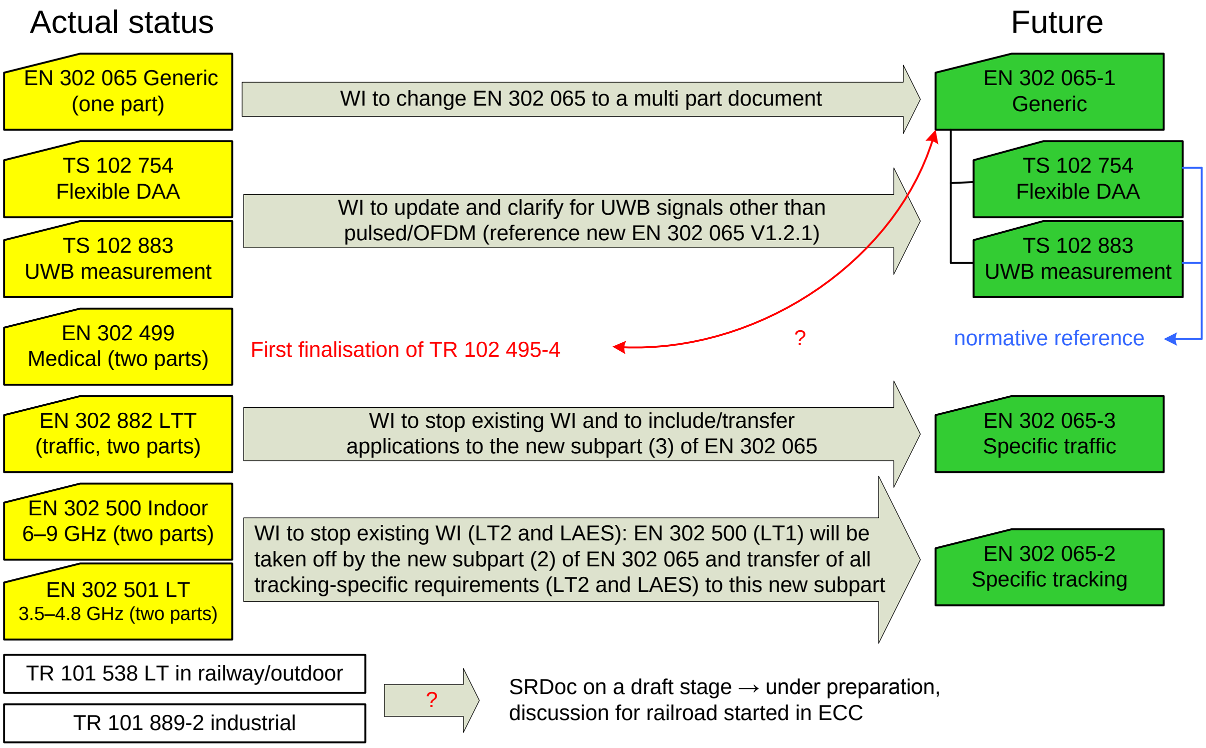


Figure 44: Current ETSI work items regarding UWB

In summary an intermediate conclusion in close collaboration with all players in the UWB field is an important step towards achieving a better regulatory environment in the various regions. In particular the inclusion of specific environment issues with additional mitigation factors and an increase of TX power in the upper band will only be possible if several players join forces. The partners within EUWB would be a good starting point. The creation of a world-wide UWB interest group covering the different technologies would be a further step in the right direction. This interest group would have as its main goal the coordination of inputs to the different regulatory bodies and their support during the development of harmonised standards along the lines of ETSI. Some partners in EUWB have already expressed their interest in participating in such an interest group.

6. Current State of the Market and Future Trends

UWB technology fills a significant gap in the marketplace. It enables the creation of products with a unique combination of features that meet the demands of modern consumers. The high data rates are consistent with the increasing need to synchronise and stream the ever-increasing amounts of media, video and other forms of data present in the everyday lives of ordinary people. Personal collections of devices (handsets, TVs, laptops, tablets) are becoming more commonplace and there is a strong drive to form them into personal ecosystems. The modest range, high data rates and lack of contention with established wireless technologies such as Bluetooth and Wi-Fi make it an ideal match for such personal networks.

If wireless technologies aimed at home and business end-users are to become pervasive they must be able to deliver consistent performance and be easy to integrate into products and have simple (preferably single) antenna requirements. They must also address the developing need for energy efficiency. UWB with its low power per bit is again well placed to fit in with our increasingly mobile lives and portable device collections.

Many of the problems with UWB standards in the early days have now been resolved. WiMedia and Wireless USB have published specifications and authorised networks of certification laboratories. In addition, the technology has room to grow with the higher data rates and energy-saving improvements defined in WiMedia 1.5.

Mature implementations are now available offering good data rates and consistent performance ready to take advantage of the UWB ‘killer application’. Historically, the catalyst for wireless communications was the headset in the case of Bluetooth and Ethernet replacement for Wi-Fi. The catalyst for UWB is video. It is found in an increasing variety of contexts and places, starting with PC to TV streaming. As multiple generations of similar products come to market and volumes increase, prices will go down and prevalence will drive recognition. The time is right for UWB as video connectivity becomes a significant concern for more and more devices in more diverse contexts (e.g. automotive, public transport etc.). Penetration of this market and the associated improved awareness will pave the way for the even higher data rates offered by VHDR.

Professional localisation applications, largely focused on urban deployments, require radio transmissions with a sufficient link budget margin for indoor operation generally in harsh environments. The current European regulation allows a mean E.I.R.P transmit power of –41.3 dBm/MHz in the 3.2–4.8 GHz band, preventing link budget greater than 50 metres in free space conditions. Therefore, the mentioned application cases in public transport, in the automotive or home environment and in heterogeneous environments are expected to be one of the main market fields of low data rate UWB with its high accuracy ranging capabilities.

To partly solve this barrier, two elements have been considered, as individual or complementary actions. The first solution consists of improving the receiver’s sensitivity by using modulations able to process the phase of the signal and by using coherent demodulators. Although significant, the gain obtained cannot considerably increase the range on its own. The second solution is based on an increased RF power at the transmitter output, an increase which can be limited to certain types of deployment such as emergency operations which are concerned with the life of citizens and for which the mercantile aspect can be held with the second plan. It is in this spirit there are ongoing discussion at the ETSI and CEPT to obtain a 20 dB increase in transmitted power in the 3.2–4.8 GHz band only for temporary emergency operations. If the regulation is fixed at this point, localisation applications for emergency services (LAES) are expected to enter the market.

All that remains is for standardisation bodies to continue to back the technology and implementers to continue refining their products, maintaining downward pressure on cost and improving robustness and simplicity of use. Finally, all participants should continue making the product manufacturers aware of the presence and value of UWB.

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