Ville Niemelä

EVALUATIONS AND ANALYSIS OF IR-UWB RECEIVERS FOR PERSONAL MEDICAL COMMUNICATIONS
VILLE NIEMELÄ

EVALUATIONS AND ANALYSIS OF IR-UWB RECEIVERS FOR PERSONAL MEDICAL COMMUNICATIONS

Academic dissertation to be presented with the assent of the Doctoral Training Committee of Technology and Natural Sciences of the University of Oulu for public defence in the OP auditorium (L10), Linnanmäki, on 10 March 2017, at 12 noon

UNIVERSITY OF OULU, OULU 2017
Impulse radio ultra-wideband (IR-UWB) technology, due to its baseband signaling, potentially offers a low cost, low complexity and low power consumption option for different short range sensor network applications. These sensor networks can be applied to many kinds of future implementations, including the Internet of Things (IoT) applications. In the medical and healthcare context, the term wireless body area network (WBAN) is often used, but, as mentioned, the wireless technology itself can be applied to any kind of body, e.g., to car or robot body networks.

This thesis studies IR-UWB receivers’ performances in different hospital environment channel models by means of computer simulation. The main focus is on receivers that are capable of detecting the signals specified either in the IEEE 802.15.4-2015 or in the IEEE 802.15.6-2012 standards. The used channel models from two independent research groups include both on-body to on-body and on-body to off-body scenarios in different hospital environments.

The evaluations and comparisons of various receivers include energy detector (ED) and rake receivers, the latter with both selective- and partial-rake structures. One of the studied receiver structures is further analyzed as it was noticed that the simulation results did not correspond to the assumed theoretical bit error probability (BEP) curves. Along the standards based studies, some modifications are also suggested for the two existing IR-UWB standards for increased compatibility and improved performance. One of the propositions resulted a Patent Cooperation Treaty (PCT) patent application. Additionally, an extensive survey is provided offering a compilation which includes presentations of IR-UWB research by other researchers, existing standards’ IR-UWB physical layer (PHY) specifications and the main global regulations concerning UWB.

Keywords: IEEE 802.15.4-2015, IEEE 802.15.6-2012, impulse radio, physical layer, ultra-wideband, wireless body area network, wireless personal area network
Niemelä, Ville, IR-UWB vastaanottimien arviointi ja analysointi henkilökohtaista lääketieteellistä tiedonsiirtoa varten.

Oulun yliopiston tutkijakoulu; Oulun yliopisto, Tieto- ja sähkötekniikan tiedekunta; Centre for Wireless Communications; Infotech Oulu


Oulun yliopisto, PL 8000, 90014 Oulun yliopisto

Tiivistelmä

Erittäin laajakaistainen impulssiradioteknologia (IR-UWB) tarjoaa potentiaalisen vaihtoehton yksinkertaisille, edullisille ja matalan tehonkulutuksen omaaville lähetin-vastaanotin-ratkaisuille, jotka soveltuvat lyhyen kantaman sensoriverkkoihin. Nämä sensoriverkot ovat monikäyttöisiä soveltuen esimerkiksi tulevaisuuden esineiden internetin (IoT) tiedonsiirtoratkaisuiksi. Esimerkiksi sairaanhoitoden ja terveydenhuolen asiayhteyksissä voidaan iskumaan monenlaisiin eri sovelluskohteisiin kuten autoon tai vaikka robotin "keholle".

Tässä väitöskirjassa on tutkittu tietokonesimulaatioiden avulla erilaisten IR-UWB vastaanotinrakenteiden suorituskykyä mallintavissa radiokanavissa. Tutkimuksen painopiste on vastaanottimissa, jotka kykenevät vastaanottamaan bonus IEEE 802.15.4-2015 tai IEEE 802.15.6-2012-standardeissa määriteltyjä signaaleja. Saatiin mallintamattomat radiokanavat perustuvat kahden toisistaan riippumattomien tutkimusryhmän mallintamii, jotka sisältävät sekä keholta-keholle että keholta-kehon ulkopuolelle -radiokanavanmallit.


Asiasonat: fyysinen kerros, IEEE 802.15.4-2015, IEEE 802.15.6-2012, impulsiradioteknologia, langaton henkilökohtainen verkko, langaton kehoverkko, ultralaajakaistainen teknologia
To my family
Preface

The work for this thesis was carried out during the years 2010-2016 at the Centre for Wireless Communications (CWC) at the University of Oulu. The main funding partners concerning this thesis have been the Finnish Funding Agency for Innovation (Tekes) and the Academy of Finland via the EWiHS (Enabling future Wireless Healthcare Systems) and DWHN (Dependable Wireless Healthcare Networks) projects, respectively. Both of these organizations are highly appreciated for supporting telecommunication research at CWC. Additionally, none of the work performed during these years would have been possible without the efforts and support of so many people who, at least some of them, I would now like to acknowledge personally.

First of all, both my supervisor Professor Jari Iinatti and advisor Docent Matti Hämäläinen deserve my warmest thanks for giving me the opportunity to pursue this doctoral degree. Besides co-authoring all of my publications, they were in charge of both the EWiHS and DWHN projects, from the very beginning. In addition, Matti was the person who interviewed me in late 2008 for a Master’s thesis position located in Vuokatti. Instead of Vuokatti, after the 45-minute interview, he offered me the opportunity to do my Master’s thesis in Italy! While enjoying in the magnificent scenery of Lago Maggiore, I had the privilege to work under the guidance of Dr.Sc. Alberto Rabbachin. Thank you Alberto for your skillful guidance and positive attitude which were the first initiators along the way leading me to consider a doctoral degree.

I would also like to thank another Kemi native Lic.Sc. Timo Kumpuniemi for the many conversations over the years and the ability to explain the basics of telecommunications in an understandable way. In addition to many on- and off-topic conversations, Timo also played a very important role in one of the papers included in this thesis.

Dr.Sc. Jussi Haapola deserves a big thanks for providing ever critical but even more constructive comments regarding different research questions and articles. You are often able to see a unique angle in your approach, which has been very useful for me and I believe for a few others as well. I hope that you never lose the sharp edge you have there.

Professor Ryuji Kohno acted as FiDiPro professor in the EWiHS project and over the years of the project provided valuable advice and broad perspectives on wireless communications. Thank you Ryuji for the various thoughts and moreover, the warm
hospitality that you and your staff at the Yokohama National University offered during my short research visit in early 2016.

Both my past and current office mates (Dr.Sc. Tommi Tuovinen, Dr.Sc. Heikki Karvonen and Lic.Sc. Juha Pyhtilä) are highly appreciated for helping me and for answering whatever questions I have had over the years. The WiMeC group (at least at some point in bureaucratic time it was called a group) members (Timo K., Tommi T., Heikki K., Harri Viittala, Juha Petäjäjärvi, Mariella Särestöniemi and Tuomas Paso) are also acknowledged here for sharing the collective productivity pressure and the numerous monthly meetings we had. I hope you get your degrees finished in no time.

Docent Kari Kärkkäinen is acknowledged as he has been around from the very beginning of my university studies, first as a tutoring teacher and later on as the chair of my follow-up group. Additionally, the pre-examiners, Professor Eryk Dutkiewicz and Associate Professor Tony Q.S. Quek, are highly appreciated for their efforts while evaluating this thesis.

I am also very grateful for the administrative personnel of CWC. Jari Sillanpää, Juha-Pekka Mäkelä, Kirsi Ojutkangas and Eija Pajunen who all keep the wheels turning in many ways. The administrative personnel also includes Hanna Saarela who, in addition to the administrative tasks, offered her assistance on English language issues that I encountered in my writing.

Furthermore, plenty of my warm thoughts go to Teemu Nyländen, Tuomo Hänninen, Kalle Kaisto, Karri Nikunen and a bunch of others who joined our guild room coffee breaks particularly in the first couple of years of the doctoral studies. Thank you guys for the coffee, company and bad jokes that you were also able to understand!

During these years, several Finnish foundations awarded personal grants for my doctoral studies. The financial support is highly appreciated and the acknowledgments go to the following foundations: Seppo Säynäjäkankaan Tiedesäätiö, Nokia Foundation, Walter Ahlström foundation, Riitta ja Jorma J. Takasen säätiö sr, Finnish Foundation for Technology Promotion (Tekniikan edistämisäätiö, TES) and Tauno Tönningin Säätiö.

Finally, my family Paula, Alma and Leevi, thank you for being there and for the balance you bring to me with the off-work activities. I can’t remember a boring moment during the past six-seven years. Additionally, big thanks go to my and Paula’s parents, Riku and Merja, Kari and Anneli, for helping us quite many times with the childcare assistance of Alma and Leevi. My sister Maija and her spouse Karo are also acknowledged for their kind help and support during this time and for providing me and my family a five star holiday base in Vantaa.
Symbols and abbreviations

\( \delta_j \)  
\begin{align*} 
& \text{delay of a signal presenting bit (sequence) } j 
\end{align*}

\( \tau_n \)  
\begin{align*} 
& \text{delay of the } n^{th} \text{ signal multipath} 
\end{align*}

\( \sigma^2 \)  
\begin{align*} 
& \text{noise variance} 
\end{align*}

\( A_i \)  
\begin{align*} 
& \text{amplitude of a signal presenting bit (sequence) } i 
\end{align*}

\( B \)  
\begin{align*} 
& \text{channel bandwidth} 
\end{align*}

\( B_f \)  
\begin{align*} 
& \text{fractional bandwidth} 
\end{align*}

\( C \)  
\begin{align*} 
& \text{link capacity} 
\end{align*}

\( c_m \)  
\begin{align*} 
& \text{differential encoding of the } m^{th} \text{ symbol} 
\end{align*}

\( d_n^m \)  
\begin{align*} 
& \text{the } n^{th} \text{ codeword component over the } m^{th} \text{ symbol} 
\end{align*}

\( E_b \)  
\begin{align*} 
& \text{energy per bit} 
\end{align*}

\( f_c \)  
\begin{align*} 
& \text{center frequency} 
\end{align*}

\( f_H \)  
\begin{align*} 
& \text{-10 dB upper point of the signal spectrum} 
\end{align*}

\( f_L \)  
\begin{align*} 
& \text{-10 dB lower point of the signal spectrum} 
\end{align*}

\( g_k^0 \)  
\begin{align*} 
& \text{the } k^{th} \text{ position modulated bit} 
\end{align*}

\( g_k^1 \)  
\begin{align*} 
& \text{the } k^{th} \text{ phase modulated bit} 
\end{align*}

\( h_{(2Km+n)} \)  
\begin{align*} 
& \text{time-hopping sequence of each waveform position for OOK modulation} 
\end{align*}

\( h_{(k)} \)  
\begin{align*} 
& \text{time-hopping sequence of the } k^{th} \text{ waveform position for BPM modulation} 
\end{align*}

\( h_{(m)} \)  
\begin{align*} 
& \text{time-hopping sequence of the } m^{th} \text{ waveform position for DPSK modulation} 
\end{align*}

\( h(t) \)  
\begin{align*} 
& \text{channel impulse response} 
\end{align*}

\( K \)  
\begin{align*} 
& \text{constellation mapper} 
\end{align*}

\( k \)  
\begin{align*} 
& \text{symbol index in the IEEE 802.15.4-2015 standard} 
\end{align*}

\( k_l \)  
\begin{align*} 
& \text{length of the bit sequence per modulation per symbol} 
\end{align*}

\( L \)  
\begin{align*} 
& \text{number of received signal multipaths} 
\end{align*}

\( M \)  
\begin{align*} 
& \text{number of different symbols} 
\end{align*}

\( m \)  
\begin{align*} 
& \text{symbol index in the IEEE 802.15.6-2012 standard} 
\end{align*}

\( N \)  
\begin{align*} 
& \text{number of bits} 
\end{align*}

\( N_0 \)  
\begin{align*} 
& \text{noise spectral density} 
\end{align*}

\( N_{cpb} \)  
\begin{align*} 
& \text{number of chips (pulses) per burst} 
\end{align*}

\( N_{hop} \)  
\begin{align*} 
& \text{number of time-hopping positions} 
\end{align*}

\( N_w \)  
\begin{align*} 
& \text{number of waveform positions} 
\end{align*}
\( n(t) \) additional white Gaussian noise process
\( p(t) \) pulse waveform
\( r(t) \) received signal
\( s_{n+kN_{ch}} \) scrambling code during the \( k \)th symbol interval
\( SNR \) signal-to-noise power ratio
\( t \) time
\( T_{\text{BPM}} \) half symbol duration
\( T_{\text{burst}} \) burst duration
\( T_{c} \) chip (pulse) duration in the IEEE 802.15.4-2015 standard
\( T_{\text{sym}} \) symbol duration in the IEEE 802.15.4-2015 standard
\( T_{\text{int}} \) integration interval
\( T_{p} \) pulse duration in the IEEE 802.15.6-2012 standard
\( T_{\text{sym}} \) symbol duration in the IEEE 802.15.6-2012 standard
\( T_{d} \) duration of \( u(t) \)
\( T_{w} \) waveform duration
\( u(t) \) locally generated reference signal
\( v \) decision variable for correlation receivers
\( v_{\text{di}} \) decision variable for energy detector receivers
\( v^{(m)} \) decision variable of the \( m \)th symbol for correlation receivers
\( w_{2N_{m}+n} \) scrambling sequence of a burst waveform
\( w(t) \) burst waveform
\( x(t) \) transmitted waveform
\( x^{k}(t) \) the \( k \)th transmitted waveform in the IEEE 802.15.4-2015 standard
\( x^{m}(t) \) the \( m \)th transmitted waveform in the IEEE 802.15.6-2012 standard
\( X_{1} \) random independent Gaussian variable
\( X_{2} \) random independent Gaussian variable
\( X_{1c} \) random independent Gaussian variable
\( X_{1s} \) random independent Gaussian variable
\( Y_{i} \) decision variable

5G 5th generation cellular systems
a-rake all rake
ARIB Association of Radio Industries and Businesses
AWGN additional white Gaussian noise
BEP bit error probability
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BER</td>
<td>bit error rate</td>
</tr>
<tr>
<td>BPM</td>
<td>burst position modulation</td>
</tr>
<tr>
<td>CM3</td>
<td>channel model 3</td>
</tr>
<tr>
<td>CWC</td>
<td>Centre for Wireless Communications</td>
</tr>
<tr>
<td>DAA</td>
<td>detect and avoid</td>
</tr>
<tr>
<td>DARPA</td>
<td>Defense Advanced Research Projects Agency</td>
</tr>
<tr>
<td>DBPSK</td>
<td>differential binary phase-shift keying</td>
</tr>
<tr>
<td>DPSK</td>
<td>differential phase-shift keying</td>
</tr>
<tr>
<td>DQPSK</td>
<td>differential quadrature phase-shift keying</td>
</tr>
<tr>
<td>DWHN</td>
<td>Dependable Wireless Healthcare Networks</td>
</tr>
<tr>
<td>ECC</td>
<td>Electric Communications Committee</td>
</tr>
<tr>
<td>ED</td>
<td>energy detector</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>EWiHS</td>
<td>Enabling future Wireless Healthcare Systems</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>EIRP</td>
<td>equivalent isotropic radiated power</td>
</tr>
<tr>
<td>FSK</td>
<td>frequency-shift keying</td>
</tr>
<tr>
<td>QoS</td>
<td>quality of service</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IR</td>
<td>impulse radio</td>
</tr>
<tr>
<td>ISM</td>
<td>industrial, scientific and medical</td>
</tr>
<tr>
<td>ISI</td>
<td>inter-symbol-interference</td>
</tr>
<tr>
<td>LDC</td>
<td>low duty cycle</td>
</tr>
<tr>
<td>MAC</td>
<td>medium access control</td>
</tr>
<tr>
<td>MB</td>
<td>multi-band</td>
</tr>
<tr>
<td>OOK</td>
<td>on-off keying</td>
</tr>
<tr>
<td>OSD</td>
<td>Office of the Secretary of the Defense</td>
</tr>
<tr>
<td>OFDM</td>
<td>orthogonal frequency division modulation</td>
</tr>
<tr>
<td>p-rake</td>
<td>partial rake</td>
</tr>
<tr>
<td>PHR</td>
<td>physical layer header</td>
</tr>
<tr>
<td>PHY</td>
<td>physical layer</td>
</tr>
<tr>
<td>PPDU</td>
<td>physical layer protocol data unit</td>
</tr>
<tr>
<td>PSDU</td>
<td>physical layer service data unit</td>
</tr>
<tr>
<td>PAM</td>
<td>pulse amplitude modulation</td>
</tr>
<tr>
<td>PCT</td>
<td>Patent Cooperation Treaty</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>PPM</td>
<td>pulse position modulation</td>
</tr>
<tr>
<td>PSK</td>
<td>phase-shift keying</td>
</tr>
<tr>
<td>PSM</td>
<td>pulse shape modulation</td>
</tr>
<tr>
<td>RF</td>
<td>radio frequency</td>
</tr>
<tr>
<td>RFID</td>
<td>radio frequency identification</td>
</tr>
<tr>
<td>RS</td>
<td>Reed-Solomon</td>
</tr>
<tr>
<td>s-rake</td>
<td>selective rake</td>
</tr>
<tr>
<td>SHR</td>
<td>synchronization header</td>
</tr>
<tr>
<td>WBAN</td>
<td>wireless body area network</td>
</tr>
<tr>
<td>WLAN</td>
<td>wireless local area network</td>
</tr>
<tr>
<td>WPAN</td>
<td>wireless personal area network</td>
</tr>
<tr>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>UWB</td>
<td>ultra-wideband</td>
</tr>
</tbody>
</table>
List of original publications

This thesis is based on the following articles, which are referred to in the text by their Roman numerals (I – IX):


VI Niemelä V, Hämäläinen M & Iinatti J (2013) On IEEE 802.15.6 UWB Symbol Length for Energy Detector Receivers’ Performance with OOK and PPM. In: The 7th International Symposium on Medical Information and Communication Technology (ISMICT), Tokyo, Japan: 33-37. DOI: 10.1109/ISMICT.2013.6521694


IX Niemelä V, Hämäläinen M & Iinatti J (2011) Improved Usage of Time Slots of the IEEE 802.15.4a UWB System Model. In: The 2nd International Workshop on Future Wellness and Medical ICT Systems in conjunction with the 14th International Symposium on Wireless Personal Multimedia Communications (WPMC), Brest, France, 1-5.

Professor Jari Iinatti supervised all the Papers [I] – [IX]. Similarly, for all the papers [I] – [IX], guidance and scientific support was provided by Docent Matti Hämäläinen. Dr.Sc. Jussi Haapola provided guidance and scientific advices for Papers [I] and [V]. Dr.Sc. Attaphongse Taparugssanagorn was in charge of the UWB hospital channel models.
and provided technical guidance related to them in Paper [III]. Regarding Paper [IV], Professor Ryuji Kohno contributed with scientific advice. Lic.Sc. Timo Kumpuniemi was involved in Paper [VIII], in which the mathematical analysis of the non-coherent IR-UWB receiver was the result of joint work of him and the author of this thesis.

Other than the above mentioned contributions, the author has written all the Papers [I] – [IX] and has developed the Matlab simulator and is responsible for the simulation results and the related evaluations presented in Papers [II] – [IX].

The work for this thesis has been conducted mainly in two projects. The Finnish Funding Agency for Innovation (Tekes) partly funded the EWiHS (Enabling future Wireless Healthcare Systems) project during the years 2011-2014 and the Academy of Finland partly funded DWHN (Dependable Wireless Healthcare Networks) project during the years 2013-2016.
Contents

Abstract
Tiivistelmä
Preface 9
Symbols and abbreviations 11
List of original publications 15
Contents 17

1 Introduction 19
   1.1 UWB history in brief with different UWB definitions 19
   1.2 Motivation and author’s contribution 22
   1.3 Outline 24

2 Regulations and standardization of UWB technology 25
   2.1 Main global regulations 25
   2.2 IEEE 802.15.4-2015 27
   2.3 IEEE 802.15.6-2012 30

3 IR-UWB signal modulation, detection and propagation channel 33
   3.1 Modulation methods 33
   3.2 Receiver structures 35
   3.3 Propagation channel 39

4 Summary of the original articles 43
   4.1 IR-UWB research based on the two existing standards 43
   4.2 Performance evaluation of IR-UWB receivers 44
      4.2.1 IEEE 802.15.4-2015 signal model and different hospital
            channel models 44
      4.2.2 IEEE 802.15.4-2015 signal model and two different WBAN
            channel models 47
      4.2.3 IEEE 802.15.6-2012 signal model and two different WBAN
            channel models 49
   4.3 Analysis of non-coherently detected orthogonal signal 50
   4.4 Bypassing PPM — enhancing scalability and network traffic volume 52

5 Conclusions 55
   5.1 Discussion 55

17
5.2 Future work ................................................................. 56
References 59
Original publications 65
1 Introduction

1.1 UWB history in brief with different UWB definitions

The history of ultra-wideband (UWB) can be traced to the 19th century and to the spark-gap transmitters which were initially used to generate electromagnetic signals. Short electromagnetic sparks, i.e., pulses, are the basis of the communications technology that is currently known as impulse radio (IR) UWB. Spark-gap equipment was used by Heinrich Hertz in the late 1880s to prove the existence of electromagnetic waves, predicted by James Clerk Maxwell in his theory of electromagnetism. Spark-gap technology was developed over the years based on the work of radio pioneers, such as Guglielmo Marconi and Oliver Lodge. These early radio systems were used for wireless transmissions of Morse code, thus replacing the wired telegraph system. Yet, the spark-gap technology at that time did not enable speech transmissions which soon became a desirable feature. By the end of the 1910s, due to inventions like the super-heterodyne receiver (by Edwin Howard Armstrong) and the development of electron tubes, continuous wave technology became dominant for wireless transmissions, enabling speech transmissions and radio signal broadcasting. The technological development of continuous waves basically ended the short pulse system development for a couple of decades. [1][2][3]

The IR concept began to attract again in the 1960s, which is also seen as the starting point for modern UWB technology. The research started with radar applications and proceeded soon to communications. [3] The term UWB was first presented by the Office of the Secretary of the Defense (OSD) and the Defense Advanced Research Projects Agency (DARPA) in the late 1980s [4]. During the 1990s, UWB started to interest the academic community, too. One of the first landmark publications was [5], followed by several others, e.g., [6] [7] [8] [9] with increasing interest to the topic. In 2002, the Federal Communications Commission (FCC) became the first regulatory body to define the UWB signal and the radio frequency allocation for UWB transmissions. A signal is considered a UWB signal if the minimum bandwidth is at least 500 MHz or the fractional bandwidth is greater than 0.2. The fractional bandwidth is expressed as [10]

\[ B_f = \frac{f_H - f_L}{f_H + f_L} \]  

(1)
where \( f_H \) and \( f_L \) are the upper and the lower –10 dB points of the signal spectrum, respectively. As stated in [10], the dual definition for a UWB signal basically means that "UWB systems with a center frequency greater than 2.5 GHz need to have a –10 dB bandwidth of at least 500 MHz while UWB systems operating with a center frequency below 2.5 GHz need to have a fractional bandwidth of at least 0.20."

The Electric Communications Committee (ECC) established its UWB regulations initially in 2006 and updated them in 2007 and in 2011 [11]. According to the ECC’s UWB definition [11], "UWB technology shall mean technology for short-range radiocommunication, involving the intentional generation and transmission of radio-frequency energy that spreads over a very large frequency range, which may overlap several frequency bands allocated to radiocommunication services".

The Japanese Association of Radio Industries and Businesses’ (ARIB) definition for UWB originated in 2006 with updates from 2008, 2010 and 2015 [12]. Based on the ARIB’s definition, a signal is UWB if its bandwidth is 450 MHz or more, measured from –10 dB points of the signal spectrum. All of the aforementioned regulatory bodies also specify maximum equivalent isotropic radiated power (EIRP) limits for UWB transmissions and designate available spectrum for UWB. This is presented in Section 2.1 in detail.

An attempt to standardize UWB for the first time was made in 2003 by the IEEE 802.15.3a task group [13], but it was withdrawn as a unanimous decision was not reached between the two competing proposals, multi-band (MB) and IR [14]. The MB-UWB approach was later included into another standard called ECMA-368 [15]. The main difference between the MB and IR approaches is that the MB approach is based on traditional (i.e., continuous wave) narrowband technology and the IR approach is based on a nanosecond scale impulse (or impulses) without carrier signal. In MB, the UWB definition (FCC in general) is fulfilled by multiple sub-carriers as in IR, a nanosecond scale impulse is adequate.

The second attempt to standardize IR-UWB succeeded in 2007. The standard IEEE 802.15.4a-2007 specified an IR-UWB physical layer (PHY) and it was an amendment to the IEEE 802.15.4-2006, a standard for low-rate Wireless Personal Area Networks (WPANs). The two WPAN standards were merged together in 2011 and the latest revision is IEEE 802.15.4-2015 [16]. The second UWB standard by the IEEE was published in 2012, IEEE 802.15.6-2012 [17], and it is for wireless body area networks (WBANs). These two standards and their UWB PHYs are presented in detail in Paper [I] and briefly in Sections 2.2 and 2.3.
In addition to the UWB topic, Figure 1 presents the popularity development of UWB, in terms of the number of annually published papers from the IEEE Xplore data base (on the 20th of January, 2017), presenting the majority of the published articles concerning UWB research. Visible in Figure 1, the most popular time for UWB research was in the late 2000s, and during the 2010s so far, the interest in UWB has been decreasing every year. Another curiosity is that nearly 30 years after the first definition of UWB, the writing of the term ‘ultra-wideband’ still varies. The original writing by OSD/DARPA was ‘ultra-wideband’ [4]. This was followed by the regulatory bodies of FCC [10], ECC [11] and ARIB [12] as well as the European commission driven UWB project EUWB [18]. Moreover, different writings include also ‘ultra-wide band’ by the IEEE 802.15.4-2015 [16], ‘ultra wideband’ by the IEEE 802.15.6-2012 [17] and ECMA-368 [15], ‘ultrawideband’ by [3] and [19], ‘ultra-wide-band’ by [20], ‘ultra wide band’ by [21] and ‘ultra-wide bandwidth’ by [22] and [9].

Fig. 1. The annual number of UWB publications in the IEEE Xplore Digital Library (Paper [I] © 2016 IEEE).
1.2 Motivation and author’s contribution

Currently, two popular and widely used short-range wireless technologies are Bluetooth [23] and ZigBee [24], standardized as the IEEE 802.15.1 and IEEE 802.15.4, respectively [25]. The data rate capability of Bluetooth, depending on the version used, is up to 24 Mbps and for ZigBee up to 0.25 Mbps [26]. Considering the two IEEE standards with UWB specifications, the WBAN standard provides PHY layer data rates up to 15 Mbps [17] and the WPAN standard up to 27 Mbps [16]. The ECMA-368 standard’s theoretical capability is claimed to be up to 480 Mbps [15].

For different medical applications, the data rate requirements are diverse. Measurements such as blood pressure, temperature, heart rate or oxygen level require some kilobits per second of data transmission whereas more demanding measurements like electrocardiograph or electromyograph can take few mega bits per second, depending on the number of sensors used in the measurements [27] [28] [29]. If video or medical imagining is utilized, its data transmission requirement can be up to 10 Mbps [27]. From this viewpoint, ZigBee is useful only for the measurements with modest data transmission requirements as the rest of the technologies can be used for a wide range of measurements. ECMA-368 and its orthogonal frequency division modulation (OFDM) is capable even of high definition video transmissions with a data rate of hundreds of megabits per second.

When considering the fundamental characteristics of UWB, the high bandwidth signal can provide capacity advantages. The Shannon’s link capacity formula is [30]

\[ C = B \log_2(1 + SNR) \]

where \( B \) is the channel bandwidth and \( SNR \) presents the signal-to-noise power ratio. The link capacity increases linearly with the bandwidth increase and has a logarithmic relation on capacity to the SNR increase.

Yet, when comparing other features, e.g., accurate positioning, power consumption, interference aspects and spectrum availability, UWB technology and particularly the IR option seems attractive. Due to the high frequency signals, UWB can provide centimeter accuracy in positioning [31] [32] [33] [34] which is especially interesting for indoor applications. The baseband nature of IR-UWB communications provides potential low-power and low-complexity features for transceiver structures [35] [36] [37] [38]. Moreover, due to the low level equivalent isotropic radiated power (EIRP) and the wide occupied bandwidth, UWB offers low probability of interception of signals as a security
feature and it provides low interference to the existing narrowband systems [39] [40] [41]. Also, the globally available UWB spectrum can be a valuable addition to the rather crowded industrial, scientific and medical (ISM) radio bands that Bluetooth, ZigBee and also wireless local area network (WLAN) devices are operating in. The article [42] summarizes the current spectrum challenges briefly and presents a low power cognitive radio based IR-UWB system to overcome the interference issues in short range communications.

For future Internet-of-Things (IoT) applications, either medical or non-medical, these qualities of IR-UWB makes it an attractive option. As concluded in Paper [I], a dual radio chip composed of both WPAN and WBAN standards can be one choice to meet these requirements. A dual radio solution could enable an IoT device with a very long battery life which could measure the condition of a human or a machine, offer radio frequency identification (RFID) with accurate ranging without causing interference to other radio technologies.

In this thesis, the aim is to provide thorough evaluations of different receiver structures that can be used for detecting the IR-UWB signal models specified in the two IEEE standards – the IEEE 802.15.4-2015 and the IEEE 802.15.6-2012. The goal is to compare these receivers’ performances in different WBAN channel models to provide understanding of how the receiver performances vary in different hospital environments and what kinds of receiver structures would be optimal in these environments in terms of bit error rate (BER). The evaluations include energy detector (ED) receivers and rake receivers with different numbers of rake fingers. There is also an analysis presented here that provides insights into an IR-UWB receiver structure whose performance is differentiated from the narrowband counterpart structure. This difference is not known to have been demonstrated earlier than in Paper [VIII]. Additionally, there are several ideas presented in the papers included in this thesis that suggest modifications to the existing standards to improve the compatibility of the standards, receivers’ detection performance, data rate capabilities or adaptability of the standard based systems to different demands of future IoT networks. Finally, this thesis provides an updated survey in which the latest global regulatory updates concerning UWB can be found along with a detailed presentation of the two IR-UWB PHY specifications and a broad literature review from the past ten years.

Regarding the author’s contribution to the original papers, the author has written all the Papers [I] – [IX] that are included in this thesis. The Matlab based transceiver system simulator is also constructed by the author of this thesis and thus, the simulation

1.3 Outline

This dissertation is organized as follows: The main UWB regulations and the standards’ PHY specifications are introduced in Chapter 2. The UWB regulations define limitations for indoor UWB transmissions specified by the corresponding regulatory bodies from the United States (US), Canada, the European Union (EU), China and Japan. The presentations of the standards’ PHYs in Chapter 2 focus on the two existing IEEE standards specifying IR-UWB – the IEEE 802.15.4-2015 [16] and the IEEE 802.15.6-2012 [17].

Presentations of IR-UWB modulation methods and receiver structures are provided in Chapter 3. The modulation methods include pulse amplitude modulation (PAM), pulse position modulation (PPM), binary phase-shift keying (BPSK), differential BPSK (DBPSK), on-off keying (OOK), frequency-shift keying (FSK) and pulse shape modulation (PSM). The receiver structures capable of detecting the signal modulated accordingly include an ED receiver and different rake receivers.

A summary of the results of the original articles is presented in Chapter 4. The number of articles included in this dissertation is nine and the summary of the results in Chapter 4 is divided into four subsections. Finally, the dissertation is concluded in Chapter 5 with some discussion and a considerations for few future work.
2 Regulations and standardization of UWB technology

This chapter presents UWB technology from regulatory and standardization perspectives. The main global regulations are presented in Section 2.1 and the IR-UWB PHY specifications of the two published IEEE standards are presented in Sections 2.2 and 2.3. The topic of this chapter was also one of the main points in Paper [I], in which the UWB PHYs of the both standards are presented in a detailed manner together with the latest updates to the global UWB regulations. In the current literature, to the best knowledge of the author, there do not exist any articles that would present a compilation of the both IR-UWB PHYs and the global UWB regulations. The IR-UWB transceiver system simulation models that are utilized throughout Papers [II] – [IX] are based on the PHY specifications of either the IEEE 802.15.4-2015 [16] or the IEEE 802.15.6-2012 [17].

2.1 Main global regulations

The global UWB spectrum regulations are diverse and in general, defined separately for devices targeted for either indoor or outdoor usage. In this section, the focus is on indoor UWB regulations. Common to all the regulations, the maximum EIRP radiation level is -41.3 dBm/MHz. The allowed frequency band, on the other hand, varies quite a lot. Figures 2 and 3 present the UWB EIRP regulations for indoors in the US [10], Canada [43], and in China [44] and Japan [12], respectively. In addition to these, at least South-Korea [18], Australia and Singapore [45] are among the countries which have defined UWB radiation limits.

Regarding the North-American radiation limits presented in the upper subplot of Figure 2, the spectrum allocation is straight forward. The US regulations by the FCC [10] allow UWB transmission with a maximum EIRP level on the sub-gigahertz band (< 960 MHz) and on the band of 3.1 – 10.6 GHz. The Canadian regulatory body sets the frequency band limits to 4.8 – 10.6 GHz [43].
Fig. 2. US, Canadian and European UWB EIRP limits for indoors.

Fig. 3. Chinese and Japanese UWB EIRP limits for indoors.
When considering the FCC’s sub-gigahertz band (< 960 MHz) and the fractional bandwidth definition in (1), it is worth noticing that a signal with center frequency, $f_c$, of 870 MHz ($f_H = 960$ MHz, $f_L = 780$ MHz) needs 180 MHz of bandwidth to qualify as UWB. Additionally, the frequency band for channel #1 of the WPAN standard [16] is 250 – 749 MHz. To fulfill the UWB definition with $f_c = 500$ MHz, the actual bandwidth needs to exceed 100 MHz ($f_H = 550$ MHz, $f_L = 450$ MHz).

The rest of the regulatory bodies including EU regulations utilize two separate frequency bands with interference mitigation techniques. Generally, the low band is between 3.1 – 4.8 GHz and the high band between 6 – 10.3 GHz. In contrast to the North-American regulations, the other regulatory bodies have set the EIRP level for UWB transmissions in the band of 4.8 – 6 GHz on a low level, very often to -70 dBm/MHz. Usually in the low band, an interference mitigation technique is required. In the EU regulations presented in the lower subplot of Figure 2, either detect and avoid (DAA) or low duty cycle (LDC) are required in the 3.1 – 4.8 GHz band and DAA in the high band extension of 8.5 – 9.0 GHz.

The Chinese regulatory specifications in the upper subplot of Figure 3 are very similar to the specifications for Singapore and Australia. The low band in Singapore is 3.4 – 4.8 GHz, in Australia 3.6 – 4.8 GHz and in China 4.2 – 4.8 GHz and the usage of the low bands requires interference mitigation techniques. The high band in China and Singapore is 6 – 9 GHz and in Australia it is 6 – 8.5 GHz.

The Japanese UWB regulations in the lower subplot of Figure 3 are very similar to the Korean UWB EIRP limits. The low band in Japan is 3.4 – 4.8 GHz and in Korea 3.1 – 4.8 GHz and the interference mitigation in this band is required in both countries. In the Korean specifications, DAA is specified. The high band in Japan is 7.25 – 10.25 GHz and in Korea it is 7.2 – 10.2 GHz.

In conclusion, the frequency band between 7.25 – 8.5 GHz is the only globally available band for an indoor UWB device. If interference mitigation is utilized, the available band is extended to 4.2 – 4.8 GHz and to 8.5 – 9 GHz bands with one exception: Canada is the only country/region which does not allow the indoor usage of UWB devices below 4.8 GHz with a maximum EIRP of -41.3 dBm/MHz.

2.2 IEEE 802.15.4-2015

The IEEE 802.15.4-2015 [16] standard’s UWB PHY specifications were presented in detail in Paper [I]. The standard for UWB PHY was first published in 2007, and
was updated in 2011 and in 2015. It is targeted at wireless personal area networks and therefore referred to as the WPAN standard in this thesis, also following the practice applied in Paper [I]. The focus in this section is on presenting the key specifications that are relevant to the simulated transceiver system.

Regarding IR-UWB PHY for the WPAN standard [16], there are two modulations specified; burst position modulation (BPM, corresponding to PPM) and BPSK. In contrast to the WBAN standard specification, these two modulations are utilized as a combination. A bit is first modulated into the position of the burst and a second bit is then modulated to the phase of the same burst. Generally, the phase modulated bit is a convolutional coded bit because the position modulated bit is a data bit. In this way, it is possible to detect the signal either coherently or non-coherently and receive the same information. Thus, coherent detection can be used for improving the detection performance.

Another standard specified channel coding method is Reed-Solomon (RS) encoding. RS-bits are position modulated and thus, can also be detected by receivers with non-coherent detection. However, the receiver side decoding of either of the above mentioned channel encoding means is optional since both of the encoding methods are systematic and redundant. Therefore, if desired, the receiver can simply ignore the coded bits without the improvement for the detection performance. The BPM-BPSK modulated and transmitted waveform during $k^{th}$ symbol interval is [16]

$$x^k(t) = [1 - 2g_1^{(k)}] \Sigma_{n=1}^{N_{cpb}} [1 - 2s_{n+kN_{cpb}}] p(t - g_0^{(k)} T_{BPM} - h^{(k)} T_{burst} - n T_c)$$

where $g_0^{(k)}$ and $g_1^{(k)}$ present the bits modulated into the position and the phase of the transmitted burst, respectively. $N_{cpb}$ is the number of chips, i.e., pulses per burst. The sequence $s_{n+kN_{cpb}} \in \{0, 1\}, n = 0, 1, ..., N_{cpb} - 1$ is the scrambling code during the $k^{th}$ symbol interval. $p(t)$ is the mandatory pulse shape at the antenna input and $T_{BPM}$ presents the half symbol delay of the position modulation. $h^{(k)} \in \{0, N_{hop} - 1\}$ is the burst time-hopping position, where $N_{hop}$ defines the number of possible hopping positions during one symbol interval, $T_{burst}$ is the burst length and $T_c$ is the duration of one pulse.

The data rate of the IR-UWB PHY is from 0.11 Mbps up to 27.24 Mbps. Similarly to the specifications in IEEE 802.15.6-2012, the data rate is related to the symbol duration and the burst duration. The highest data rates are achieved with the shortest symbol and burst durations. The shortest symbol duration is 32 ns corresponding to a burst of two pulses and it corresponds to the highest data rate of 27.24 Mbps. The longest symbol
duration is 8205 ns, which corresponds to the lowest data rate of 0.11 Mbps with various options for the burst lengths. The highest number of pulses per burst is 512. [16]

Figure 4 presents the UWB symbol specified in the standard, where \( T_{dsym} \) is the duration of one symbol interval. The duty cycle can have different values depending on the number of hopping positions during one symbol quarter. The value of \( N_{hop} \) can be 2, 8 or 32 and the corresponding duty cycle is 12.5 %, 3.1 % or 0.8 %, respectively.

\[
T_{BPM} = \frac{T_{dsym}}{2}
\]

\[
T_{burst} = N_{cpb} \times T_c
\]

Fig. 4. IEEE 802.15.4-2015 UWB symbol structure (Paper [I] © 2016 IEEE).

Figure 5 presents the flowchart of the transmitter as it is specified in the standard. When compared to the simulation models in Papers [II] – [V] and [IX], a few aspects have been omitted as they are not relevant to the receiver structure simulations and comparisons. These are the bits of physical layer service data unit (PSDU), which are randomly generated in the simulations, the physical header (PHR) and the synchronization header (SHR) bits, as they are assumed to be known and they are not the focus of the research. Neither is radio frequency (RF) front-end modeled in the simulations, as it is normal procedure with the simulation approach when not specifically focusing on this aspect.
2.3 IEEE 802.15.6-2012

A detailed description of the IEEE 802.15.6-2012 [17] PHY specification for UWB is presented in Paper [I]. The standard is targeted at wireless body area networks and therefore it is referred to the WBAN standard in this thesis, following the practices applied in Paper [I]. Similarly to the previous section, the focus here is on presenting the key specifications that are relevant to the simulated transceiver system.

Besides frequency modulation (FM) UWB, there are two IR-UWB modulations specified in the WBAN standard; on-off keying (OOK) and differential phase-shift keying (DPSK). The differential modulation can be implemented in binary or in quadrature phases. The binary option (DBPSK) is targeted at the traditional IR-UWB with a pulse duration of typically less than 2 ns and the quadrature (DQPSK) targets a chirp pulse type signaling constructed on one relatively long pulse. In the simulations presented in Paper [VI], OOK modulation was applied and in Paper [VII], DBPSK was applied. With the OOK modulated signal, the transmitted waveform in the $m^{th}$ symbol is expressed as [17]

$$x^m(t) = \sum_{n=0}^{2K-1} x_n^m w_{2Km+n} p(t - n(T_{sym}/2) - mK T_{sym} - n(2Km+n) T_w)$$  \hspace{1cm} (4)
where $K$ is a constellation mapper mapping either 1 or 4 bits per symbol to a code word. In the simulations in Paper [VI], $K$ was set to 1. $d_n^m$ is the $n$th code word component over the $m$th symbol. $T_{\text{sym}}$ is the symbol time, $h^{(2Km+n)}$ is the time-hopping sequence of each waveform position and $T_w$ is the duration of the waveform which corresponds to the pulse duration $T_p$ when single pulse option is applied. $w_{2Km+n}$ is a scrambling sequence of a burst waveform with a duration of $T_w$ consisting of $N_{\text{cpb}}$ concatenated and dynamically scrambled short pulses, each of a duration of $T_p$.

A linear feedback shift register specifies both the scrambling code of the pulses in the burst and the time-hopping sequence. The same register is also applied to the DBPSK and DQPSK signaling, but without pulse scrambling because a static scrambling is utilized. The transmitted $m$th waveform with DBPSK and DQPSK modulation is [17]

$$x^m(t) = \sum_{m=0}^{N} c_m w(t - mT_{\text{sym}} - h^{(m)}T_w)$$  \hspace{1cm} (5)

where $N$ is the number of bits of the physical layer protocol data unit (PPDU), which is a frame format composed of bits that are converted into RF signals. With DQPSK, $N$ is divided by two. $c_m$ is the differential encoding of the symbol which carries one bit of information with DBPSK and two bits with DQPSK. $w(t)$ is the pulse waveform constructed of $N_{\text{cpb}}$ concatenated and statically scrambled pulses. With DBPSK modulation, the minimum value of $N_{\text{cpb}}$ is specified as two in the standard.

The IR-UWB PHY layer data rate scale is from 0.487 Mbps up to 15.60 Mbps with OOK modulation. With DBPSK, the data rate scale is from 0.487 Mbps up to 7.80 Mbps. The data rate depends on the symbol duration and the burst duration defined by the number of pulses; the shortest symbols contain the shortest bursts and provide the highest data rates. The duration of one OOK modulated symbol is from 64 ns up to 2051 ns with corresponding burst durations of 2 ns (equals to one pulse) and 64 ns (32 pulses). For DBPSK, these are from 128 ns up to 2051 ns for symbol durations with 4 ns to 64 ns for burst durations, respectively. [17]

The UWB symbol structure specified by the WBAN standard [17] is presented in Figure 6. For OOK, the symbol is divided into two halves due to the waveform coding with a code-word length of $2K$. The duty cycle is limited to $1/N_w$ which corresponds to 3.125% due to the number of pulse waveform positions, $N_w$, set to 32 by the standard. Figure 7 presents the flowchart of the transmitter as it is specified in the standard with the two possible IR modulations.

A few aspects have been omitted from the standard specifications when compared to the simulation models in Papers [VI] and [VII], as they are not relevant to the receiver
structure simulations and comparisons. These are the bits of the PSDU which are randomly generated in the simulations, the PHR and the SHR bits as they are assumed to be known and are not the focus of the research. Neither is the RF front-end modeled in the simulations as it is normal procedure in the simulation approach when not specifically focusing on it. The spreading, which is optional with DBPSK/DQPSK, was also left outside of this research.

Fig. 6. IEEE 802.15.6-2012 UWB symbol structure (Paper [I] © 2016 IEEE).

Fig. 7. IEEE 802.15.6-2012 IR-UWB transmitter structures (Paper [I] © 2016 IEEE).
3 IR-UWB signal modulation, detection and propagation channel

This chapter introduces the modulation methods that are generally used in IR communications, and presents different receiver structures used to detect the IR signal and also briefly describes the channel models used in the evaluations. While this thesis focuses on IR-UWB, the following modulations are also widely used in narrowband communications and they can be utilized in IR communications whether the UWB definitions are fulfilled or not. The majority of the presented modulations are utilized in either of the two standards, presented in the previous section. The rest of the presented modulations are introduced to provide a more thorough description of UWB communications and because Paper [IX] suggested that utilizing other modulations than the ones specified in the standards could be beneficial for optimizing some specific features such as detection performance.

Regarding the presented receiver structures, some modulations require specific receivers for the signal detection. For example, PSK based signaling requires a coherent detection method while PPM or OOK can be detected by both coherent and non-coherent receivers. In general, coherent detection is more complex in real implementation than non-coherent detection but coherent detection provides better performance metrics, too. In addition, the channel conditions can make a significant difference to the performance of a receiver. One of the goals of this thesis is to evaluate different receiver structures in different channel conditions, in this case, different WBAN channels inside a hospital environment. The evaluations include both partial (p) and selective (s)-rake receivers with a wide range of rake fingers against the performance of the ED receiver. The rake receivers are based on coherent detection and the ED receivers are constructed with non-coherent detection.

3.1 Modulation methods

Different modulations that can be used in IR-UWB include at least the following:

- PAM – pulse amplitude modulation
- OOK – on-off keying
- BPSK – binary phase-shift keying
– DBPSK – differential binary phase-shift keying
– PPM – pulse position modulation
– PSM – pulse shape modulation
– FSK – frequency-shift keying

A signal modulated with PAM, OOK, BPSK, DBPSK or PPM can be expressed as

$$x(t) = A_i p(t - \delta_j)$$ (6)

where $A_i$ is a unique amplitude out of $2^k$ different amplitudes of a signal, $p(t)$ is the transmitted pulse (or burst of pulses) and $\delta_j$ represents a unique position in time out of $2^k$ different positions (delays) of a signal. Different $A_i$ values are applied in PAM, OOK, BPSK and DBPSK and different $\delta_j$ values in PPM. The $i$ and $j$ are defined as

$$i, j = [0, \ldots, (2^k) - 1], \quad k_l = 1, 2, 3, 4, \ldots$$ (7)

where $k_l$ is the length of the bit sequence per modulation per symbol. Typically, the value of $k_l$ does not exceed 2 as IR-UWB communications are considered low complexity. If one modulation only is utilized, then $\delta_j = 0$ for PAM, OOK, BPSK and DBPSK. For PPM only, the $A_i$ is constant and $\delta_j$ presents $2^k$ different delays. Additionally with one modulation of a signal, either $i$ or $j$ present the decimal value of the bit sequence.

If a modulation combination is utilized, the length of the bit sequence per symbol is summed up as $k_l$ per modulation method, i.e., $nk_l$, $n$ presenting the number of different modulations utilized. With a modulation combination, for example BPSK-PPM, both $A_i$ and $\delta_j$ are applied.

OOK, BPSK and DBPSK are presented together with PAM as they can be seen as binary special cases of the amplitude modulation. For them all, OOK, BPSK and DBPSK, $k_l = 1$ and the value of the transmitted bit is either zero or one and the value of $i$ is accordingly

$$i = \begin{cases} 0, \text{ or} \\ 1 \end{cases}$$ (8)

Yet, the difference is that with OOK, a signal is not transmitted (= off-state) when expressing the other bit, generally bit zero, and a signal is transmitted (= on-state), which generally presents a bit one as

$$A_i = \begin{cases} 0, \text{ when } i = 0 \\ 1, \text{ when } i = 1 \end{cases}$$ (9)
In the BPSK, opposite phases of the signal are used to express the different bits as

\[
A_i = \begin{cases} 
-1, & \text{when } i = 0 \\
1, & \text{when } i = 1 
\end{cases}
\] (10)

If (10) is applied to DBPSK, \(A_i\) presents the amplitude of the previous bit as the information is carried by the phase change of consecutive symbols/bits.

PSM and FSK are expressed with different pulse waveforms, \(p(t)\), instead of different amplitudes or delays. In PSM, \(2^k\) different pulse shapes are used and, generally, they are orthogonal to each other [46] [47], for example, the 1st and the 2nd derivatives of Gaussian pulses [35] [48]. Hermite pulses are also used and studied [46] [48] [49] with PSM. FSK is a rarely used expression in IR-communications but using a different length of the pulses results in different center frequencies [48] [50], which can be used to express \(2^k\) different bit sequences. This principle is similar to traditional narrowband communications with FSK [51] and it has also been applied to IR-UWB under the expression of “time-energy frequency distribution” [52].

Regarding the IR-UWB modulations, Paper [I] also presents a literature review on different modulation combinations that can be utilized in IR-UWB communications. Both [35] and [48] provide illustrative figures on different modulations and their differences. Additionally in [48], a detailed table is presented related to the pulse width and to the Gaussian derivatives and their effect on pulse behavior in the frequency domain.

3.2 Receiver structures

A general division regarding different receiver structures is based on the knowledge of the signal phase. When the phase information is utilized at the receiver, a receiver is coherent and if the phase is not utilized, it is non-coherent. Coherent receivers are based on a correlation between the received signal and a reference/template signal and non-coherent receivers, in general, are energy detector (ED) receivers. The following presents receiver structures and detections methods that are relevant for this thesis and that are applied in the included Papers.

A typical expression for the received signal is [51]

\[
r(t) = x(t) * h(t) + n(t), \quad 0 \leq t \leq T
\] (11)
where \( x(t) \) is the transmitted signal as, e.g., in (6), \( h(t) \) is the channel impulse response, * states the convolution and \( n(t) \) is additive white Gaussian noise (AWGN) with a two-sided power spectral density of \( \sigma^2 = \frac{N_0}{2} \). In correlation based receivers, a locally generated reference signal is expressed as

\[
u(t) = x(t) * h(t).	ag{12}\]

The decision variable with maximal ratio combining technique for the coherent detection is

\[
v = \sum_{n=1}^{L} \int_0^{T_u} r(t - \tau_n) u(t) dt
\]

(13)

where \( L \) is the number of received signal multipaths, \( T_u \) is the length of \( u(t) \) and \( \tau_n \) is the delay of the \( n \)th multipath propagated signal. When considering rake receivers that receive multipath propagated signals for decision making, an all (a)-rake receiver is a theoretical approach taking into account all the possible multipath components. An s-rake receiver selects the \( n \) strongest multipath components and a p-rake receiver combines the \( n \) first arrived multipath components for the decision making. Both the a-rake and s-rake receivers require estimations of all the possible multipaths which demands a high level of computing power. Therefore, a p-rake is the simplest of the rake receiver options.

For the decision making, there are several options. If the transmitted signal is modulated with BPSK or DBPSK, \( v \) is compared to zero as

\[
\begin{align*}
\text{−1}^v & \text{ if } v \leq 0. \\
\text{0}^v & \text{ otherwise.}
\end{align*}
\]

(14)

If \( v \) is greater than zero, the bit is detected as 1, otherwise it is 0. The difference between the BPSK and the DBPSK is that in the BPSK the \( u(t) \) is as it is defined in (12) but in the DBPSK, \( u(t) \) is the previously received symbol including AWGN noise. Another option is to perform differential decoding of the DBPSK modulated IR-signal by utilizing the locally generated reference as in (12). The decision for the differential decoding is executed by multiplying the two consecutive decision variables as

\[
\begin{align*}
\text{−1}^{v(m-1) \times v(m)} & \text{ if } v^{(m-1)} \times v^{(m)} \leq 0. \\
\text{0}^{v(m-1) \times v(m)} & \text{ otherwise.}
\end{align*}
\]

(15)
If the multiplication of the consecutive decision variables is positive, the \( m \)th received bit is 1, otherwise it is 0. In other words, if there is a phase change between the consecutive symbols, a bit 0 has been received and if the phase remains the same, a bit 1 is received. The probability of error in the differentially encoded BPSK is approximately twice as high as in the BPSK [51].

In binary orthogonal signaling with coherent detection, the decision making is performed as

\[
\begin{align*}
&0^* \quad v_0 \geq v_1. \\
&1^* \quad v_0 < v_1.
\end{align*}
\]

This can be applied to PPM, PSM or FSK. If \( k_l > 1 \) signaling is applied, the largest \( v_i \) is selected.

In correlation based receivers, non-coherent detection of orthogonal signals can be applied to PPM, OOK, PAM, PSM, or FSK. The decision variables for binary signaling for PPM, PSM and FSK are absolute values of the correlation output as

\[
\begin{align*}
&1^* \quad |v_0| \geq |v_1|. \\
&0^* \quad |v_0| < |v_1|.
\end{align*}
\]

If \( k_l > 1 \) signaling is applied, the largest \( v_i \) is selected. With OOK and PAM, non-coherent detection requires estimations of thresholds, to which the decision variable \( |v_i| \) is compared. For example, in [53] regarding auto-correlation receivers, due to the threshold estimation, OOK is not considered a low complexity modulation option.

ED receivers are also receivers that perform non-coherent detection and can be used in PPM, OOK, PAM or FSK modulations. The decision variable is

\[
v_{ed} = \int_0^{T_{int}} r(t)^2 dt
\]

where \( T_{int} \) is the integration time which in the Papers of this thesis is optimized for the used channel model. In binary PPM and FSK decisions, it is based on direct comparison as

\[
\begin{align*}
&1^* \quad v_{ed0} \leq v_{ed1}. \\
&0^* \quad v_{ed0} > v_{ed1}.
\end{align*}
\]

If \( k_l > 1 \) signaling is applied, the largest \( v_{edi} \) is selected. In OOK and PAM decisions, it requires the threshold estimation procedure. Paper [V] presented different threshold
estimations techniques briefly and few other propositions can be found, e.g., in [54] and [55].

Figure 8 presents the well-known bit error probability (BEP) curves for different binary signal detection methods. The dashed curves with different markers include the BEPs of BPSK, differential encoded BPSK, coherent and non-coherent detections of orthogonal signals (binary FSK) which have been thoroughly analyzed, for example, in [51]. Additionally, Figure 8 presents a BEP curve with a solid line for the binary orthogonal IR-signal with non-coherent detection that was analyzed in Paper [VIII].

![Fig. 8. Widely known and approved theoretical BEP curves together with the novel BEP curve which was analyzed and presented in Paper [VIII].](image)

The receiver structure investigations presented in Papers [II] – [IX] are based on the decision rulings presented in (13) – (19). Paper [VII] presented two BER curves under AWGN conditions. The two receivers detected the BPSK and differentially encoded BPSK modulated IR-UWB signals, based on the decision rulings in (13) and (14). The BER of the BPSK and the differentially encoded BPSK modulated IR-UWB signals are equal to the theoretical BEP curves of the corresponding narrowband signals, presented in Figure 8.
and analyzed, e.g., in [51]. While performing the analysis of the binary orthogonal signaling with non-coherent detection, presented in Paper [VIII], the coherent detection of the PPM modulated IR-UWB signal (according to (16)) was also evaluated. The BER curve matches the BEP curve of the binary FSK curve in Figure 8. The binary orthogonal IR-UWB signal with non-coherent detection does not match the narrowband non-coherent FSK and it is analyzed in Paper [VIII] and summarized in Section 4.3.

There are several different receiver structures that perform the demodulations presented in (13) – (19). Categorization of these receivers is somewhat challenging. As pointed out at the beginning of this section, the general division is between coherent and non-coherent receivers and for example, [56] present a comparison of coherent and non-coherent receivers. In [56] though, the compared non-coherent receiver is a rake receiver performing differential detections between the consecutive symbols. Differential detection is sometimes considered a non-coherent detection method because the actual phase is not estimated but the phase change is.

Another option for the categorization could be the division between the ED receivers and rake receivers. The ED receivers are perhaps the easiest to categorize with non-coherent squaring and integration of the received signal. Additionally, in the UWB literature, there are number of articles that deal with them. One of the latest, [57], proposes an ED structure for the bio-implanted IR-UWB devices. Other articles include, e.g., [58], [59], [60] and [61], the last one presenting a signal time-of-arrival accuracy comparison between a correlation based receiver and an ED receiver.

The rake receivers’ category would then include both coherent and non-coherent detection schemes that utilize the correlation operation, including autocorrelation receivers [53][62] and different signaling options, such as transmitted reference [63][64][65]. Different rake receivers are also a popular topic and the article [66] was one of the first publications to consider rake receivers in UWB communications. Other articles dealing with rake receivers include, at least, [56], [67], [68] and [69] which suggests the use of UWB rake receivers at 60 GHz frequencies.

3.3 Propagation channel

UWB propagation studies interested researchers at the start of the 2000s resulting in a number of published measurements and analyses, for example, [70], [71] and [72]. A measurement and simulation based UWB channel model [73] that gained wide acceptance in the research community was also accepted as a standard UWB channel
model by the IEEE 802.15.4a Task Group. The channel model in [73] for WBANs was measured in an anechoic chamber with several distances between the transmitter and a receiver on a human body. The resulting channel models are averaged results over these distances and do not include indoor environment reflections from the walls or from typical indoor equipment, e.g., tables.

During the development of IEEE 802.15.6-2012 [17], the channel modeling subcommittee of the IEEE 802.15.6 published a technical report regarding channel models for body area networks [74]. The document includes an on-body to on-body UWB channel model, which is named channel model 3 (CM3). Another measurement study on UWB body area networks was executed by the Centre for Wireless Communications (CWC) [75][76]. The resulting UWB WBAN channel models, based on the measurements and analysis, are named CWC channel models. Both CM3 and CWC channel models are based on fixed antenna locations on a human body in hospital environments, in contrast to the averaged approach of the [73] in an anechoic chamber. These two UWB WBAN channel models, CWC and CM3, have been utilized in the simulations in the majority of the Papers included in this thesis. A more precise, CWC channel model is utilized in Papers [II] – [VII] and [IX] and CM3 is utilized in Papers [IV] – [VII]. For further reading on UWB channel models and propagations, the latest studies include at least [77], [78], [79], and [80].

Figure 9, published in Paper [IV] presents the channel impulse responses of the two channel models. As compared briefly in Papers [IV] – [VII] and more thoroughly in [81], there are quite big differences between the two channel models, both in terms of the number of arrival paths and the delay distribution of the signal arrival paths. In CM3, the average number of arrival paths is 38 [74] and they are almost evenly distributed within the 70 ns window. In the CWC channel model, the first arriving signal cluster contains most of the signal energy and there are over 500 distinguishable arrival paths on average [82].
Fig. 9. Normalized impulse responses of the used channel models (Paper [IV] © 2011 ACM).
4 Summary of the original articles

This chapter briefly summarizes the results of the original articles. The results have been divided into four sections. Section 4.1 presents the work of Paper [I] related to the existing research on standard based IR-UWB studies. Section 4.2 presents the work of Papers [II] – [VII]. These papers evaluate IR-UWB receivers capable of detecting the signal models defined in the two published IEEE standards. In Section 4.3, the results of Paper [VIII] are summarized; an IR-UWB receiver structure that detects orthogonal signal in non-coherent manner is analyzed and its performance is compared to the corresponding narrowband receiver’s BEP. Section 4.4 presents an idea for bypassing PPM modulation, which was published in Paper [IX].

4.1 IR-UWB research based on the two existing standards

Paper [I] surveyed research that is related to the two existing standards on IR-UWB, particularly that concerning PHY research. The main focus of the paper is on the time scale of 2007 – 2015, i.e., starting from the first release of the WPAN standard. During this time scale and to the best knowledge of the author, there are only three articles that can be considered as UWB review articles which are [83], [84] and [85]. However, none of these three presents a compilation that would provide UWB PHY specifications for the two IEEE standards, global UWB regulatory definitions and a comprehensive literature survey jointly, in one article. Additionally, Paper [I] presented and categorized the published articles based on different research topics. These topics included ranging, interference and medical scenarios, among a few other areas. Channel and propagation topics as well as medium access control (MAC) were excluded from the focus of Paper [I], because they constitute extensively wide topics on their own and recent detailed articles already existed, for example [86] [87] and [88]. Besides IR-UWB, MB-UWB was briefly presented and compared to IR-UWB together with the two main short range technologies, i.e., ZigBee and Bluetooth. Additionally, Paper [I] presented the leading global regulatory restrictions for indoor UWB and detailed descriptions of the UWB PHYs specified in the IEEE 802.15.6-2012 and in the IEEE 802.15.4-2015. The paper provides an in-depth overview of the IR-UWB research, a detailed presentation of the standards’ PHY specifications and the regulatory definitions. The regulatory aspects and
the standards’ specifications were presented also in Chapter 2 of this thesis, based on the presentations in Paper [I].

4.2 Performance evaluation of IR-UWB receivers

This section presents the results of Papers [II] – [VII]. The results are divided into three subsections. In Sections 4.2.1 and 4.2.2, the results are presented for receivers able to detect the WPAN standard defined signal model and in Section 4.2.3, for the receivers able to detect the WBAN standard signal model.

In Section 4.2.1, the focus is on receiver performance for different channel models inside a hospital. In Sections 4.2.2 and 4.2.3, the receivers’ performances are evaluated in two channel models which have been constructed by different authors. The UWB channel models were CM3, an on-body link defined by the IEEE 802.15.6-2012 channel modeling subcommittee [74] and a corresponding UWB channel model based on the measurements carried in a real hospital environment [82] by the CWC.

4.2.1 IEEE 802.15.4-2015 signal model and different hospital channel models

Paper [II] presented receiver performance comparisons in a measured and modeled hospital environment [82]. There were five different receiver structures able to detect the WPAN standard defined signal model. A sixth receiver structure that detected only the phase information of the signal was used as a reference. Table 1 presents the receiver structures with different demodulations and the number of bits per symbol. One or more of these receiver structures are used for the evaluations also in Papers [III] – [V] and in Papers [VIII] – [IX], depending on the focus of each paper.

Figure 10 presents the BER performances of the different receiver structure types in a regular hospital room. Note that types 3-6 present the performance curves of a-rake receivers which is not a realistic implementation but indicates an ideal performance. Other BER comparisons in Paper [II] included ED receiver and p- and s-rake receivers with different numbers of rake fingers. Also the BER improvement for Reed-Solomon encoding was demonstrated in the CWC channel model in which the errors, in general, come up in bursts.

It was found in Paper [II] that a correlation based p-rake receiver in the used hospital channel required at least 10 rake fingers to have equal or better performance
on a BER level of $10^{-3}$ compared to a simpler ED receiver. With the s-rake receiver, the required number of rake fingers is 4 to reach the same performance as the ED receiver. Additionally, the performance of the s-rake receiver was found to saturate with

**Table 1. Different receiver types, demodulation and bits per symbol.**

<table>
<thead>
<tr>
<th>Receiver types</th>
<th>BPM detection</th>
<th>BPSK detection</th>
<th>Bits/symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>Energy detection</td>
<td>no</td>
<td>1 data bit</td>
</tr>
<tr>
<td>Type 2</td>
<td>Energy detection</td>
<td>yes</td>
<td>2 data bits</td>
</tr>
<tr>
<td>Type 3</td>
<td>Binary orthogonal</td>
<td>no</td>
<td>1 data bit</td>
</tr>
<tr>
<td>Type 4</td>
<td>Binary orthogonal</td>
<td>yes</td>
<td>1 data bit +</td>
</tr>
<tr>
<td>Type 5</td>
<td>Binary orthogonal</td>
<td>yes</td>
<td>2 data bits</td>
</tr>
<tr>
<td>Type 6</td>
<td>No / Assumed to be known</td>
<td>yes</td>
<td>1 data bit</td>
</tr>
</tbody>
</table>
approximately 15 fingers in the used channel model. When comparing the difference between the best (in this case the ideal a-rake, type 6) and the worst performing receiver (ED receiver, type 1) structure, it was noted to be up to approximately 8 dB, visible in Figure 10. The effect of the Reed-Solomon encoding in the BER curve inspections was found to be less than 1 dB. Paper [II] also provided a description of the IEEE 802.15.4-2015 UWB PHY specifications relevant to the transceiver system simulator and a detailed presentation of the evaluated receiver structures.

Paper [III] focused on p-rake receiver performances in two different hospital environments, a regular hospital room and a surgery room [82]. Figure 11 presents a comparison of three different receiver structures with an increasing number of rake fingers and with fixed $E_b/N_0 = 13$ dB. Additionally, the performance of the ED receiver is presented for comparison.

![Fig. 11. P-rake receiver comparisons in two different hospital channel models (Paper [III] © 2011 IEEE).](image)

Based on the results of Figure 11 and the other results in Paper [III], there are quite big differences in the detection performances of the p-rake receivers in the two different hospital environments. With 15 fingers or less, the performance of the p-rake receiver
is worse in a regular hospital room than in a surgery room. The saturation point for p-rake receivers is achieved with 12 fingers in the surgery room and it requires more than 20 fingers in a regular hospital room for the performance to reach saturation on the fixed $E_b/N_0$ level. The performance differences are due to the different channel models in these two hospital environments. As stated in Paper [III], there was more medical equipment in the surgery room in close range of the human body than in the regular hospital room which may cause the second arriving signal cluster to scatter and therefore, the performance of p-rake receivers with small number of fingers is better in the surgery room. Additionally, Paper [II] presented a comparison of the number of measured multipaths which came to over 450 in the regular hospital room and approximately 300 in the surgery room. This results in better performance for p-rake receivers in the surgery room with a small (and equal) number of fingers because the proportional energy is bigger in the surgery room than in the regular hospital room.

When comparing the p-rake performance curve to the ED receiver’s performance curve, it is noted that depending on the channel model, selected ED receiver parameters and the inspected p-rake receiver structure, the required number of fingers for the p-rake receiver varies from 3 to 10 to achieve the same performance as the ED receiver on the same channel and with the same $E_b/N_0$ value.

4.2.2 IEEE 802.15.4-2015 signal model and two different WBAN channel models

Papers [IV] and [V] presented BER results for different receiver structures in the two aforementioned UWB channel models. Figure 9, in Section 3.3, presented the channel impulse responses of these two channel models. Figure 12 presents the optimized integration intervals for different burst lengths to be used with the channel models. Figure 9 was presented in Paper [IV] and Figure 12 in Paper [V]. As discussed earlier, there are quite big differences between the two channel models, both in terms of the number of arrival paths and the delay distribution of the signal arrival paths.

Regarding the integration interval differences visible in Figure 12, there is only a small BER improvement in the CWC channel model when the interval is extended in addition to the symbol duration as the BER clearly improves in CM3 resulting up to 60 – 70 ns of extension. The BER difference between different burst lengths is due to the normalization of energy. With a longer burst, the receiver needs to integrate a longer
burst period which increases the noise power at the receiver, thus a signal with fewer pulses results in a better BER performance with the ED receiver.

Due to the differences in the used channel models, the BER performances of the receivers also vary. It was noted in Paper [IV] that when using CWC channel models, the BER performances of p-rake receivers saturate with approximately 10 rake fingers, as in the case of CM3, the BER improves as the number of rake fingers is increased. The reason for this are the different number of signal arrival paths and how their magnitudes are distributed with different delays. In the CWC channel, the first arriving signal cluster contains relatively more energy vs. noise than in the CM3. Additionally, when increasing the number of received and processed signal components, i.e., taps, the proportional number of taps is much higher in CM3 than the CWC channel model and thus, contains much more signal energy. Similar comparisons were presented in Paper [IV] for an s-rake receiver, but with a fixed number of correlator branches. In that paper, the differences between the same receiver structures in the two different channel models were from 6 to 8 dB on a BER level of $10^{-3}$.

Paper [V] concentrated on evaluating the BER of ED receivers in the two channel models by different authors. For optimizing the channel specific BER performance,
both the integration interval and the energy threshold in OOK detection were examined and optimized by simulation before the actual receiver performance simulations. BER curves were used to compare the receivers in the two different channel models and to compare the difference between the two demodulation methods – OOK and PPM. OOK is defined as a mandatory modulation in the WBAN standard and PPM in the WPAN standard. Note that the simulated OOK was not a detailed construction of the WBAN specification, but a modification of the PPM. In the WBAN standard’s OOK specifications, minimum two-bit code-words are specified. This was not applied in Paper [V], because the WBAN standard was published at the same time the paper was being finalized.

Based on the results presented in Paper [V], the difference between the two modulation methods was found to be 2 – 4 dB and the channel model’s impact on this difference was small. In contrast to this, the differences between receivers with the same modulation in different channel models was fairly big. For example, to achieve BER level of $10^{-4}$ in the CM3 required $E_b/N_0 = 18$ dB with PPM-ED and $E_b/N_0 = 21$ dB with OOK-ED. For the CWC channel models, these were 28 dB and at least 32 dB, respectively. Other than these comparisons, it was presented in Paper [V] that the predefined OOK threshold evaluations with a good degree of precision would require high-resolution accuracy leading to highly increased simulation times.

4.2.3 IEEE 802.15.6-2012 signal model and two different WBAN channel models

Paper [VI] compared ED receivers’ performances in the CM3 [74] and in the CWC channel models [82]. The ED receivers were able to detect the WBAN standard specified signal model and their integration times were optimized for both of the studied channel models.

Two different modulations were utilized in the studied ED receivers, PPM and OOK. This is due to the signal model specified in the WBAN standard. The OOK modulation with a two-bit code-word is equal to binary PPM and thus, both demodulation methods can be used at the receiver end. In addition to the optimized integration interval, the energy threshold related to the OOK demodulation’s decision variable was also optimized for both of the used channel models and for different $E_b/N_0$ values. For the used WBAN standard’s specified symbol durations, the two shortest ones (corresponding to the highest
PHY data rates) were chosen to evaluate the impact of the inter-symbol-interference (ISI) on the ED receivers’ performances in the used channel models.

The results presented in Paper [VI] demonstrated that, depending on the channel model, ISI can significantly impact the performance of a receiver. If the highest data rate provided by the WBAN standard is desired, it can cause ISI in certain channel conditions reducing the receiver performance. In addition to the BER performance comparisons, Paper [VI] also presented the optimized integration times for different channel models, showed a few optimized OOK energy threshold values and demonstrated the standard’s time-hopping sequence specification which tries to prevent ISI between the consecutive symbols.

Paper [VII] presented simulation results for receivers capable of detecting the differentially encoded BPSK signal. DBPSK modulation is mandatory in the WBAN standard for the high quality of service (QoS) mode and optional in the default mode [17]. BER curves are presented using both AWGN and the two WBAN channel models. The AWGN BER curves are identical to the theoretical curves, thus verifying the correctness of the simulation model. The BER curves in the WBAN channel represented the performances of ideal receiver structures, i.e., a-rake receivers taking into account all the different propagation paths at the receiver. Besides the BER comparisons with different channel models, Paper [VII] demonstrated the differences between two demodulations that can be used for WBAN standard defined signal detection. If using a previous received signal as a template, the detection performance decreases by approximately 10 dB when compared to an option where a noiseless signal template is utilized with differential decoding. The channel model was found to have an approximately 5 dB impact on the performance difference. The receivers in the CM3 channel model performed better than the same receivers in a much more scattered CWC channel model.

4.3 Analysis of non-coherently detected orthogonal signal

Paper [VIII] analyzed the BEP of a binary orthogonal signaling receiver with non-coherent detection. It was demonstrated that there is a difference between the traditional narrowband receiver with binary orthogonal non-coherent detection and an IR-UWB receiver with a corresponding receiver structure. Figure 13 presents the two receiver structures with FSK and PPM modulations, respectively.

The narrowband receiver is able to detect the binary modulation of FSK and the IR-UWB receiver is able to detect a binary PPM modulated signal. For the narrowband
FSK, the decision variable is the well-known square root-sum of the two independent Gaussian variables which for the IR-UWB receiver can be transformed to a simpler presentation as

\[ Y_1 = \sqrt{X_{1s}^2 + X_{1c}^2} \rightarrow Y_1 = |X_1| \quad (20) \]

where \(X_{1s}, X_{1c}\) and \(X_1\) are independent random Gaussian variables. With a zero mean, the square root expression is also known as the Rayleigh distribution with two degrees of freedom. For a non-zero mean, a Rician distribution with two degrees of freedom is utilized [89].

For the IR-UWB, a simplified form is applied. The absolute value of \(X_1\) corresponds to the folded normal distribution with a non-zero mean. This is also referred to as the Rician distribution with one degree of freedom. For a zero mean, this corresponds to half a normal distribution or a Rayleigh distribution with one degree of freedom. [90]

The BEP analysis is presented in Paper [VIII] and its results was shown in Figure 8 in Section 3.2. The BEP of the IR-UWB receiver with non-coherent detection is smaller (= better) than the narrowband orthogonal signaling BEP curve with non-coherent
detection. Regarding the BEPs of the coherent detection with both orthogonal and antipodal signals, the IR-UWB receiver and the narrowband receiver have identical BEPs but they are different when comparing them with non-coherent detection for orthogonal signaling. This has not, to the best knowledge of the authors, been analyzed before Paper [VIII].

4.4 Bypassing PPM — enhancing scalability and network traffic volume

Paper [IX] proposed an idea related to both PPM modulation and to the WPAN standard defined symbol structure. The UWB symbol structure was presented in Figure 4 in Section 2.3. According to a novel idea, the PPM modulation is bypassed and other IR-UWB modulation is used instead, including, at least, PAM, OOK, PSK, PSM and FSK.

Using other modulation leads to different possible options:

1. Doubling the data rate by transmitting two bits per symbol. Two bits equals two separate burst transmissions with one modulation method. Note that when applied to the WPAN (or WBAN) standard, it doubles the PHY data rate only.
2. Allowing an additional user to transmit during the other half of the symbol. This would require synchronization between two nodes and a hub, which does not follow the current MAC specifications of the standard where one node at a time transmits data to the hub.
3. Continuing transmitting one burst per symbol. The only effect of this is that the receiver receives and detects only one burst interval in contrast to the detection of two intervals when PPM demodulation is used.
4. Improving the BER performance by either sending the same data bits twice or using the additional bit for a channel encoded bit. This would increase the overhead while the PHY data rate would remain the same when compared to the original specifications.

Related to the first two options, it was verified in [91] that doubling the PHY data rate by sending two bits per symbol increases the successful traffic volume of a WPAN.
network by up to 74 percent. This is due to the reduced number of transmitted symbols from the nodes to the hub. The number of symbols per node per one superframe is limited in the standard. The result presented in [91] is the most important outcome of the idea presented in Paper [IX]. In addition, allowing the use of different modulations, including different combinations, would increase the scalability of a sensor network to adapt to different demands. These might be, e.g. BER performance, a high data rate or long battery life, which can all be partially optimized with the help of modulation.
5 Conclusions

This thesis studied several different receiver structures that are capable of detecting the IR-UWB signals defined either in the IEEE 802.15.6-2012 or in the IEEE 802.15.4-2015. The majority of the Papers presented BER performance curves of the receivers in two different UWB WBAN channel models. There was also an improvement presented in Paper [IX] concerning the used symbol structure and the PPM modulation of the IEEE 802.15.4-2015. The suggested improvement was filed as a patent application but left to expire due to a lack of external funding. A non-coherent receiver structure with binary orthogonal signaling was analyzed in Paper [VIII] and it was noted that there is a difference in BEPs between narrowband and IR receivers, a difference which is not known to have been reported earlier. Additionally, Paper [I] combined and presented detailed descriptions of the both IR-UWB PHYs of the two standards together with the existing global spectrum regulations and a comprehensive literature survey regarding the IR-UWB research related to the standards. Paper [I] also discussed the potential data rate increase of the current standards, based on the solutions found in the literature.

5.1 Discussion

One of the challenges for UWB are the global regulations: the allocated spectrum for UWB transmissions differs from country to country and from continent to continent. Another challenge is that despite the two existing standards on IR-UWB, there are very few companies that manufacture IR-UWB devices or chipsets. When comparing the popularity of UWB to ZigBee and particularly to Bluetooth, the current situation for UWB technology does look a bit uncertain. Yet, the advantages of UWB still provide a potential technology for future IoT networks and applications. As discussed in Paper [I], ZigBee and Bluetooth cannot offer small enough power consumption levels that would enable years of lifetime for wireless sensor devices. Neither can these two currently popular short range technologies offer an accuracy in localization that would surmount the accuracy of UWB. Moreover, the frequency spectrum allocated for the currently popular narrowband technologies is limited which results in interference issues. The limited spectrum also concerns the future 5th generation cellular systems (5G) and its use for future IoT applications.
In the author’s opinion, UWB technology is capable of meeting the aforementioned requirements which are potentially critical for future IoT applications. An IoT device designed for condition monitoring of a person or a machine would not necessarily require very high data rates but perhaps many years of battery life. Additionally, high ranging accuracy for future RFID applications may be crucial requirement and a widely available spectrum — even though the spectrum differs from country to country — can provide valuable features which can be more difficult to achieve with the current technology than with the UWB.

As pointed out by several Papers of this thesis, compatibility between the two existing IR-UWB standards could be one option to overcome the above mentioned challenges and future requirements. A dual radio chip composed of both WPAN and WBAN standards could enable a device which could have a long battery life, high ranging accuracy, RFID capability and low interference levels for the existing narrowband systems. With increased compatibility or even a merged standard, all the above mentioned features could be provided by a single technology, UWB. Another potential future solution could be transmit only radios that were briefly presented in Paper [I]. Transmit only devices can provide power efficient alternatives for some specific applications which might not require to receive control/feed-back information.

5.2 Future work

The two existing standards on IR-UWB specify different methods to overcome the burst type errors of a typical UWB channel. In the WPAN standard, both RS-coding and convolutional coding have been specified to improve the signal detection performance. In the WBAN standard, BCH-coding and bit interleaving are used against errors for improving the signal detection. One of the first future works that is already on the list is to complete the existing IEEE 802.15.6-2012 simulator. Comparing the aforementioned error correction methods with different rake and ED receivers in a real measured and modeled UWB channel would be interesting. It would be extremely useful to observe how the known theoretical capabilities of these methods would result in real UWB channel models with sub-optimal receiver structures. Additionally, comparisons of these error correction methods under multi-user and WBAN-to-WBAN interferences would be valuable to evaluate in different channel scenarios and for different receiver types. After all, one potential future scenario would be for a space, for example, a natural disaster area or a triage room of a hospital packed with people and many of them
wearing a WBAN device measuring physiological parameters. These WBAN devices would interfere with each other as they would appear as uncoordinated networks to themselves.

Another future work would be to make accurate power consumption comparisons of IR-UWB, Bluetooth and ZigBee in a clearly specified scenario. In other words, to compare two or more different technologies with exactly the same parameters and set up and for example, with the same BER requirement. As briefly presented in Paper [I], there exist comparisons of power consumptions between different technologies. However, the consumption figures are generally simulated, roughly estimated or measured from one technology only and then compared to results measured with other technologies which are based on referenced work by others in different scenarios or based on various manufacturer’s power consumption measurements.

One more future work relates to the analysis that was presented in Paper [VIII] for binary signals. It would be interesting to perform the analysis for M-ary signals and to see how the BEP would differentiate from the BEP of the traditional narrowband approach.
References

3151–3166.
Original publications


VI Niemelä V, Hämäläinen M & Iinatti J (2013) On IEEE 802.15.6 UWB Symbol Length for Energy Detector Receivers’ Performance with OOK and PPM. In: The 7th International Symposium on Medical Information and Communication Technology (ISMICT), Tokyo, Japan: 33-37. DOI: 10.1109/ISMICT.2013.6521694


IX Niemelä V, Hämäläinen M & Iinatti J (2011) Improved Usage of Time Slots of the IEEE 802.15.4a UWB System Model. In: The 2nd International Workshop on Future Wellness and Medical ICT Systems in conjunction with the 14th International Symposium on Wireless Personal Multimedia Communications (WPMC), Brest, France, 1-5.

Reprinted with permission from IEEE (I, III, VI, VII), Inderscience Publishers (II), ACM(IV), ICST (V), IET (VIII) and WPMC (IX).

Original publications are not included in the electronic version of the dissertation.
<table>
<thead>
<tr>
<th>Title</th>
<th>Author</th>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rakentamisen nyöcurvallisuteen suhtautuminen toimijoiden kokemuksina</td>
<td>Erkkilä-Häkkinen, Srpa</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>Thermo-mechanical behaviour of ground-source thermo-active structures</td>
<td>Hassani Nezhad Gashiri, Ehsan</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>Modelling of slag emulsification and slag reduction in CAS-OB process</td>
<td>Sulasalmi, Petri</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>Enhancing security and scalability of Virtual Private LAN Services</td>
<td>Liyanage, Madhusanka</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>Synthesis and characterisation of catalysts used for the catalytic oxidation of sulfur-containing volatile organic compounds; focus on sulfur-induced deactivation</td>
<td>Darif, Bouchra</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>Hybrid membrane processes in industrial water treatment: separation and recovery of inorganic compounds</td>
<td>Juholin, Pia</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>Efficiency and stability studies for organic bulk heterojunction solar cells</td>
<td>Augustine, Bobins</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>Towards optimal local binary patterns in texture and face description</td>
<td>Ylioinas, Juha</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>Hydrological and hydraulic design of peatland drainage and water treatment systems for optimal control of diffuse pollution</td>
<td>Mohammadighavam, Shahram</td>
<td>2017</td>
<td></td>
</tr>
<tr>
<td>Dynamic environmental indicators for smart homes: assessing the role of home energy management systems in achieving decarbonisation goals in the residential sector</td>
<td>Louis, Jean-Nicolas</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>Greenhouse gas fluxes from drained peat soils: a comparison of different land use types and hydrological site characteristics</td>
<td>Mustamo, Pirikki</td>
<td>2017</td>
<td></td>
</tr>
<tr>
<td>Disintegration of packaging material: an experimental study of approaches to lower energy consumption</td>
<td>Upola, Heikki</td>
<td>2017</td>
<td></td>
</tr>
<tr>
<td>Runoff generation and load estimation in drained peatland areas</td>
<td>Eskelinen, Riku</td>
<td>2017</td>
<td></td>
</tr>
<tr>
<td>Nanoscale sensor networks: the THz band as a communication channel</td>
<td>Kolkkoniemi, Joonas</td>
<td>2017</td>
<td></td>
</tr>
<tr>
<td>Co-primary multi-operator resource sharing for small cell networks</td>
<td>Luoto, Petri</td>
<td>2017</td>
<td></td>
</tr>
</tbody>
</table>

Book orders:
Granum: Virtual book store
http://granum.uta.fi/granum/
EVALUATIONS AND ANALYSIS OF IR-UWB RECEIVERS FOR PERSONAL MEDICAL COMMUNICATIONS

Ville Niemelä