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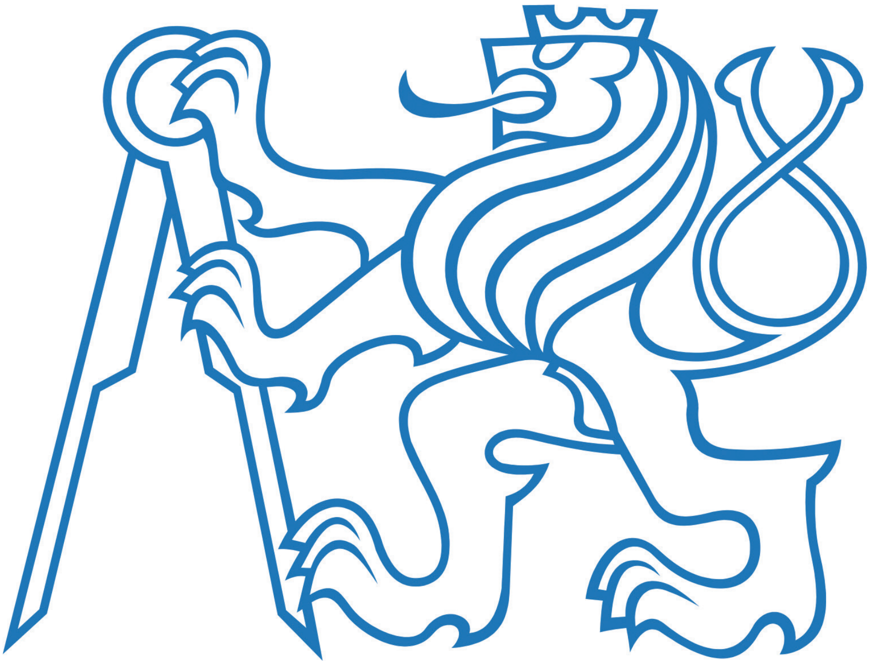

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Electromagnetic Field

Robert Urban

SPECIFIC APPLICATIONS OF UWB TECHNOLOGY IN COGNITIVE NETWORKS

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Contents

1 Current State of Research in Intelligent Networks

1.1 Introduction

Communication systems have undergone a lot of changes over the last few decades. The carrier pigeon was replaced by wired connections like the telegraph and now, classic metal cables are being replaced by optical cables which could carry several Tbit/s [1] over several hundred kilometers. The density of wireless services is now at an extreme level [2]. Cellular network operators are claim to have 99% coverage of the population by their wireless networks in western countries and nearly 100% of the whole planet is covered by numerous wireless services from satellites. A new problem of increasing the number of wireless systems has arisen. There are no “available” frequencies for new services and different services are sharing the same frequency bands. From this reason, the frequency spectrum become a marketing product which could be easily sold for hundreds of millions of dollars by governments [3, 4].

As mentioned, numerous types of wireless systems have overfilled some parts of the frequency spectrum. Spectrum management is now mostly done by governmental authorities [5, 6] based on the recommendation of the ITU [7] which develops technical standards and allocates global radio spectrum. These regulators assign frequency spectrum licenses for specific geographical regions. In regulation system of long-term blocking of frequencies, a large portion of the frequency spectrum is sporadically used and some frequency bands are licensed but underutilized. That could be solved by Dynamic Spectrum Access (DSA) which was addressed to increase frequency spectrum utilization by reallocating certain services into the free parts of the frequency spectrum. One possible way to enable DSA is to use modern Cognitive radio (CR) [8]. CR is capable of optimizing network channels and minimizing interference in the system based on information for actual time and location.

Ultra wideband (UWB) technology uses another radio spectrum access technique where carrier frequencies need no longer be used in these systems, and pulses can be defined in a time domain to carry the information – the so-called Impulse Response UWB (IR-UWB) [9, 10] UWB systems, which were originally designed as spectrum sharing technology, is a new user of the frequency spectrum and needs to be friendly to primary users (user or provider which pays for a license or first user of the frequency spectrum). As opposed to Cognitive Radio, UWB systems tend to be originally used in an underlay sharing mode.

The regulatory (spectral mask and maximal radiated power) was recently changed and for this reason it is necessary to develop a pulse shaping solution for spectrum shape. The pulse shaping should also be used to extend the transmission range. It is necessary to adopt intelligent solutions to increase the transmission power in unused parts of the frequency spectrum. This can be overcome by using cognitive radio techniques such as spectrum sharing. It is clear that spectral background information is needed to accomplish this sharing technique and this topic is discussed within this thesis.

1.2 Ultra Wideband Technology

The first modern UWB communication research began in the 1990s without any regulation of the wide frequency band. The FCC released its radio emission mask and definition [6] of the UWB in 2002. The establishment of this basic set of rules started a new epoch in UWB communication. The system could be called ultra wideband if the Fractional Bandwidth (*FB*) is higher than 0.2 and the total bandwidth is greater than 500 MHz. The fractional bandwidth is given by (1.1):

$$\begin{gathered} FB = 2\frac{f_h - f_l}{f_h + f_l}, \\ FB > 0.2 \end{gathered} \tag{1.1}$$

where f_h is the highest frequency of the signal and f_l is the lowest frequency of the system.

UWB systems are primarily presented as low-power consumption technology for the physical layer [9, 10] of wireless communication systems in baseband without a carrier. The large bandwidth of the wireless channel (7.5 GHz by FCC spectral mask [6], for ECC presents spectral mask in [11, 12]) gives UWB the potential for future multi-service platforms. WiMedia Alliance has developed MB-OFDM UWB (Multi Band Orthogonal frequency Multiplex) [13-16] systems for Wireless USB (WUSB) and other hi-speed (video) applications. In contrast to the “classical” approach of using any available frequency band by the OFDM technique, it is possible to use the pulse technique for data transmission as it uses a different technique to access the physical layer which corresponds with the optics principle [17]. It is the classic “pure time domain” UWB technique which uses single pulses to carry information. The key benefits of pulse UWB technology are:

- **High data rates**
- **Low equipment cost**
- **Multipath immunity**
- **Ranging**
- **Low power cost**

The measurement of the UWB system is slightly different from classical “narrowband” system. There are two possible options for channel sounding to measure the UWB radio channel. Firstly, the channel can be measured by a spectrum analyzer or a vector network analyzer in the frequency domain (FD) using a frequency sweeping technique. Frequency measurement is very often accelerated by using several single frequencies [9, 10] which are selected to simulate UWB pulse (or bandwidth) instead of sweeping technologies. Secondly, the channel can be measured by a sampling oscilloscope in the time domain (TD). A wideband sampling oscilloscope measures the channel impulse response for the generated pulse in real time. This measurement type is much faster than a measurement in FD. Synchronization between the pulse generator and oscilloscope is necessary for a precise measurement.

Theoretically, both of the presented techniques give the same result by recalculation with FFT (IFFT) if there is a static measurement environment. The problem is that it is not possible to have a totally static environment for living scenarios. Also, there is a limitation of recalculation by FFT (IFF) which was not designed for the pulse technique. Most of the measurements are done in the frequency domain [9, 10].

1.3 UWB Pulse Shaping

The most common pulse shape in UWB systems are pulses based on the Gaussian function or Hermite polynomials forms. Unfortunately, the basic Gaussian pulse has a high DC component and for this reason it is not suitable for radiation. To insert the Gaussian pulse into an appropriate spectral mask, it is necessary to shape a wide pulse (in the frequency domain) to reach its optimal spectrum adaptation and this is why, consequently, pulse shaping is required for future UWB applications. There are several possibilities how to shape Gaussian pulse as a UWB pulse. Firstly, the derivatives (first and second) of Gaussian pulse are used [9]. Secondly, filters are used for their simplicity [18] and it is possible to design filters with a specific impulse response to adopt a pulse to the antenna distortion scheme and create a pre-equalization circuit [19]. Shaping the pulse in the frequency domain derives some advantages in the propagation channel or in a wireless system which is presented in [20]. Finally, it is possible to shape the pulse directly in the time domain to improve the generation system by multiplying the Gaussian pulse with harmonic function in a wideband mixer [9].

To show how the multiplication with a harmonic function works, we present a pulse function $y_s(t)$ for shaped Gaussian pulse, which is given by (1.2) [9]:

$$y_s(t) = \sqrt{2}E_c e^{-\left(\frac{t}{\tau}\right)} sin(2\pi f_s t), \tag{1.2}$$

where the variable f_s is the “shaping” frequency which causes movement of the maximal spectral value to this, E_c is an energy constant and τ is the time-scaling factor.

Using the presented shaping technique, it is possible to create a suitable pulse for the communication system while complying, where necessary, with FCC rules. The regulations are largely specified in the frequency domain. The conversion between time domain and frequency domain is done using the conventional Fast Fourier Transform (FFT).

1.4 Cognitive Radio – Intelligent Spectrum Access

The idea of cognitive radio was first promoted in the thesis of J. Mitola [21] in 2000 followed by the idea of ideal Cognitive Radio which was published in [8, 22, 23]. There are many definitions of cognitive radio but most agree that it is defined as follows [8]: *Cognitive radio is a wireless system that cans change its transmitter and receiver parameters based on interaction with the environment in which it operates*. The aim of Cognitive radio was to modify the radio from a basic receiver to an intelligent system capable of exploiting the spectrum more, and to include more user options. For most users, it is appealing to have a hand-held device which can make emergency calls if your stamina parameters decrease, and to increase data throughput by allocating unused parts of spectrum [8, 24, 25].

Given the many variations present in wireless communications, dynamic spectrum access technology is needed to achieve better overall use of the spectrum. DSA is the opposite of the current static spectrum management policy. However, various approaches are possible to make spectrum management more adaptive, as presented in. In this chapter; the focus will be on those approaches that involve coexistence and dynamic spectrum sharing.

For the spectrum survey we use energy detection, which is a non-coherent detection method that needs only basic information on the signals. The drawback of energy detection is that it is less accurate than matched filter detection for a given number of samples or sensing time. The prior knowledge of the primary users signal is not necessary for successful detection for energy detection [2], but there are some drawbacks. The main challenge of energy detection is the setup of the decision (threshold) level $L_{threshold}$. Another challenging issue is that of energy detection which cannot distinguish between primary users and other secondary users sharing the same frequency channel [26].

2 Objectives of Dissertation

This doctoral thesis is aimed to connection of UWB technology which is equipped by pulse shaping with cognitive system. Firstly, it is necessary to develop a system to accomplish the various spectral masks used throughout the world [6, 11, 12] by pulse shape designing. The limited power of the UWB spectral mask evokes underlay spectrum sharing, but in cognitive systems it should be possible to also use the overlay sharing principle to increase the range of the wireless system, or to create an interference avoidance system. For both of these goals – maximal spectrum utilization and dynamic spectrum access – it is possible to solve the problem by shaping the pulse by multiplying the pulse with harmonic frequencies.

To enable the dynamic spectrum access in the UWB system it is important to have actual information about the occupied frequencies. Spectrum surveys provide this type of data. These data could be used to simulate a cognitive system based on a UWB system. The pulse could be shaped in the frequency domain to fulfill white spaces in the spectrum and enable overlay sharing to increase the range of the UWB system in unoccupied areas of the spectrum.

As a result of the facts presented, the targets of this doctoral thesis were established as follows:

- **Examination of UWB propagation to achieve suitable parameters for pulse shaping.**
- **Development of a pulse adapting system to maximize the utilization of a spectral mask**.
- **Assembly of a measurement system for spectrum surveys.**
- **Accomplishment of spectrum survey measurements for different scenarios.**
- **Development of the cognitive UWB system concept.**

3 Measurements in the Ultra Wideband Channel

UWB system measurements require a completely different approach than those of conventional systems. In the measurements, it is used only time domain measurements and, afterwards, the results were recalculated into the frequency domain because of regulation purposes only. The presented measurement campaigns were prepared to enhance the knowledge of dispersion and reflection characteristics of the UWB wireless environment which is a necessary feature of further analysis. We moved from a low-complexity channel created in an anechoic chamber to a high-complexity scenario which was represented by a traditional administrative room with normal equipment.

3.1 Dispersion of the Gaussian Pulse

Dispersion is certainly the main factor for signal propagation in the time-invariant channel. In fact, one common UWB received mode utilizes a comparison of the received signal with its replica (coherent detection using correlation with replica). This reception mode is, crucially, dependent of the non-dispersive character of the pulse. Several measurements were performed to confirm or disprove such a feature (see the measurement setup in Figure 3.1). Highly similar pulses to the Gaussian pulse were used in these measurements. These pulses were characteristic of the Gaussian monocycle (first derivative of Gaussian pulse) generated from the pulse generator [27] with the trigger frequency set to 500 MHz (2 ns period of pulses).

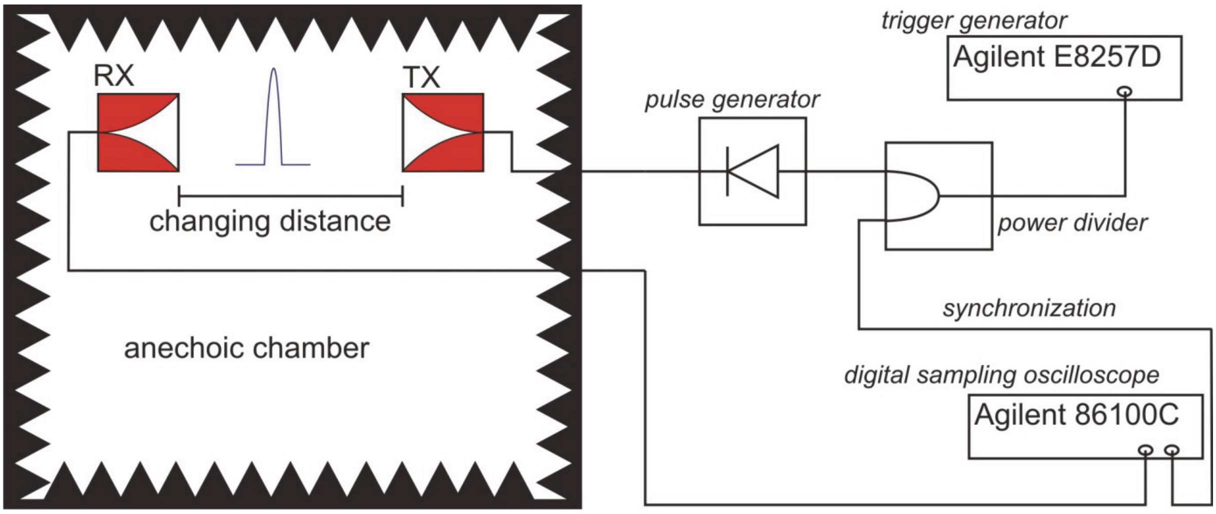

Figure 3.1 – Setup for measurements of signal dispersion in an anechoic chamber

The dispersion of the UWB pulse in the wireless channel was investigated as changes in duration of the pulse over several distances. To compensate for the time shifts between pulses measured at different distances, we used a “peak-to-peak” method. This method finds two consecutive peaks of the pulse which were separated at a minimum of half of the repetition rate of the pulse. This function allows the recognition of exactly one measured Gaussian pulse from a measured sequence of pulses (pulse train). The “peak-to-peak” method allows also a synchronization of the pulse in time, so at some point it should be possible to calculate the extension of the pulse by dispersion in the UWB propagation channel. Time Domain plots for measured distances were plotted in Figure 3.2.

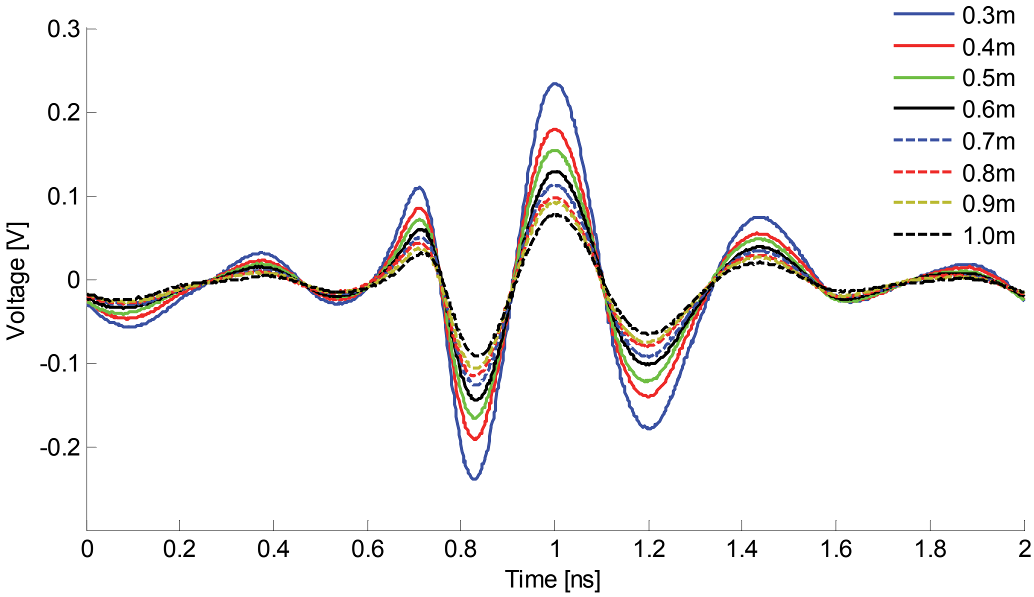

Figure 3.2 – Measurement of signal dispersion for different distances

It is obvious that all pulses have the zero crossing at the same point which proves that there is no pulse dispersion of the pulse in the measured scenario. The amplitude changes of the pulses are caused by propagation losses over greater distances. It must be also emphasized that the same measurements were obtained from the real room, not only from the anechoic chamber – no dispersion of pulse was observed in any scenario for measured distances (0.3 up to 1 m in anechoic chamber and up to 6 meters in the real room).

3.2 Prediction and Measurement of Reflected Pulses

A lack of interference is an advantage of the UWB systems [10]. However the combination of a direct and reflected pulse could seriously harm the UWB communication system. The effect of reflection is studied in this chapter. The simulation is made using the two-ray model. Based on the precise prediction (confirmed by measurements) of the time arrival of pulses, it is possible to accommodate ray-tracing models in a variety of complex environments [28]. The ray-tracing models enable us to predict when some interference arises and whether this phenomenon will have a constructive or destructive influence on signal reception. Small differences between the direct pulse and the reflected pulse path cause an interference (overlapping) of these two signals. Over large distances, other pulses in the pulse train may be influenced, nevertheless a large distance, i.e. higher path loss, very often results in undetectable interference signals. Therefore, a measurement campaign was carried out with an emphasis on the prediction and measurement of reflected pulse behavior.

Measurement results of the time delay between the direct and reflected pulses, as compared to the. The maximum deviation between the measured and simulated values is 0.17 ns (i.e. 8.2% of the transmitted pulse duration) for antennas with a height of 1 m and less than 4% for the long-corridor scenarios (6 meter distance between antennas), which were measured with a more powerful pulse generator. In this measurement, it was proved, based on the scenario definition, that the dominant reflection could be precisely calculated as the measurement system provides sufficient dynamic to make this type of measurement. The differences between measured and simulated values were only 1.7 ns.

3.3 Measurement of Overlapping Region

The overlapping region of the pulses was investigated and it is obvious that the pulses started to overlap when the path difference was smaller than the pulse duration. In these scenarios different pulse generators are used to measure greater distances because it produced amplitude of up to 12V in addition to several pulse widths and repetition rates of the Gaussian pulse.

The overlapping region of the pulses was investigated and it is clear that the pulses started to overlap when the path difference was smaller than the pulse duration. Pulse shape is strongly dependent on the time of arrival of the LOS pulse and all other NLOS artifacts and pulse shape. Distortion of the pulse is a main topic for pulse UWB system developers.

A propagation system with two dominant paths was examined not only in the anechoic chamber, but also in the “office room”. Two typical situation of the pulse interaction is depicted in Figure 3.3. The first considers a direct path and a reflection from a conductive metal plate, and the second takes into account the fact that the ground and conducting plate were covered by an absorptive material to prevent pulses reflections. For the shortest distances between antennas, the path difference is maximal and the reflected pulse can be easily detected: Figure 3.3 a) 0.5 m distance. For greater distances, the path difference decreases and the pulses overlap: Figure 3.3 b) 1m distance.

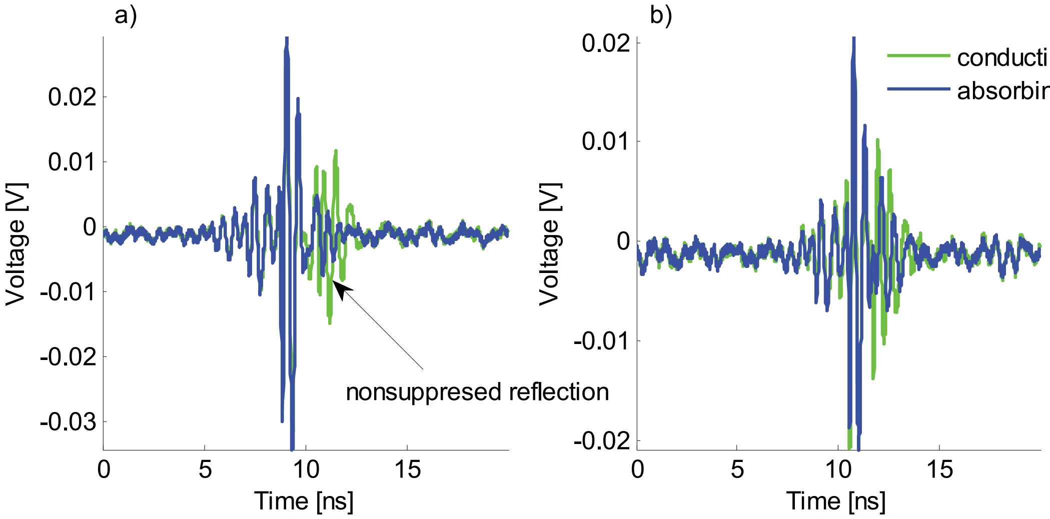

Figure 3.3 – Measured received signals from two-path propagation with dominant reflection for distance 0.5m a) and distance 1m b)

For differential time below 1.4 ns (equal to the differential distance 0.4 m), the overlapping signal pulse echo arriving by ground reflection is not delayed enough to be distinct from the directly arriving pulse (see Figure 3.4). For these small distances between the conducting plate and the axis between antennas, the reflected pulse overlapped in a destructive way. Increasing the differential distance, the direct and reflected pulses become clearly distinguishable. Utilizing a rake receiver in the “non-overlap region”, energy from both the direct and reflected signal could be yielded. The reflected pulse has a strong influence on the direct pulse for small differences between direct and reflected pulse path, which could seriously destroy the direct pulse information.

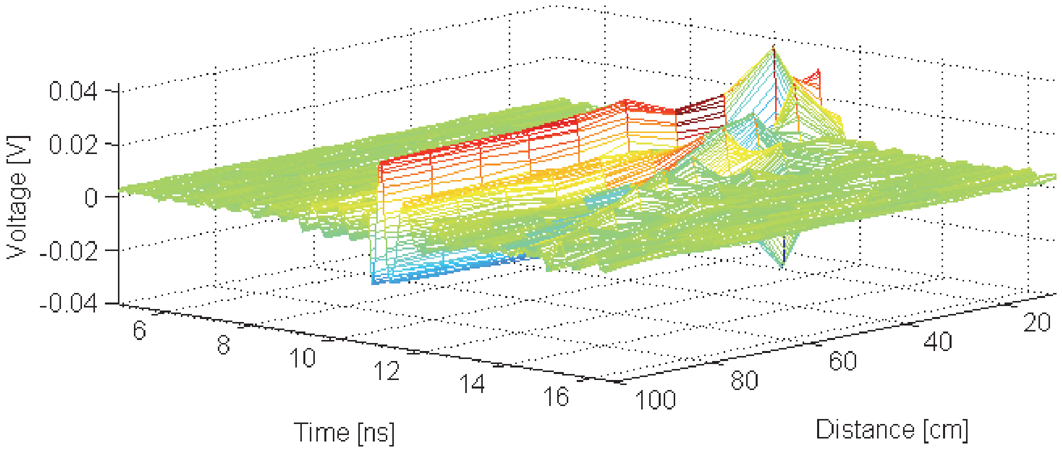

Figure 3.4 – Measured received signals from two-path propagation, with the reflection from the vertically placed conducting plate

4 UWB Pulse Shaping

The limitations, as given by the spectral mask, are quite restrictive and the radiated power was set quite low to allow underlay sharing. Moreover, many countries define their own spectra which may be more or less limiting than the FCC’s. In addition, pulse shaping could be used for cognitive applications. For this reason it is important to develop a dynamic system which enables different spectrum conditions to be accomplished according to the current location. It is necessary to design optimal pulse shape, in both time and frequency domain, to reach maximal utilization of spectrum and total radiated power in one pulse.

Pulse shaping can be used for optimal dynamic filling of the spectral mask and for avoiding interference with other services. The whole technique is based on pulse shaping and multiplication of several harmonic frequencies. In contrast to other pulse shaping papers, we used a time domain approach which was verified by measurement. Miscellaneous pulse shapes can be created by the combination of pulses and several harmonic functions which can be used to fill the available frequency spectrum very well. The generated signal y_{comb} is given by (4.1).

$$y_{comb}(t) = \sum_N y_s(t) = \sum_N \sqrt{2}E_c e^{-\left(\frac{t}{\tau}\right)} C_s sin\left(2\pi f_{s,N} t\right), \qquad (4.1)$$

where N is the number of harmonic “shaping” frequencies, C_s is the energy coefficient of the Nth shaping frequency and the $f_{s,N}$ is Nth shaping frequency.

Pulse shaping created by multiplying the UWB pulse with harmonic frequencies has great potential. It is possible to create a dynamic system based on the specific number of shaping frequencies f_s. This system is proposed for dynamic control of the spectral mask and for interference avoidance as it is demonstrated in Figure 4.1, where example for 4 shaping frequencies presents.

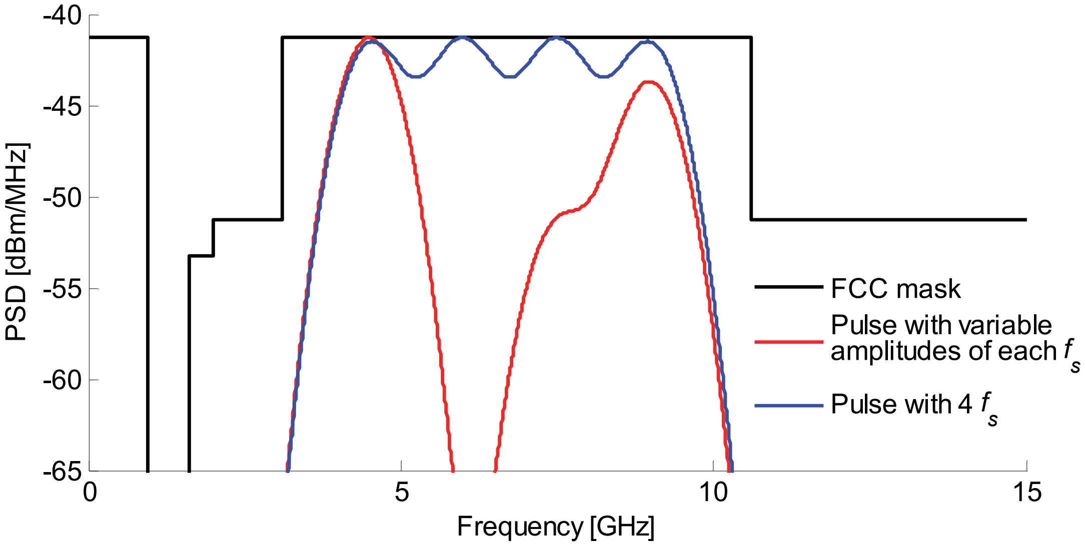

Figure 4.1 – Simulation of pulse shaping by 4 shaping frequencies and shaping with variable coefficients

The proposed shaping system was experimentally verified for special case N=1, before a deeper analysis was made. It is necessary to find a low-cost option to shape pulses generally and dynamically if we wish to implement UWB systems into ordinary usage. In our experiment, we used a wideband mixer to modulate generated pulses with harmonic frequency.

The measurement proved that pulse shaping by multiplying harmonic function is possible. It is clear that the Gaussian pulse was shaped to the target frequency (f_s= 5 GHz) as it is depicted in Figure 4.2. This measurement was performed over several pulse durations with the same results. It is obvious that the shaping theory works hence one can create a dynamic system for pulse shaping cheaply.

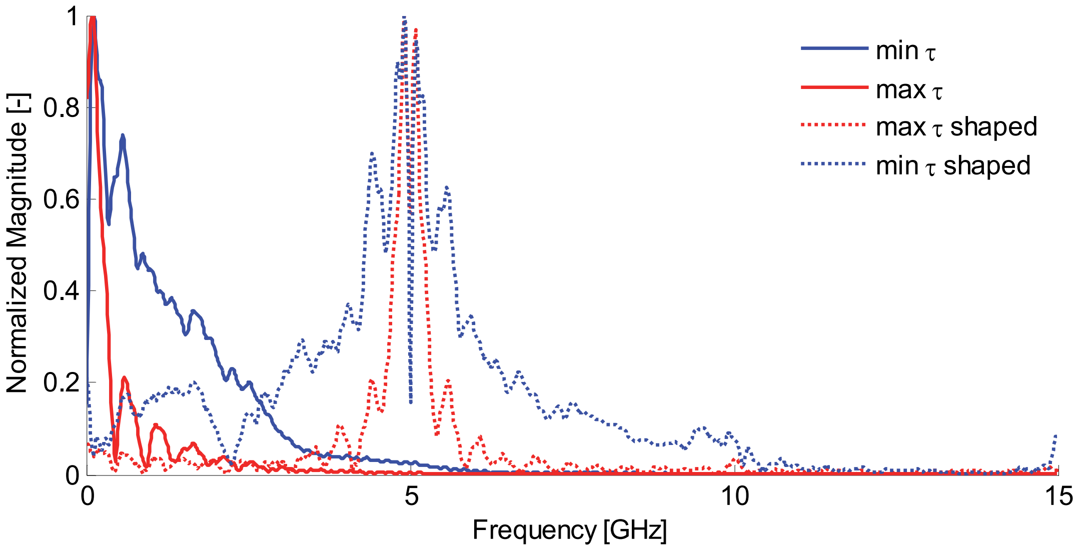

Figure 4.2 – Pulse shaping measurement for original generated pulses and shaped pulses in frequency domain

4.1 Pulse Adaptation

The limited total power of the UWB system is given by the FCC rules [6]. The higher the amplitude we require, the higher the power of the pulse waveform we need. Usage of the spectrum depends on the number of shaping frequencies *N* and the frequency spacing between shaping frequencies *δf*. The usage parameter gives the comparison of the quality of filling the FCC spectral mask using the appropriate power level over the frequencies of interest. To achieve a variable pulse shape, the whole UWB bandwidth is divided into *N* bands (4.2) with the frequency width of the band *δf* and the pulse width τ *(Δf)*. We tried to find the optimal output pulse shape (combination of *δf* , N and τ). The dependence of the usage of the frequency spectrum and the inverse time scaling factor (τ^{-1}) is shown in Figure 4.3 for several *δf* values. The parameter of the calculation is shown in equation (4.2).

$$\begin{aligned} &\frac{1}{\tau} = 30{,}60{,}90 \cdots 3990\ \text{MHz} \\ &\delta f \in \{30,60,90,120,300,600,1200\} MHz \\ &N = \frac{10.6 - 3.1 GHz}{\delta f} = floor\left(\frac{7500\ MHz}{\delta f\ MHz}\right) \\ &\rightarrow N \in \{250,125,83,62,25,6\} \end{aligned} \tag{4.2}$$

To reach the maximal usage, it is necessary to choose the correct time scaling factor τ because a wrong combination of δf and τ causes loss of power within the UWB spectrum. The area in Figure 4.3 could be divided into two parts for each curve. On one hand, whenever τ is too small, we lose a significant amount of power between the bands – the pulses do not fill the band correctly (in the figure this is shown as the area on the left side of the maximal value). On the other hand, quite low τ causes the pulses to be too wide in the frequency domain, meaning that they are not able to fill the spectral mask fully.

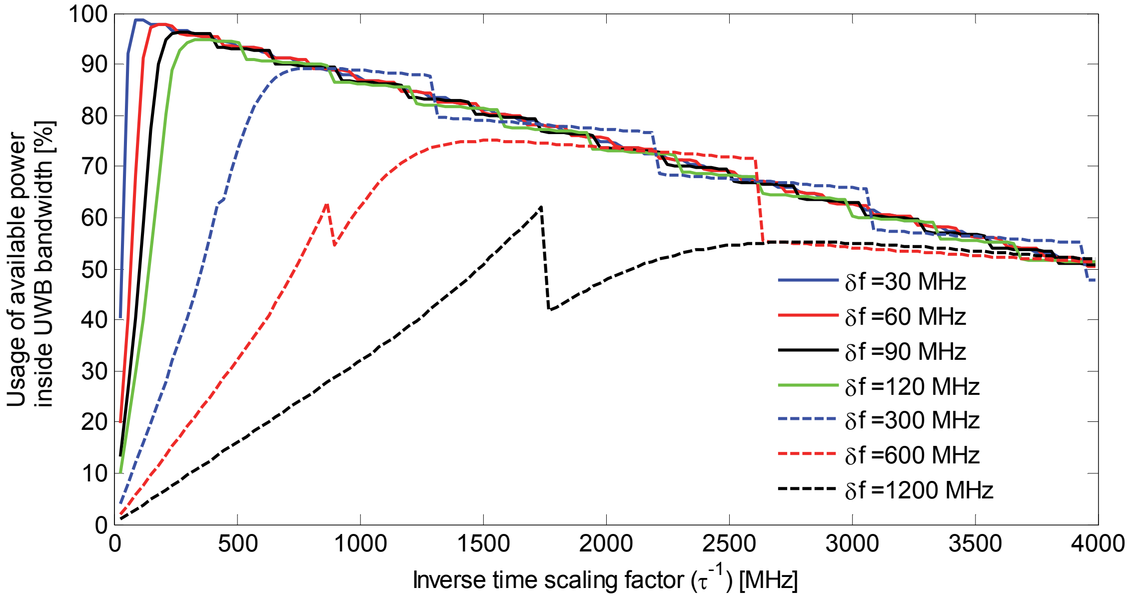

Figure 4.3 – Usage dependence of the FCC UWB spectral mask and the τ^{-1} for several bands width spacing *δf*

The main advantages of the proposed system are: dynamically controlled usage and power in the frequency band, variable data rate and a higher than average spectrum utilization (up to 98%). This system could be used for DSA or for interference avoidance.

5 Measurement System for Spectrum Survey

To establish pulse shaping into real system, it is necessary to obtain frequency spectrum background measurements. This type of measurement is called a spectrum survey. Besides spectrum sensing, a spectrum survey is measured outside the cognitive cycle, and it is not a part of the cognitive system, but it could provide offline data for the cognitive system. Spectrum survey is important from several perspectives such as spectrum regulation or dynamic spectrum access. The standard approach in the similar measurements is to use several antennas to cover the whole measured band. Our approach is somewhat different. The presented system measures data in a row which means that the whole band is measured without any interruption. The main advantages of our measured system are portability (system could work without electricity for more than 4 hours), speed and resolution.

5.1 Controlling Software

Generally speaking, the controlling software is a key part of system presented. It was specially developed for spectrum survey measurements on the PR100 device. The controlling software establishes communication and sets the parameters necessary for the PSCAN mode mentioned in chapter, and also manages data storage. This device includes a fast Ethernet interface for remote control through the TCP/IP network. The remote control is operated by a special R&S native language with uncomplicated language working as a “command-answer” base. The Ethernet interface could also be used for sending data to be stored on a remote PC connected to the same network.

Measurements with our software consist of several steps which are listed below. The whole measurement process is also depicted in Figure 5.1.

- **Measurement initialization**
- **Measurement setup**
- **Measurement process**

The device is set up before each measurement starts. The user cannot change the parameters because it is necessary to provide the same system conditions for all measurements. For example, the “automatic gain option” for all measurements is set to be off as well as the input attenuator. We are not presuming to measure dangerous (power meaning) signals for the detector. After selecting, these parameters, the measurement is prepared to start. These parameters are uploaded to the PR100 using TCP. The setup needs to be confirmed before the start button is enabled.

5.2 Measurement Process

Measurement process describes everything between the beginnings of the measurement until termination. After pressing the START button, the measurement trace is created and the receiver sends the data through the UDP with a large number of packets sent through the Ethernet interface.

Every packet is decoded and data are checked, and the cycle is declared as complete if the next starting frequency is detected. Only the end mark of the measurement is provided by the receiver, but it is rarely used because a measurement is mostly finished by the controlling software. When the end of the cycle is found, an additional "ending" condition is tested (Figure 5.1) to finish or continue the measurement.

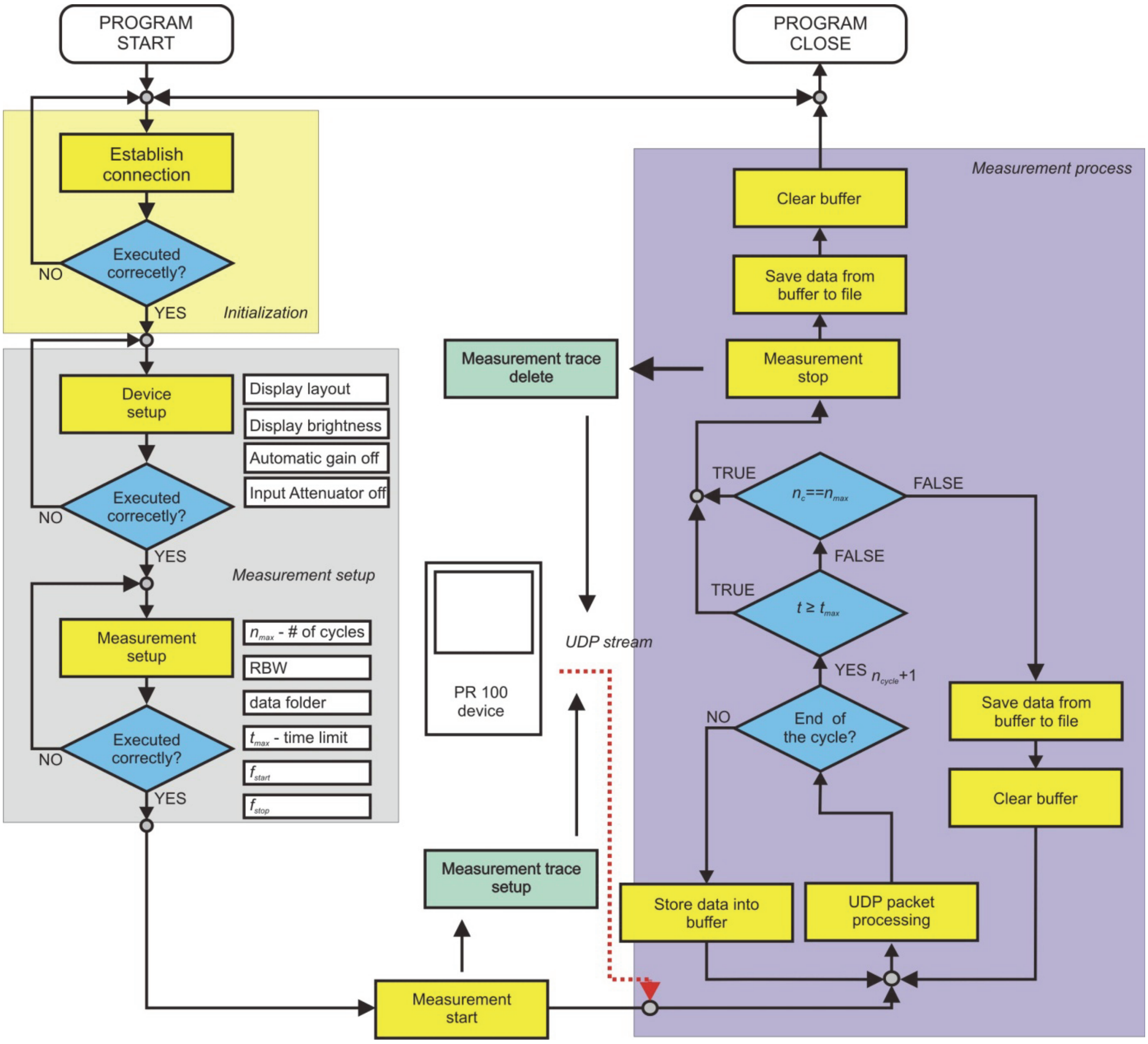

Figure 5.1 – Flowchart of measurement process

Therefore, every detected UDP packet is stored in the buffer and when the cycle is finished, buffer is stored into the 4 column file. The first column stands for the number of milliseconds from the beginning of the measurement (start button), the second is a serial number of the cycle, the third shows the measurement frequency in [Hz] and the last column stands for the measured level in [dbµV]. On the whole, additional information is stored about measurement and configuration of the receiver is stored to be able to repeat a measurement with the same configuration. Timestamp of the beginning of the measurement is also stored for data synchronization as time information is required for data synchronization.

6 Spectrum Survey Measurement

The main purpose of this chapter is to present measurement results based on the measured system presented in previous chapter. The measurement campaigns were conducted in completely different locations to obtain general data with rural, sub-urban, urban and special case scenarios being measured. As a special case, a lecture hall will be presented. During a lesson there were a large number of students generating wireless traffic. Data were collected at the same place at different times of day. In the measurement we focused on:

- **Frequency spectrum usage measurement** – the underutilization of the spectrum is expected in a spectrum survey. We focused primarily on usage measurement and on the localization of the white spaces in the frequency spectrum.
- **Spectrum changes in time** – the measurements were performed over longer times, or placed in the scenarios where changes in spectrum usage are customary.

6.1 Measurement Post-processing

Measured data need to be post-processed (Figure 6.1). Final data calculations are processed in Matlab environment and it could be divided into several steps:

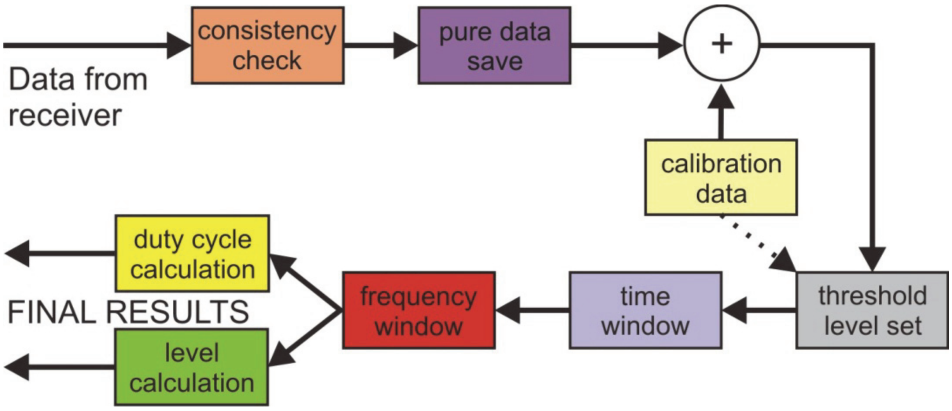

Figure 6.1 - Flow chart of post-processing

The most important part of this cycle is described in more detail:

- **Consistency check** – some information could be lost during the measurement process therefore a consistency check is necessary. The typical error rate in the presented measurement was less than 1%.
- **Data save** – consistent data are saved as a binary data file for future possible analysis. This type of file consumes less space and they are easy to operate.

- **Calibration data** – data measured in an anechoic chamber are used to minimize noise and frequency dependence of the antenna and.
- **Threshold data – $L_{threshold}$** – above this level the measured values for frequency points are marked as “**occupied**” by another service. The threshold is essentially estimated as 10 dB over the mean level of the signal which guarantees sufficient performance.
- **Time window and Frequency windoe– W_{time}, W_{freq}** – measured data are collected with a higher repetition rate than is possible to display as several consecutive cycles are processed together in both domains – time and frequency.

The main indicator of spectrum utilization is not the level of the signal but the duty cycle (6.1), which is defined as the number of detected peaks $N_{detected}$ divided by the number of total frequency and time points in the measurement N_{tatal}.

$$Duty\ Cycle = \frac{N_{detected}}{N_{total}} \tag{6.1}$$

6.2 Short-term Measurements

The short-term measurements were focused on detecting fast changes in the spectrum. It is possible to detect most of the GSM calls or other services. The performed measurement focused on the band from 700 MHz to 2.7 GHz. A mainstream of mobility services (GSM, UMTS, WIFI) is located in this band. Systems operating in the measured band were found according to CTO frequency plans [5]. Some of these frequency bands are examined in more detail for selected systems (e.g. GSM, UMTS, WIFI). The time and frequency window vary according to the service examined to reach a minimum of 2 samples per channel bandwidth.

From the measured data, it is clear, that the spectrum contains a lot of the white spaces suitable for future utilization. The frequency spectrum could be evaluated in more detail in the limited bandwidth. The average measurement cycle duration is 1.7 s which enables a study channel to be performed during this time. For example, the DVB-T band was evaluated using a very low frequency (0.5 MHz) and a time window (1.7 s) to examine the utilization of TV channels which could be easily found in the presented figures according to the typical shape of the OFDM frequency mask. Using the white spaces in the spectrum in the TV band is an actual topic of discussion [29]. GSM, UMTS and WIFI bands were also analyzed in the same way (Figure 6.2). Same procedure was done also for outdoor urban, suburban and rural location. The average spectrum utilization is around 5 % which is similar to another measurement project [30].

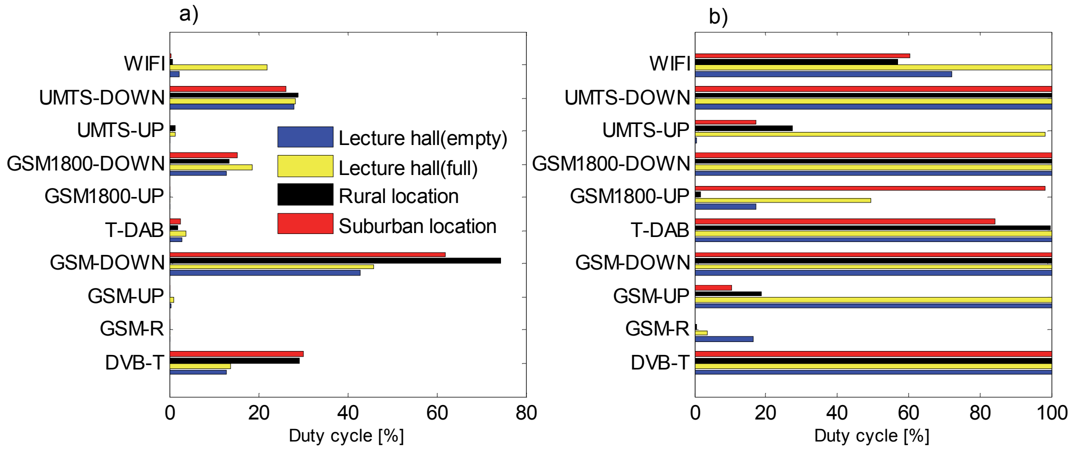

Figure 6.2 – Utilization of the selected services for selected scenarios for a) optimistic scenario and b) pessimistic scenario

6.3 Long-term Measurement

The long-term measurements are designed to observe the overall situation in the frequency spectrum usage in time. These measurements were processed for several hours. In this type of measurement we did not focus on fast changes in the channel, but on the utilization of the spectrum and white spaces in the frequency spectrum. The suburban location was also chosen for long-term measurements. This measurement produced a large quantity of data. The cycle duration for this measurement was 61 s (f_{start} = 300 MHz, f_{end} = 7000MHz).

The low utilization from is given by a large, scanned bandwidth with a very small frequency step. The *Duty cycle* calculation depended on the number of measured frequencies. It is easy to see that the higher frequencies are very rarely occupied. There were measured other location such as roof at the CTU building in Prague. Generally, the long-term measurements prove that the spectrum occupancy is dependent on time (The *Duty cycle* of the GSM 900 MHZ band varies from 6 % during the day time and 4 % for night hours). As a result of the low utilization of the whole bandwidth, it is logical to use a dynamic spectrum allocation to data throughput. The optimal bands for dynamic spectrum access are TV bands, where utilization has decreased due to digitalization.

More over WIFI band is examined in detail to find typical duration of white space and the sharing opportunities in this band.

7 Intelligent Ultra Wideband System

The concept of the cognitive system based on UWB technology is introduced. This system is a mixture of the underlay and overlay sharing method. We assume that the UWB band is rarely utilized most of the time. As the measurement presented in previous chapter proved, the measurable part of UWB is utilized less than 2%, which is an ideal situation for cognitive radio in terms of dynamic spectrum access. We assume that our “cognitive radio” has data from spectrum sensing and we have information about a primary user’s distribution in frequency and time to enable overlay sharing on in spectrum holes. Some frequency bands, such as frequency hopping users, are not suitable. One setback could be that the band managed for UWB is highly regulated these days and allocated to different types of services. The primary services within the UWB frequency band are concentrated in the frequency bands around 3.1 GHz(WiMAX), 5 GHz (including the popular IEEE 802.11a, IEEE 802.11e) and 10 GHz (ISM band).

7.1 Model Definition

The system is using several generators of harmonic frequency mixed with a Gaussian pulse. Each generator contains an amplifier $E_{c,N}$ because it is easier to create an amplifier of one single frequency than a wideband amplifier with constant gain through the whole UWB band. The fast, controllable switches, which are necessary for successful band cancelation and pulse shaping, are managed by a control unit (cognitive engine) which has to change according to the input cognitive data. This cognitive unit changes based on input values from another part of the cognitive radio, namely its radio parameters, and designates the current spectral limitation which needs to be filled. Clearly, the control unit of this radio is the most essential aspect of it. It controls pulse repetition rate, shaping frequencies switches and gain of the amplifiers.

7.2 Spectrum Sharing and Adaptation

Using the results from the pulse shaping and spectral mask usage, it is possible to solve the complex power estimation for a particular scenario. For our simulations we assume input values from the awareness part of the cognitive radio, i.e. frequency sensing. We also assume that high power radiation is available in this system.

Energy coefficients C_s (7.1) for each shifting frequency $f_{s,N}$ need to be a variable for our cognitive IR-UWB (7.1) from a zero value (disabled band) up to a value that corresponds to the highest power across all bands. The whole bandwidth is divided into two types of bands with δf width. On the one hand, there are N_{FREE} bands without a primary user. This type of band contains the shaping frequency f_{FREE} and its' power C_S coefficient which has no significant reason to be limited to fit FCC mask. On the other hand, N_{P_U} bands (with f_{P_U}) are detected as primary user systems (the power of the detected primary user above the threshold value). In this type of band, the power of the UWB system is limited to avoid interference with primary users. This type of band is disabled ($C_{P\_U}=0$) in (7.1).

$$\begin{gathered} C_s(N) = 0 \cdots \infty \rightarrow C_{P_U} = 0, C_{FREE} \leq 1 \\ y_{cognitive}(t,\tau) = \sum_N \sqrt{2} E_c e^{-\left(\frac{t}{\tau}\right)^2} C_S(N) \sin\left(2\pi f_{s,N} t\right) \end{gathered} \tag{7.1}$$

The decision algorithm of the cognitive IR-UWB users needs to take into account several parameters. One of them is the maximum level of interference to be tolerated by the primary users. This may mean not using the additional frequency band(s) adjacent to the detected frequency in order to keep adjacent channel interference at acceptable levels. Thus, the omitted bands will almost certainly be wider than the width of the primary user transmission. The level of avoidance in band N_{P_U} is set by the detected power of primary users on the N band, plus the additional frequency range around the detected primary user.

By using an array of these coefficients, we are able to shape the waveform in the frequency domain very well. The output from this shaping procedure is shown in Figure 7.1, where the UWB pulse in the time and frequency domains is shown. In this figure, the C coefficients are assigned according to equation (7.1).

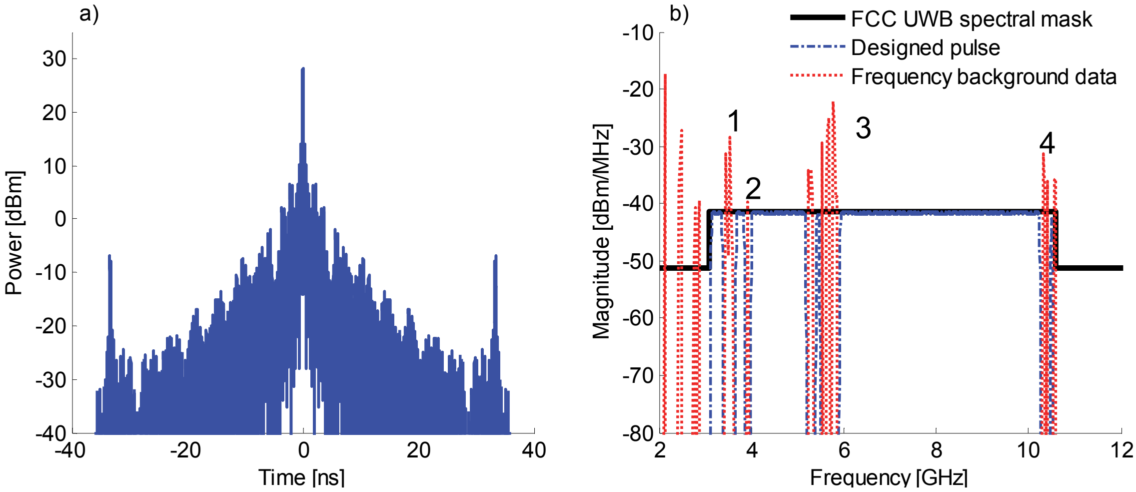

Figure 7.1 – Time domain a) and frequency domain b) representation of the designed pulse for the specific scenario

The designed pulse is the case that results in the highest amplitude from for values N_{FREE}= 199, τ^{-1}= 60 MHz (maximal data rate 7.5 Mbit/s) and δf= 30 MHz. The peak power of this pulse is 28 dBm. In Figure 7.1, the shape of the Gaussian pulse in the time domain is determined by 250 shaping frequencies (199 of them with $C_s = 1$ and 51 of them with $C_s = 0$). The modified pulse has a significant peak, which is necessary for synchronization and also for decoding OOK symbols. Moreover, Figure 7.1 also presents the capability of creating variable pulse shapes to reach an appropriate avoidance level.

Interference avoidance is presented for a real scenario in the underlay sharing mode. The band, which was used by primary users, was only released for this service. Significant improvements for the SINR parameter were calculated for the SINR rapidly increases the designed UWB pulses up to 58 dB.

8 Conclusions

This thesis was focused on specific aspects of ultra wideband technology and, in particular, pulse behavior in complex scenarios was examined. The principle area of the measurements mainly focused on pulse reflections, overlapping region and dispersion. In all measurement scenarios, no dispersion in the UWB propagation channel was proved.

The presented pulse shaping technique was focused to accomplish a variety of spectral masks, or, to minimize interference on other users using the same band. The principle of pulse shaping was also measured with real UWB pulses to prove the effectiveness of this technique. In the simulations utilization of more than 90 % of selected bands was achieved making it possible to use a standard Gaussian pulse (without any derivations or filters) for the impulse UWB system. To enable cognitive radio principles, spectrum survey measurements were performed in many different areas. The utilization of the spectrum was calculated using several methods at each location. The average utilization of the spectrum is 6 % in the band from 700 MHz to 2700 MHz. Measurements were performed in several completely different scenarios to create a database of utilization and to find the main differences between the measured scenarios. This database should be used as an input for cognitive radio simulation or for local spectrum regulators. The utilization of the GSM 900 MHz band was highest in the rural area (34.92 %). The WIFI band was most used in the full lecture hall where 17.92 % of the measured points were marked as occupied. In the long term-scale, overall utilization is 2% higher during the day than night.

The concept of the cognitive network based on UWB pulse shaping was proposed. It used a combination of the underlay and overlay sharing methods which were used to minimize interference caused by UWB systems and to maximize range of UWB systems. We increased the power of the IR-UWB pulse in some parts, which were not used by any other services (spectrum sensing), to increase the UWB system range. It was proved that it is possible to dynamically shape the pulse shape to fit the current spectrum situation efficiently and more power could be added to the UWB system to increase service range. An interference avoidance principle was also applied to bands occupied by primary users. These bands were released and SINR was improved up to 68 dB for primary users.

9 References

[1] (2011). *Apollo*. Available: http://www.apollo-scs.com/transatlantic-capacity

[2] L. Berlemann and S. Mangold, *Cognitive radio and dynamic spectrum access*: John Wiley & Sons, 2009.

[3] J. Regan. (2011, 22.9.). *UPDATE 1-France sells 4G mobile licences for 936 mln eur*. Available: http://www.reuters.com/article/2011/09/22/france-telecoms-4g-idUSL5E7KM45920110922

[4] J. Garside. (2011, 9.10.). *Auction of high-speed 4G spectrum set to raise £3bn*. Available: http://www.guardian.co.uk/business/2011/oct/09/auction-of-4g-spectrum-set-to-raise-3bn

[5] (2011). *Czech Telecommunication Office*. Available: http://www.ctu.eu/

[6] FCC, "First Report and Order," April 2002.

[7] (2011). *ITU (International Telecommunication Union)*. Available: http://www.itu.int/en/

[8] J. Mitola, *Cognitive radio architecture : the engineering foundations of radio XML*. Hoboken, N.J.: Wiley-Interscience, 2006.

[9] M. Ghavami, L. Michael, and R. Kohno, *Ultra Wideband Signals and Systems in Communication Engineering*, 2nd ed. West Sussex, England: John Wiley & Sons Ltd, 2004.

[10] K. Siwiak and D. McKeown, *Ultra-Wideband RadioTechnology*. West Sussex: John Wiley & Sons Ltd, 2004.

[11] (2009). *2009/343/EC, Commission Decision,* . Available: http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32009D0343:EN:NOT

[12] (2007). *2007/131/EC, Commission Decision*. Available: http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32007D0131:EN:NOT

[13] G. R. Hiertz, Z. Yunpeng, J. Habetha, and H. Sirin, "Multiband OFDM Alliance - The next generation of Wireless Personal Area Networks," in *Advances in Wired and Wireless Communication, 2005 IEEE/Sarnoff Symposium on*, 2005, pp. 208-214.

[14] Z. Honggang, Z. Xiaofei, K. Y. Yazdandoost, and I. Chlamtac, "Multiple signal waveforms adaptation in cognitive ultra-wideband radio evolution," *Selected Areas in Communications, IEEE Journal on,* vol. 24, pp. 878-884, 2006.

[15] K. Ohno and T. Ikegami, "Interference mitigation study for UWB radio using template waveform processing," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 54, pp. 1782-1792, 2006.

[16] W. Xianren, T. Zhi, T. N. Davidson, and G. B. Giannakis, "Optimal waveform design for UWB radios," *Signal Processing, IEEE Transactions on,* vol. 54, pp. 2009-2021, 2006.

[17] G. P. Agrawal, *Fiber-optic communication systems*, 3rd ed. New York: Wiley-Interscience, 2002.

[18] E. Pancera, J. Timmermann, T. Zwick, and W. Wiesbeck, "Signal Optimization in UWB Systems," in *German Microwave Conference*, 2009.

[19] Z. Xiaofei, K. Y. Yazdandoost, Z. Honggang, and I. Chlamtac, "Cognospectrum: spectrum adaptation and evolution in cognitive ultra-wideband radio," in *Ultra-Wideband, 2005. ICU 2005. 2005 IEEE International Conference on*, 2005, pp. 713-718.

[20] N. C. Beaulieu and H. Bo, "A novel pulse design algorithm for ultra-wideband communications," in *Global Telecommunications Conference, 2004. GLOBECOM '04. IEEE*, 2004, pp. 3220-3224 Vol.5.

[21] J. Mitola, "Cognitive Radio: an Integrated Agent Architecture for Software Defined Radio," Teleinformatics, Royal Institute of Technology, Kista, 2000.

[22] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey," *Comput. Netw.,* vol. 50, pp. 2127-2159, 2006.

[23] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *Selected Areas in Communications, IEEE Journal on,* vol. 23, pp. 201-220, 2005.

[24] W. Beibei and K. J. R. Liu, "Advances in cognitive radio networks: A survey," *Selected Topics in Signal Processing, IEEE Journal of,* vol. 5, pp. 5-23, 2011.

[25] J. Mitola, "Cognitive Radio Architecture Evolution," *Proceedings of the IEEE,* vol. 97, pp. 626-641, 2009.

[26] N. S. Shankar, C. Cordeiro, and K. Challapali, "Spectrum agile radios: utilization and sensing architectures," in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, 2005, pp. 160-169.

[27] R. Tesar, "Generator for Ultra-wideband Applications," diploma, Department of electromagnetic field, Czech Technical Univeristy in Prague, Prague, 2007.

[28] U. J. Moenich, C. Sturm, H. Boche, and W. Wiesbeck, "Empirical capacity and the fading characteristics of ultra-wideband indoor propagation channels," in *Radio and Wireless Symposium, 2008 IEEE*, 2008, pp. 607-610.

[29] O. Ser Wah, A. A. S. Naveen, Z. Yonghong, V. P. Kumar, T. P. C. Le, K. Kua, and Z. Weiqiang, "White-Space Sensing Device for Detecting Vacant Channels in TV Bands," in *Cognitive Radio Oriented Wireless Networks and Communications, 2008. CrownCom 2008. 3rd International Conference on*, 2008, pp. 1-6.

[30] M. H. Islam, C. L. Koh, S. W. Oh, Q. Xianming, Y. Y. Lai, W. Cavin, L. Ying-Chang, B. E. Toh, F. Chin, G. L. Tan, and W. Toh, "Spectrum Survey in Singapore: Occupancy Measurements and Analyses," in *Cognitive Radio Oriented Wireless Networks and Communications, 2008. CrownCom 2008. 3rd International Conference on*, 2008, pp. 1-7.

List of Candidate’s Works Relating to the Doctoral Thesis

Articles in Impacted Journals

[1] R. Urban, D. Grace, and P. Pechac, "Impulse Radio UWB Pulse Shaping for Cognitive Radio Applications," accepted (11/2010) to *Wireless Personal Communications,* pp. 1-14, DOI: 10.1007/s11277-010-0158-6. (33%)

Publications Listed in Web of Science

[2] R. Urban and S. Zvanovec, "Dispersion and Pulse Interferences Investigation for UWB Signal Propagation," Radioengineering, vol. 17, pp. 60-65, Sep 2008. (50%)

[3] R. Urban, L. Subrt, and P. Pechac, "Ultra wideband pulse shaping using frequency mixer," in RF Front-ends for Software Defined and Cognitive Radio Solutions (IMWS), 2010 IEEE International Microwave Workshop Series on, 2010, pp. 1-4. (33%)

[4] R. Urban, S. Zvanovec, and P. Pechac, "Time Domain Detection of Interference Signals using Ultra Wideband Techniques," in 2009 3rd European Conference on Antennas and Propagation, Vols 1-6, New York, 2009, pp. 178-181. (50%)

[5] R. Urban and S. Zvanovec, "On the indoor propagation of UWB signals," in Proceedings of the 14th Conference on Microwave Techniques: Comite 2008, Praha 6, 2008, pp. 77-80. (50%)

Anotace

Disertační práce se zabývá pulsní technologií UWB (Ultra WideBand) a jejím využitím v kognitivních sítích. Důraz je kladen především na minimalizaci rušení již fungujících systémů. V úvodu práce je čtenář nejprve seznámen se základními principy a historií UWB technologie. Je představena spektrální maska, která limituje UWB systémy ve frekvenční oblasti a jsou zmíněny možnosti tvarování pulsu, aby bylo možné toto omezení splnit. Také je zmíněn princip fungování kognitivního rádia se zaměřením na dynamické přidělování spektra. To je založeno na podrobné znalosti spektrálního pozadí v daném čase a místě, a proto jsou zmíněny možné techniky snímání a sdílení spektra.

Práce má stanoveno následujících pět cílů: experimentální ověření některých parametrů šíření UWB pulsů v bezdrátovém kanálu, systém pro tvarování pulsů pro maximální využití spektrální masky, měřicí systém pro širokopásmové snímání spektra, měření využití spektra v různých scénářích a následný návrh konceptu využívající pulsní UWB technologii.

Pro splnění všech cílů disertační práce bylo potřeba nejprve ověřit některé zákonitosti UWB technologie měřením. Důraz byl kladen především na disperzi a na studium odrazů pulsů od vodivých překážek. Dále je vysvětlen princip tvarování pulsů za pomocí násobení pulsu s harmonickou frekvencí. Jsou provedeny simulace, jejichž koncept je ověřen měřením, které potvrdilo, že navržený způsob tvarování je možné použít.

Pro fungování kognitivního systému je důležité získat data o využití frekvenčního spektra. Z tohoto důvodu byla sestavena mobilní měřící aparatura, která je založena na přenosném radiovém přijímači R&S PR 100. Tento přijímač vyniká především velkou citlivostí a rychlostí měření. Oproti obdobným měřením je použita jedna širokopásmová anténa, která pokrývá celé měřené spektrum. Pro splnění cílů měřící kampaně bylo potřeba vyvinout program pro ovládání přístroje a ukládání dat na řídící počítač přes ethernetové rozhraní.

Měření probíhalo v několika zcela odlišných lokalitách od městské zástavby po venkov. Měření bylo také zaměřeno na efekt měnícího se počtu osob v uzavřených prostorách (přednášková místnost během výuky a během dne pracovního klidu). Z měřených dat bylo následně vypočteno využití frekvenčního spektra včetně časového vývoje. Některé služby (GSM, WIFI, atd.) byly vyhodnoceny zvlášť pro zjištění časového vývoje spektrálního obsazení těchto služeb.

Na základě naměřených dat spolu s tvarováním pulsů byl následně představen koncept kognitivního systému využívající UWB technologii. Představený koncept zpracuje data o obsazení spektra a navrhne tvar pulsu tak, aby nedocházelo k rušení stávajících uživatelů spektra. Dále je umožněno zvýšit vyzářený výkon v neobsazených frekvenčních pásmech tak, aby došlo k získání dosahu tohoto sytému. Bylo ukázáno, že při zachování konstantního vysílacího výkonu je možno snížit rušení se stávajícími uživateli spektra o 68 dB. Celý systém také vyhodnocuje vhodnou šířku pulsu tak, aby došlo k maximalizaci přenosové rychlosti při modulaci OOK.

Práce je uzavřena zhodnocením zadaných cílů a jsou definovány další možné směry výzkumné činnosti v této problematice.