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RF Channel Characterization in Industrial, Hospital and Home Environments

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Abstract

The rapid development of electronic components has resulted in the emergence of new mobile applications targeted at industry and hospital sectors. Moreover, a lack of available wireless frequencies as result of the growth of wireless systems is becoming a problem. In this thesis we characterize industrial and hospital environments in order to provide the knowledge necessary to asses present and future development of critical wireless applications. Furthermore, we investigate the possibility of using TV white space by analysing the interference from secondary to primary user in home environments.

Some of the wireless solutions used in industries and hospitals come directly from systems designed for home or office, such as WLAN and Bluetooth. These systems are not prepared to handle problems associated with interference of impulsive character found in industrial processes and electrical systems.

Typically, industrial environments have been classified as reflective environments due to the metallic structure present in the buildings. In this thesis, we demonstrate that although this may be generally true, some locations in the industry may have special properties with wave propagation characteristics in the opposite direction. Stored materials can absorb wireless signals, resulting in a coverage problem. From the measurement campaign we are able to distinguish three main classes of indoor environments (highly reflective, medium reflective and low reflective) with different propagation characteristics.

Improving spectrum efficiency can be a solution to the growing demand for wireless services and can increase a system's robustness against interference, particularly in critical applications in industrial and hospital environments. One improvement in spectrum efficiency can be for secondary consumers to reuse unassigned portions of the TV spectrum at a specific time and geographical location. This thesis studies the effect of inserting white space devices in the TV broadcast spectrum. Note that any new model must state the maximum power allocated to secondary users to avoid harmful interference with the primary signal.

The content of this thesis is divided into three parts. The first part is the most comprehensive and addresses electromagnetic interference and multipath characterization of industrial environments. In this part, we have developed a method for channel characterization for complex electromagnetic environments and have produced results from different industrial environments. The second part presents a preliminary study that characterizes the electromagnetic interference in a hospital environment. The third part is a study of secondary users reusing the TV white spaces.

Acknowledgements

First of all, I would like to thank my supervisors Doctor José Chilo, Professor Peter Stenumgaard and Professor Ben Slimane. I feel fortunate to have these three encouraging researchers who offered me important support during the past three years.

This work would not have been possible without the support of staff from Stora Enso, SSAB, Green Cargo, Åkerströms, Syntronic and Agilent Technologies. I want to thank them for their great support and encouragement, and I will never forget the time spent together doing measurements in Borlänge, Luleå, Kiruna and Stockholm, as well as at the bridge in Gothenburg.

I would also like to express my thanks to the University of Gävle and the Swedish Knowledge Foundation (KKS) for funding the project "Reliable wireless machine-to-machine communications in the electromagnetic disturbed industrial environments." This thesis is one of many results from this project.

Most of my time has been spent at the Centre for RF Measurements working with my colleagues, Sathyaveer Prasad, Per Landin, Charles Nader, Mohamed Hamid, Efrain Zenteno, Helena Eriksson, Claes Beckman, Radarbolaget members and EMI's research group: Per Ängskog, Carl Karlsson and Carl Elofsson. Nor I can forget the white space measurements done with Evanny Obregon and Lei Shi; I very much enjoyed conducting that set of measurement campaigns. Many sincere thanks to all.

Personally, I would like to thank my girlfriend and my family, including my father, mother, brother and sister for all the happiness, love and support that they have given me over the years.

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List of Acronyms & Abbreviations

AACI	Aggregate Adjacent Channel Interference
A/D	Analog-Digital
ADC	Analog-Digital Converter
APD	Amplitude Probability Distribution
BEP	Bit Error Probability
BER	Bit Error Rate
BPSK	Binary Phase-Shift Keying
CDF	Cumulative Distribution Function
CSMA	Carrier Sense Multiple Access
dB	Decibel
DECT	Digital Enhanced Cordless Telecommunications
dBi	The forward gain of an antenna compared with the hypothetical isotropic antenna in dB
dBm	Power relative to 1 milliwatt in dB
DTV	Device Television
DVB-T	Digital Video Broadcasting-Terrestrial
ECG	Electrocardiogram
EM	Electromagnetic
EMI	Electromagnetic Interference
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission

FM	Frequency Modulation
FPGA	Field-Programmable Gate Array
GHz	Gigahertz
GSM	Global System Mobile
GUI	Graphical User Interface
IFFT	Inverse Fast Fourier Transform
IM	Inter Modulation
ISI	InterSymbol Interference
ISM	Industrial, Scientific and Medical radio bands
KTH	Kungliga Tekniska Högskolan
LoS	Line of Sight
MAC	Media Access Control
MHz	Megahertz
MIG	Metal Inert Gas
MIMO	Multiple Input Multiple Output
M2M	Machine-to-Machine
ns	Nano Seconds
NLoS	Non-Line of Sight
OFDM	Orthogonal Frequency-Division Multiplexing
PDF	Probability Distribution Function
PDP	Power Delay Profile
PSD	Pulse Inter-Arrival Time Probability Distribution Function
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RF	Radio Frequency
SNR	Signal-to-Noise Ratio
TETRA	Terrestrial Trunked Radio

Ts	Symbol Period
UHF	Ultra High Frequency
VNA	Vector Network Analyzer
WLAN	Wireless Local Area Network
WSD	White Space Device

Chapter 1

Introduction

1.1 Background

Wireless communication has grown considerably in the last decade and it is expected that the demand for wireless services will continue increasing. More and more new applications continue appearing in different environments such as office, home, industry, and hospital. Due to the special nature of industrial and hospital environments, together with the malfunction claims and reported accidents involving these systems [1], it is necessary to analyze these environments through a comprehensive measurement study. Another important issue related to radio frequency measurements involves the spectral efficiency and the possibility of spectrum sharing, in which secondary users can reuse the frequency white spaces of primary users. In this thesis we present results from an extensive measurement study conducted in three different environments, namely, industrial, hospital and home environments.

Current commercial wireless applications are developed mainly for office environments and outdoor conditions. No special applications have been designed for a higher security in industrial and hospital environments. Therefore, it is necessary to understand how these environments can affect wireless communication. Furthermore, little research has been done to characterize the electromagnetic environment in industrial or hospital areas [2–4]. Previous work has been focused mainly on outdoor environments related with TV broadcasting, mobile communications [5–8] and indoor office environments [9–11]. Regarding industrial environments, a study at Lund University of Sweden has investigated how metal structures in one industrial environment affect the multipath propagation of radio waves in the 3.1 to 4 GHz frequency band [12]. In that work, no measurement of the electromagnetic interference (EMI) was performed.

Characterization of industrial environments by means of electromagnetic interference and multipath propagation should be the first step in developing new wireless applications and improving the current wireless technologies. This would allow us to select an appropriate frequency band and adapt communication technologies thus minimize the risk of interference problems. The electromagnetic interferences, in the case of industry, arise from different electronic systems industrial processes and maintenance works [2]. Another degradation source is multipath propagation, the metallic structures in industrial buildings cause time dispersion in the wireless signal. In cases in which the symbol period of the wireless system is short as compared with the time dispersion of the channel, the environment will introduce considerable intersymbol interference (ISI), potentially disrupting the communication links [13].

Accidents caused by electromagnetic interference with medical monitors and other hospital devices are well-documented for many years. This electromagnetic interference arises from different electronic systems (e.g., TV transmitter and computers), from communication systems (e.g., police radios and cellular phones) and from processes and maintenance systems [14, 15]. This problem is worsening with the rapidly growing market of wireless communications for machine to machine (M2M) communications in industries and hospitals. Standards to ensure the immunity of electronic medical equipment from electromagnetic disturbances need to be formulated. To achieve this objective, a systematic investigation of electromagnetic interference in hospital environments must be conducted.

Currently, the demand for new wireless services is a fact nowadays, the number of users is growing and higher data rate are needed. Fulfilling this demand is becoming a problem for operators where all available frequency bands are assigned. The lack of spectrum has become a serious problem due to the constant increment in radio communication technologies and applications. However, cognitive radio can use the spectrum in a better way. This technique can sense the environment and then alter power, time, frequency, modulation and other parameters dynamically to reuse available resources but this technique is not mature enough. In 2004, the Federal Communications Commission (FCC) proposed that unlicensed wireless devices reuse vacant television channel frequencies using cognitive radio. However, the unlicensed wireless devices can generate harmful interference to licensed broadcast TV services if they are not properly controlled. Because no existing simulation tool can properly model the behavior of such systems, the effect of these interferences must be investigated in a real home environment via measurements. Some groups have studied the influence of secondary user transmitting in the primary frequency spectrum [16–19] but a realistic evaluation needs to be performed of the spectral opportunities with more than one low power indoor system.

1.2 Problem Formulation

Industrial and hospital environments usually exhibit significantly higher levels of radiated electromagnetic interference than office environments. Current commercial wireless technologies are not designed for these types of radio-hostile environments. Applications involving wireless communication must satisfy both real-time and reliability requirements simultaneously; otherwise a loss of time and money or even physical damage can be the result. Moreover, in the case of industrial environments, there are major problems associated with multipath propagation due large halls and multitude of objects with metallic surface. In order to develop and improve wireless communication systems for these environments, a good understanding of the characteristics of these environments are needed.

The emergence of new applications in home environments and the limited amount of available radio spectrum calls for a better spectrum usage. Reusing the TV white space in an adaptive way has been proposed as a possible solution for the spectrum shortage in home environments. However, to develop wireless systems that use the same spectrum as TV broadcasting, need to investigate the effect on the performance and signal quality of the primary system.

The main objectives of this thesis can be summarized as follows:

- Develop a method for channel characterization of complex industrial environments. In this method, a combination of interference level measurement, statistical properties and multipath propagation measurements is used. This new combination of methods for channel characterization and assessment of present wireless technologies is necessary to cope with the complex environments in industrial applications.

- Characterize three different industrial environments: paper mill, steel mill and freight train marshalling yard. This characterization is based on electromagnetic interference and multipath measurements. The interferences encountered in these environments are often of impulsive character arising from electrical equipment and processes. Typically, communication systems are designed by analyzing the ratio of the radio signal energy to Gaussian noise power spectral density without considering the presence of impulsive noise. Impulsive noise has different statistical properties and affects wireless systems differently. In addition, impulsive noise presents higher variance and mean values in comparison with Gaussian noise as shown in Figure 1.1.

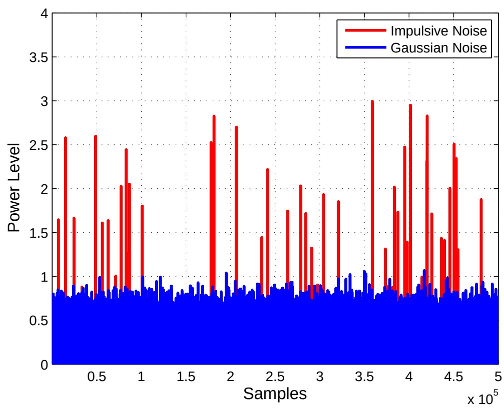

Figure 1.1: Power level of Gaussian and impulsive noise.

- Determine and quantify time dispersion as the second source of degradation in industrial environments caused by industrial building structure and metallic objects.

The multipath components arrive at the receiver at different times and with different amplitude attenuations. If the time spread of the channel is larger than the symbol period (Ts), the transmitted signal will suffer from intersymbol interference (ISI), see Figure 1.2.

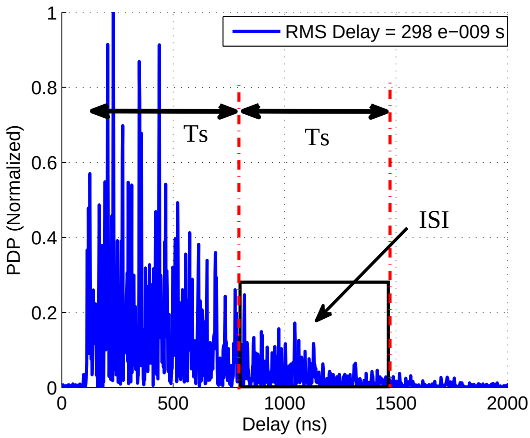

Figure 1.2: Power Delay Profile with ISI.

- Perform a preliminary characterization of a hospital environment based on three areas: the entrance of the hospital, ECG room and telemetry room. We characterize the main sources of interference in a hospital environment and analyze their statistical properties. The hospital of Gävle is taken as a case study.
- Study and quantify the effect of adding secondary users in the frequency white spaces of a primary user. This is one way to increase the available spectrum for future wireless industrial applications, hospital and home environments. The insertion of a secondary user can produce harmful interference to the primary user and this approach needs to be studied and quantified. Reusing the unused TV channels in the 470 to 790 MHz frequency band can be a possible solution to improve the spectrum efficiency in home environments.

1.3 Overview of the Thesis Contributions

This section provides a brief description of the technical papers that conform this thesis and their scientific contributions to the understanding of wireless communication in industrial environments. The main contributions of this thesis are presented in Chapter 3, 4 and 5. The contribution of each chapter and its relationship to the published technical papers is given. The contribution of the author in each technical paper is also highlighted.

Chapter 3: Industrial Environments

This chapter presents the measurement results from industrial environments. We start describing some related wireless communication incidents reported by end users. Then, the results of electromagnetic characterization base on measurement studies and computer simulations are reported. Finally, a conclusion section analyzes the problems found in industrial environments.

The content of Chapter 3 is based on the following five technical papers:

Paper 1: J. Ferrer Coll, C. Karlsson, P. Stenumgaard, P. Ängskog and J. Chilo, "Ultra-wideband propagation channel measurements and simulations in industrial environments," *Proceedings of International Symposium on EMC*, Wroclaw, Sep. 2010.

This paper presents results on multipath fading obtained from simulations and measurement campaigns in two industrial environments: steel mill and paper mill. The obtained results showed that the simulation results are quite close to the results obtained from measurements. Hence, one can use the simulation software to characterize industrial environments where it is not possible to perform measurements.

The author contributed to the paper both theoretically and experimentally by serving as the main person responsible for both simulations and measurements. He was also the primary writer of the paper and presented the paper at the conference.

Paper 2: P. Ängskog, C. Karlsson, J. Ferrer Coll, J. Chilo and P. Stenumgaard, "Sources of disturbances on wireless communication in industrial and factory environments," *Asia-Pacific International Symposium on Electromagnetic Compatibility,* Beijing, pp. 285-288, Apr. 2010.

This paper presents the main results from the measurement campaign with regard to interferences and multipath spread parameters. Sources of electromagnetic interference are determined and other factors that affect the poor performance of wireless systems in industrial environments are also presented.

The author contributed by co-writing the paper, performing the measurement work and analyzing the data to determine multipath spread parameters. He also presented the paper at the conference.

Paper 3: J. Ferrer Coll, P. Ängskog, C. Karlsson, J. Chilo and P. Stenumgaard, "Simulation and measurement of electromagnetic radiation absorption in a finished-product warehouse," *Proceedings of IEEE EMC Symposium,* Fort Lauderdale-Florida, vol.3, pp. 881-884, Jul. 2010.

The presence of a non-reflective industrial environment in wireless communications is presented in this paper. Here, we are investigating a highly absorbent environment where radio propagation is strongly dependent on the frequency and possible electromagnetic interference could even be absorbed.

The contribution of the author to this paper was primarily with measurements, computer simulations, and data analysis. He also wrote a large part of the paper.

Paper 4: J. Ferrer Coll, J. Chilo and S. Ben Slimane, "Radio-frequency electromagnetic characterization in factory infrastructures," *IEEE Transactions on Electromagnetic Compatibility,* accepted September 2011.

This paper analyzes multiple results from a measurement campaign in which amplitude probability distribution (APD) and time distribution were used to characterize three industrial environments. The APD measurements confirm the presence of impulsive noise which must be considered when evaluating wireless digital communication systems in industrial environments. In addition, time spread measurements show the different levels of reflectivity in these environments.

The author contributed by performing measurements, computer simulations, and analyzing the different results. He was also the primary writer of the paper.

Paper 5: C. Karlsson, P. Ängskog, J. Ferrer Coll, J. Chilo and P. Stenumgaard, "Outdoor electromagnetic interference measurements in industrial environments," *Proceeding AMTA 31st Annual Symposium*, Salt Lake City, pp. 365-368, Nov. 2009.

Measurement results regarding the electric field strength and electromagnetic interference in outdoor industrial environments are presented in this paper. The amplitude probability distribution (APD) is used to determine whether electromagnetic interference is of impulsive nature or not.

The author's contribution to this paper was his active participation during the measurement campaign. He also contributed in writing the paper and he presented it at the conference.

Chapter 4: Hospital Environments

Chapter 4 introduces a preliminary characterization study performed in a hospital. We highlight a number of serious accidents where electromagnetic interference has been the source of electronic malfunctions. Then, we present the measurement results from the hospital and a corresponding statistical analysis. We end this chapter with conclusions regarding hospital environments.

Part of the results of this chapter has been published in the following technical paper:

Paper 6: J. Ferrer Coll, J.J. Choquehuanca, J. Chilo, and P. Stenumgaard, "Statistical characterization of the electromagnetic environment in a hospital," *Asia-Pacific International Symposium on Electromagnetic Compatibility,* Beijing, pp. 293-296, Apr. 2010.

A statistical method to characterize the electromagnetic environment in a hospital is presented in this paper. The author's contribution to this paper was mainly experimental performing measurements at the hospital. He was also the main author responsible for writing and presenting the paper at the conference.

Chapter 5: Home Environment - TV White Space

Chapter 5 starts by introducing the lack spectrum problematic. Continuing measurement results that analyze the harmful interference generated by unlicensed wireless devices (i.e., secondary users) to licensed broadcast TV services (i.e., primary user) are presented. The chapter ends with conclusions discussing the results obtained.

The main results of this chapter has been published in the following technical papers:

Paper 7: E. Obregon, L. Shi, J. Ferrer Coll, and J. Zander, "Experimental verification of indoor TV white space opportunity prediction model," *5th International Conference on Cognitive Radio: Wireless networks and communications*, Cannes, pp. 1-5, Jun. 2010.

Paper 8: E. Obregon, L. Shi, J. Ferrer Coll, and J. Zander, "A model for aggregate adjacent channel interference in TV white space," *IEEE Vehicular Technology Conference*, Budapest, May 2011.

In these two papers, we have used measurements to evaluate the prediction model developed by the KTH group to assess TV white space. Validation through measurements conducted at the laboratory and in home environments has shown that the assumptions and parameter settings of the prediction model corresponds to our measurement results.

The author's contribution to these papers was mainly experimental; he manage the design and implementation of the measurement system and performed the measurements. He also collaborated in writing the papers.

1.4 Thesis Outline

This work is organized in two parts:

The first part contains Chapter 2 through 6. Chapter 2 provides the theoretical background and the measurement methods. Chapter 3, 4, and 5 present the results obtained from the measurement campaigns performed in industrial, hospital, and home environments regarding electromagnetic interference and time dispersion. Chapter 6 provides concluding remarks of this work and proposes some steps for future research.

The second part of the thesis presents verbatim copies of all technical papers included in the thesis work.

Chapter 2

Theoretical Background and Measurement Methods

2.1 Introduction

The presence of electrical motors, cranes, vehicles and medical equipments can produce interference in communication systems. These interferences are a composition of random high energy spikes with randomly occurrence in terms of time and frequency, which does not correspond to a Gaussian noise; they are defined as impulsive interference. Consequently, the statistical properties of this type of impulsive interference are different from additive white Gaussian noise (AWGN) and, therefore, affect the performance of communication systems differently. Previous studies have considered the amplitude probability distribution (APD) as way of characterizing impulsive interferences [20–22] as well as the impact of microwave ovens radiation on several modulation schemes [23, 24]. The APD is also known in the literature as the complementary cumulative distribution function. Recently, research has been conducted to develop multichannel APD measurements using an ADC-FPGA board [25, 26]. However, this measurement system has only been used in laboratory environments to characterize the properties of a single interference source. Thus, the APD has not been used to characterize impulsive interferences in industrial environments. In this thesis, we have developed a measurement methodology for measuring the APD in complex industrial environments.

Industrial environments are quite complex including buildings with large structures that are often composed by metallic elements. Due to the metallic surfaces, the signal reflects, diffracts and scatters, creating multiple paths which cause propagation delays to the transmitted signal. As a results of these effects, radio signals within such environments suffer from both amplitude and delay distortion. The delay distortion introduces intersymbol interference (ISI) and puts a limit on the maximum achievable transmission data rate of the radio link. Some studies have used multipath measurement methods to characterize industrial environments [27, 28] but these studies have generalized these environments as reflective and have not consider special cases where the industrial environment is absorbent.

The demand for more broadband services increases the need for additional radio spectrum in the market. Improving the spectrum efficiency in used bands can solve this problem. The TV broadcast band is located from 470 MHz to 790 MHz and a good percentage of this frequency band is not used. Inserting secondary users into this band can be a solution in terms of spectrum efficiency, but these secondary users should be adequately controlled to avoid distorting the received signal at the TV device or, more generally, to the primary user. Previous works [17, 18] have analyzed the interference generated by secondary users into the TV device reception. However the presence of white space devices (WSDs) transmitting in the proximity of TV device receiver in indoor scenarios has not been studied. Hence, new models that limit the maximum power of secondary users in the proximity of TV device receivers need to be developed.

This chapter contains the theoretical background of this licentiate thesis, the measurement methodology implemented during the measurement campaigns and a brief conclusions of the chapter.

2.2 Theory

In this section, we present the theoretical background used in the subsequent chapters. We start by describing the statistical properties of impulsive noise and how it can affect the bit error probability (BEP) of different modulation schemes. We then present the time dispersion analysis of the channel, the power delay profile and its quantitative parameters. We end this section by discussing the power limitations of secondary users transmitting in the TV-broadcast frequency band.

Statistical Properties of Impulsive Noise

Communications systems are designed to operate properly at a certain average received signal-to-noise ratio (SNR). These systems usually assume that the added noise in question is AWGN with a constant power spectral density. However, in industrial environments, the presence of impulsive noise sources such as electric motors, vehicles and repair work, produces powerful components in the signal spectrum that are not AWGN but rather impulsive interferences. Impulsive noise has statistical properties different from AWGN and, moreover, affects wireless communication links differently. The effect of this impulsive noise can be analyzed by calculating its statistical properties.

We will start defining the cumulative distribution function (CDF), denoted by $F_X(\cdot)$, which is a statistical distribution showing the probability that a random amplitude X does not exceed a certain amplitude x_0. The CDF of a random variable X is defined as

$$F_X(x_0) = \Pr\left[X < x_0\right] \tag{2.1}$$

and its probability density function (pdf) is written as

$$f_X(x_0) = \frac{d}{dx_0} F_X(x_0) \tag{2.2}$$

The APD, also known as the complementary cumulative distribution function, is a distribution function showing the probability that a random amplitude X exceeds a certain amplitude x_0. It is theoretically defined as

$$\mathrm{APD}(x_0) = \Pr\left[X > x_0\right] = 1 - F_X(x_0). \tag{2.3}$$

The APD is used to analyze non-Gaussian noise interferences and many authors have studied the advantages of the APD when measuring impulsive signals [29, 30].

Figure 2.1 provides a graphical depiction of the APD for a Gaussian random variable and an impulsive noise random variable. Using the APD it is possible to distinguish when an impulsive noise is present in a wireless environment.

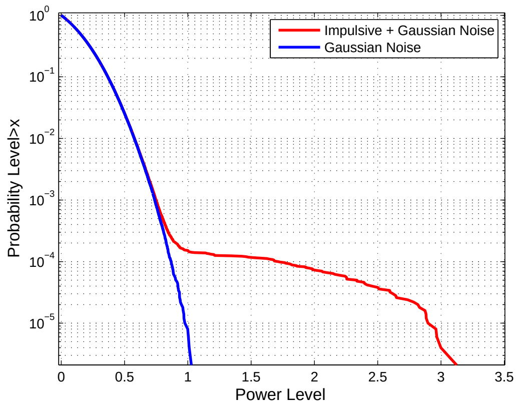

Figure 2.1: APD for Gaussian, and impulse noise with Gaussian noise.

The APD can be estimated from measured data by finding the ratio of the time that the amplitude of a random signal exceeds a certain level x_0 to the total time of the data under analysis [31], see Figure 2.2.

$$\mathrm{APD}(x_0) = \frac{\text{Time signal level exceeds } x_0}{\text{Total time}}. \tag{2.4}$$

The APD has been discussed in recent years concerning its correlation to the bit error rate of digital radio signals [32–34]. The relationship, between the APD of an interfering signal and $P_{b,max}$ (i.e., the worse case bit error probability) for different modulation, is defined as

$$P_{b,\max} \approx \alpha \mathrm{APD}\left(\beta\sqrt{E_b\frac{Z_0}{T_b}}\right), \tag{2.5}$$

where β, α vary for each modulation schemes, E_b is the average energy per bit Z_0, is the impedance of the receiver and T_b is the duration of the bit interval. For different modulation schemes β and α can be obtained from Table 2.1:

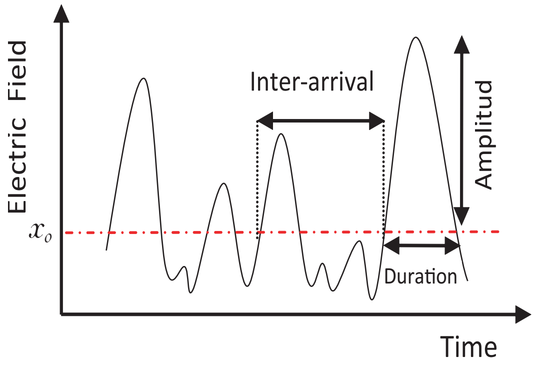

Figure 2.2: Simplified EMI baseband model.

Table 2.1: Bounds derived for different modulations

Modulation	β	α	$P_{b,max}$
BPSK	1	1	$P_{b,\max} \approx \text{APD}\left(\sqrt{E_b}\right)$
QPSK	1	1/2	$P_{b,\max} \approx \frac{1}{2}\text{APD}\left(\sqrt{E_b}\right)$
16-QAM	0.63	1/4	$P_{b,\max} \approx \frac{1}{4}\text{APD}\left(0.63\sqrt{E_b}\right)$

In Figure 2.3 we can see the APD of two different interferences and modulation requirement levels taken from Table 2.1. In the case of BPSK with a typical value P_b of 10^{-3} and $\sqrt{E_b \frac{Z_0}{T_b}}$ of $10\mu V$, we can observe that a receiver, capturing noise levels as interference 2, will not fulfil the minimum P_b of the modulation requirements, contrary receiver detecting interference 1 will not have problems fulfilling the minimum P_b needed in each modulation.

The noise pulse inter-arrival time probability distribution function (PSD) is defined as the probability that the time duration between two consecutive noise pulses exceeds certain temporal threshold, τ_s

$$\text{PSD}(\tau_s) = 1 - F_X(\tau_s), \tag{2.6}$$

Experimentally, once the threshold x_0 is specified, the PSD(τ_s) will be defined by the ratio of the number of times the inter-arrival time τ_a exceed a time τ_s, to the number of consecutive observed pulses n

$$\text{PSD}(\tau_s) = \frac{\text{Number of times } \tau_a > \tau_s}{n}. \tag{2.7}$$

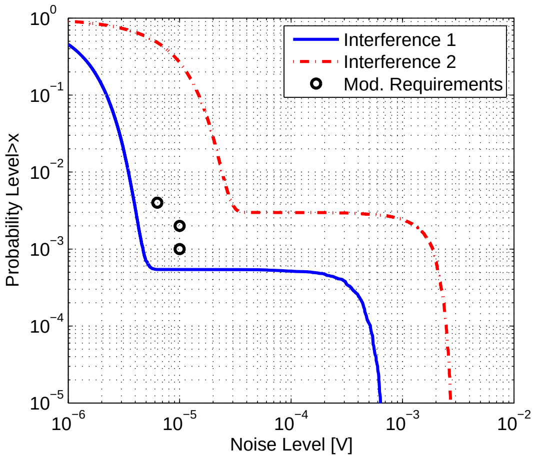

Figure 2.3: Amplitude Probability Distribution for two interferences with modulation requirements.

Impulsive noise can be defined theoretically which gives the possibility to understand better APD. There are several statistical physical models that define the probability density function of impulsive noise. The most extended is Middleton class A model which is defined as [35]

$$f_x(x) = \sum_{m=0}^{\infty} \left(\frac{A^m}{m!} e^{-A} \right) \left(L_m D e^{xD - L_m e^{xD}} \right), \tag{2.8}$$

where

$$D = \frac{\ln(10)}{10} \tag{2.9}$$

and

$$A = \overline{\lambda}\,\overline{l}, \tag{2.10}$$

where $\overline{\lambda}$ is the mean number of emissions per second, and $\overline{l}$ is the mean length of an emission in seconds. L_m is given by

$$L_m = \frac{A\,(1+\Gamma)}{I_N\,(m + A\Gamma)}, \tag{2.11}$$

where m is the number of possible interfering signals and I_N is the instantaneous noise power.

In order to find the Gaussian Factor Γ, a threshold has to be defined to separate the signal in Gaussian and impulsive (non Gaussian) part, then by calculating the ratio of the mean of the Gaussian σ_G^2 part to the mean of the impulsive part σ_I^2, the Gaussian Factor Γ is obtained

$$L_m = \frac{\sigma_G^2}{\sigma_I^2}. \tag{2.12}$$

By varying the Middleton parameters A and Γ, interference distributions ranging from Gaussian to highly impulsive can be obtained. The APD for this Class A noise is found to be

$$\Pr(X \geq x_0) = \int_{x_0}^{\infty} f_x(x)dx = \sum_{m=0}^{\infty} \left(\frac{A^m}{m!}e^{-A}\right)\left(e^{-L_m 10^{x/10}}\right). \tag{2.13}$$

Impulsive interferences have different statistical properties than Gaussian noise, as we have seen. To illustrate the effect of Gaussian and impulsive noise on the error probability of several modulation schemes, the BEP for different modulation schemes can be analyzed.

To quantify the impact of impulsive noise under different digital modulation schemes, we have simulated communication systems by inserting Gaussian and impulsive noise. The block diagram of the communication system in Figure 2.4 shows a random sequence of binary data that is modulated and sent through a Gaussian and impulsive channel. The receiver consists of a demodulator and an error detector that measures the BEP.

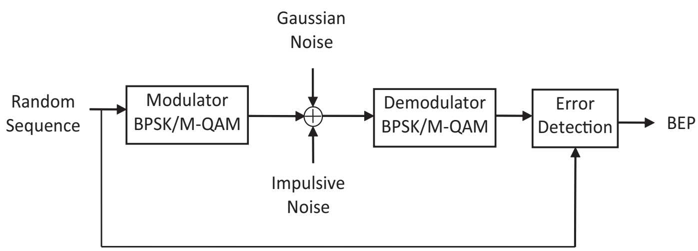

Figure 2.4: Block diagram of a simulated digital communication system.

For an additive white Gaussian noise (AWGN) channel, the BEP for binary phase-shift keying (BPSK), quadrature amplitude modulation (QAM) and quadrature phase-shift keying (QPSK) are given by [36]

$$P_e = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{2.14}$$

where E_b is the average energy per bit and N_0 is the single-sided power spectral density [W/Hz] of the noise.

In general, for M-QAM modulation, the BEP over AWGN channels is given by [37]

$$P_e = \frac{2\left(1-\frac{1}{\sqrt{M}}\right)}{k}\mathrm{erfc}\left(\sqrt{\frac{3k}{2(M-1)}\frac{E_b}{N_0}}\right) \times \left[1-\frac{1-\frac{1}{\sqrt{M}}}{2}\mathrm{erfc}\left(\sqrt{\frac{3k}{2(M-1)}\frac{E_b}{N_0}}\right)\right] \quad (2.15)$$

where $k = \log_2(M)$ is the number of bits per symbol.

The obtained simulation results for coherent BPSK modulation and 16-QAM are illustrated in Figure 2.5 as a function of the average received signal energy-to-noise power spectral density E_b/N_0. The inserted impulsive interference corresponds to a Middleton noise with $A = 0.001$ and $\Gamma = 0.1$.

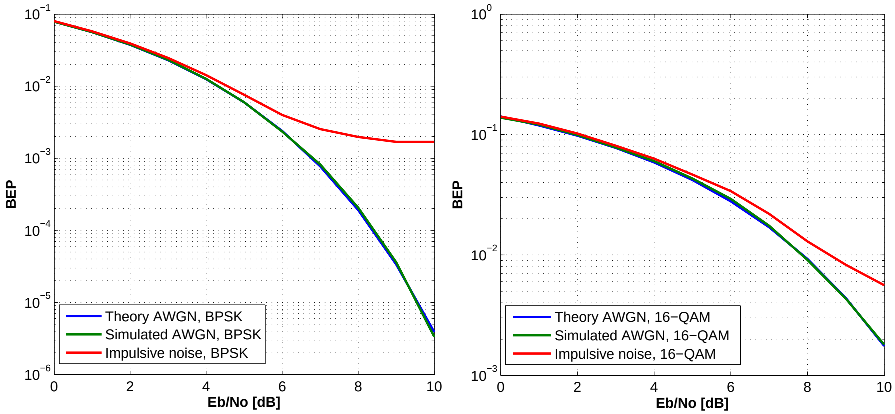

Figure 2.5: BPSK and 16-QAM with pure Gaussian and impulsive noise with Gaussian.

It is observed that the effect of impulsive noise is clearer at high values of E_b/N_0 where the appearance of an error floor can be easily observed with respect to the bit error probability. This error floor depends on the strength of the impulsive noise.

Fading Multipath Channels

The time dispersion of a channel is an important property that needs to be studied in the characterization of different environments. Depending on the duration of the symbol period of a radio system and the properties of the environment, the radio signal may suffer from intersymbol interference (ISI). ISI will introduce bit error that cannot be reduced by increasing the transmitted power. The only way to reduce such bit error and achieve the required service quality is by using a more complex receiver with equalization or by reducing the transmission data rate.

The impulse response defines the dispersive properties of a channel and can be obtained from the frequency response. In our work, the frequency response was determined by performing a spectrum analysis of the channel with a vector network analyzer that obtains the complex channel transfer function $H_m(f)$, as shown in Figure 2.6.

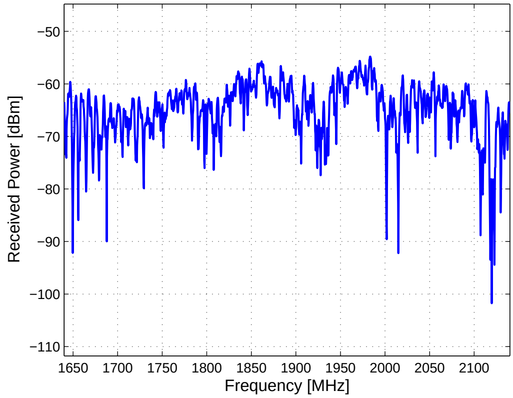

Figure 2.6: Frequency response of the channel.

The frequency response of Figure 2.6 is weighted through a Blackman-Harris window $H_w(f)$. The window provides larger delay spread values as compared to other windows such as Hanning or Rectangular windows as indicated in [38].

The channel transfer function after windowing can be written as follows:

$$H_c(f) = H_w(f) \times H_m(f). \tag{2.16}$$

Hence, the time domain response of the radio channel is obtained by taking the inverse Fourier transform or approximated using the inverse discrete Fourier transform (IDFT)

$$\begin{aligned} h_c(\tau) &= \frac{1}{W_s}\int_{W_s} H_c(f)e^{j2\pi f\tau}df \\ &\approx \frac{1}{N}\sum_{k=0}^{N-1} H_c(k\Delta f)e^{j2\pi k\Delta f\tau} \end{aligned} \tag{2.17}$$

where W_s is the width of the Blackman-Harris window and $\Delta f = \frac{W_s}{N}$. By letting $\tau = m\Delta\tau = m/W_s$ we obtain the discrete samples of the channel impulse response as

$$h_c(m) = \frac{1}{N}\sum_{k=0}^{N-1} H_c(k\Delta f)e^{j2\pi\frac{km}{N}}, \qquad m = 0, 1, \cdots, N-1. \tag{2.18}$$

Radio channels are usually modelled as wide sense stationary with uncorrelated scattering and the PDP, which is the expected power per unit of time received with a certain excess delay. The PDP is defined as the autocorrelation function of the channel impulse response and can be written as

$$\phi_h(\tau) = E\{h_c(\tau_1 + \tau)\, h_c^*(\tau_1)\}. \tag{2.19}$$

where $E\{\cdot\}$ represents the expected value.

Figure 2.7 illustrates the measured PDP of a certain radio environment.

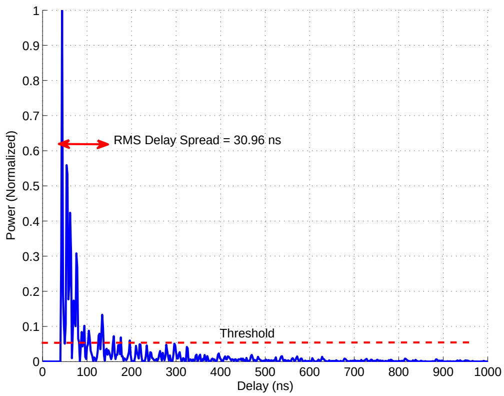

Figure 2.7: Power Delay Profile of the channel.

Further, in order to obtain quantitative parameters of the time spread in the environment, the mean excess delay (τ_{mean}) and rms delay spread (τ_{rms}) can be obtained from the discretized PDP [36]. The mean excess delay is the first moment of the power delay profile of the channel and is defined as

$$\tau_{mean} = \frac{\sum_k \phi_h(k\Delta\tau)k\Delta\tau}{\sum_k \phi_h(k\Delta\tau)}, \tag{2.20}$$

The rms delay spread is the square root of the second moment of the PDP and is defined as

$$\tau_{rms} = \sqrt{\left(\frac{\sum_k \phi_h(k\Delta\tau)(k\Delta\tau)^2}{\sum_k \phi_h(k\Delta\tau)}\right) - (\tau_{mean})^2}. \tag{2.21}$$

The maximum excess delay is the time spread during multipath components are above a certain threshold and is defined as

$$M_D = \tau_{\max} - \tau_{\min}, \tag{2.22}$$

where $\tau_{\min}$ and $\tau_{\max}$ are the arrival time of the first and the last multipath components, respectively.

Radio White Spaces

Spectrum efficiency is an important topic in the research world nowadays. Unused spectrum can be useful for secondary users, but adding additional users should be done in a controlled manner so that primary users are not affected. Radio white spaces, such as a guard band or an unused radio spectrum, exist naturally between used radio channels. In this thesis, we are interested in the coexistence of primary user with a single and multiple secondary users. Our objective is to validate interference models developed for a white space device (WSD).

The first model is based on the results presented in [39] and uses the desired power-to-undesired power ratio, denoted as D/U, as a required threshold to analyze the interferences from one secondary user (WSD) into a primary user (DTV receiver). The desired power is defined as

$$D = \left(\frac{E^2 c^2}{4 Z_0 f^2} \right) G_{TV}(\theta_D), \tag{2.23}$$

where E is the signal strength of the TV channel in the receiving antenna, c is the speed of light, Z_0 is the impedance of the antenna, f is the frequency of the channel, G_{TV} is the gain of the TV antenna and θ_D is the arrival angle.

The undesired power is defined as

$$U = P_{WSD} G_{WSD} \left(\frac{G_{TV}(\theta)}{Lb_1} + \frac{G_2}{Lb_2} \right), \tag{2.24}$$

where P_{WSD} is the transmit power of the WSD, G_{WSD} is the gain of the WSD antenna, G_{TV} is the gain of the TV receiving antenna, G_2 is the attenuation of the TV cable, Lb_1 and Lb_2 are the path loss between the WSD antenna, TV antenna and TV cable, based on the Keenan-Motley model [40].

The second model is an extension of the first model using the aggregate adjacent channel interference (AACI) to characterize the interferences from multiple WSDs.

For AACI model the maximum interference power accepted in a certain TV channel N is obtained by

$$\sum_{k \neq 0} I_{N+k}\, \gamma_k \leq S_N, \tag{2.25}$$

where I_{N+k} is the power of channel $N+k$ injected to the TV channel N, S_N is the power of the TV channel N and γ_k is the threshold in channel $N+k$ between interference power and TV signal strength for acceptable image quality in channel N.

2.3 Measurement Methods

This section contains the measurement methods developed and used during our measurement campaigns. Electromagnetic interference, multipath and white space measurement setups are described in this section.

Electromagnetic Interference Measurement Method

The electromagnetic interference measurement method for complex environments involves conventional instruments such as a spectrum analyzer, a digitizer and a personal computer. The spectrum analyzer used is the PSA-E4440A and the 12-bit A/D converter is the DP310 from Agilent Technologies. The antennas chosen for this measurement are directive and correspond to the CBL6112A which covers from 30 to 2500 MHz and the Rohde & Schwarz HE200 which is a low weight antenna covering from 20 to 3000 MHz.

To perform a time analysis of the environment the signal detected by the antenna is fed to the spectrum analyzer in the zero-span mode. Connecting the PSA to the A/D converter the board digitizes the video output from the spectrum analyzer with 12-bit resolution at a sampling rate of at least 10 times of RBW and then stores the digitized data on the computer hard disk. The setup of the spectrum analyzer and the parameter-setting for noise measurement are both controlled from the graphical user interface implemented on a personal computer. Once the measurement is completed and stored, the data are analyzed to derive the relevant statistical properties. Figure 2.8 shows a block diagram of this process, for more details of the measurement setup see Paper 5.

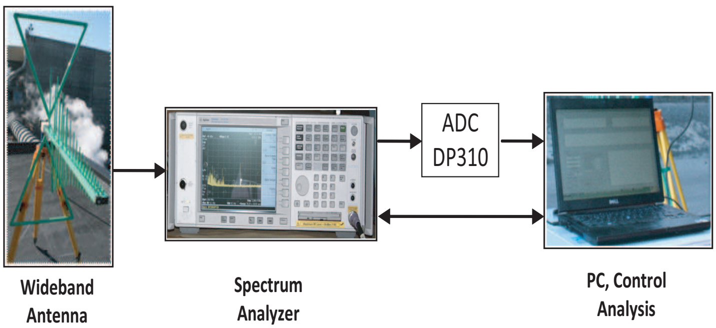

Figure 2.8: Interference measurement setup.

The measurement method is based on the CISPR 16-2-3 [41] and is accomplished according to the following steps:

1. Scan the maximum frequency range of the broadband antenna using Max Hold mode with the peak detector.
2. Calculate the total scan time for this frequency sweep mode depending on the frequency range, resolution bandwidth and the signal to be detected.
3. Localize the frequency points affected by the interference.
4. Center the frequency of the spectrum analyzer in the interested frequency and set zero-span mode.
5. Use greater resolution bandwidth depending on the bandwidth of the wireless system of interest.
6. Ensure that the sampling rate of the ADC should be at least 10 times more than the resolution bandwidth.
7. Calculate the APD.
8. Estimate the interference impact on the wireless system.

Figure 2.9 illustrates the received power level as a function of time and the corresponding amplitude probability distribution for a radio signal disturbed by an impulsive interference based on the measurement procedure described above. For instance, if a system tolerates a maximum error probability of 10^{-3} then the received power level should be higher than -77.7 dBm.

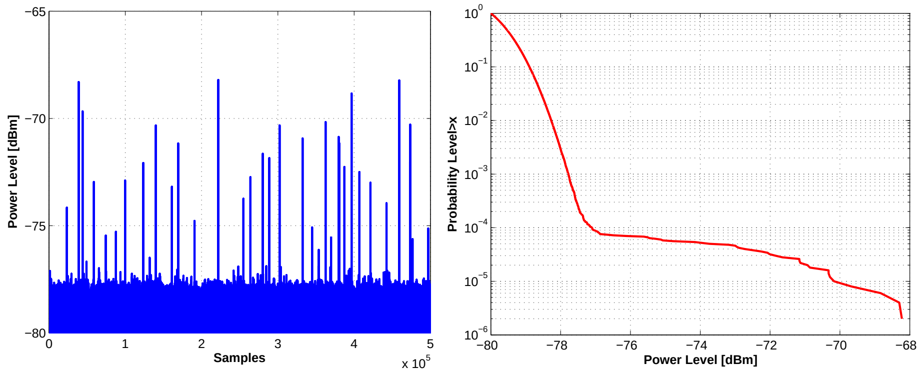

Figure 2.9: Time domain measurement (left) and APD of the data (right).

Fading Multipath Measurement Method

The fading multipath measurement setup used in this thesis work is shown in Figure 2.10. It consists of a vector network analyzer (VNA), an ultra-wide band omnidirectional antenna pair, which is connected to the analyzer by low-attenuation coaxial cables, and a computer with a graphical user interface (GUI) that controls the entire system, as specified in Paper 4. Once the data is stored in the computer, the software calculates the desired parameters. The VNA and cables are calibrated for every measurement. Each antenna is mounted on a tripod at a height of 1 m above the floor and then moved to various positions in the measurement location.

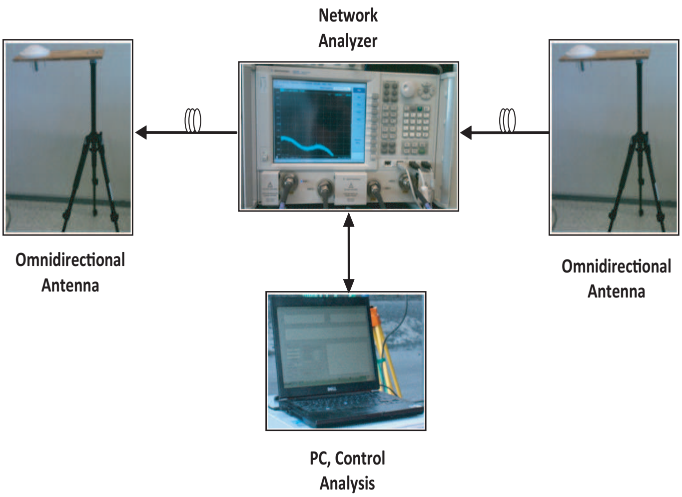

Figure 2.10: Multipath measurement setup.

The calibration steps are performed as follows:

1. Select the interested frequency band.
2. Set the output power to 10 dBm to reach longer range.
3. Select the proper calibration kit.
4. Connect the low-attenuation coaxial cables.
5. Perform response calibration for transmission measurements.

The measurement method is carried out as follows:

1. Place the antennas in the desired location.
2. Perform a calibration in the interested frequency band.
3. Excite the channel with the VNA.
4. Obtain multiple frequency response of the channel $H(f)$.
5. Transfer the data to the computer.
6. Replace the antennas and start another time the process.

Once the data is transferred to the computer a Blackman-Harris window is apply to the $H(f)$. Then, using the inverse fast Fourier transform the impulse response of the channel is obtained. Finally, the power delay profile and quantitative parameters are extracted.

The system has a maximum detectable delay, τ_{max}, after this delay, multipath components are not captured. The formula for the maximum detectable delay is obtained as follows:

$$\tau_{\max} = \frac{N_{\text{points}} - 1}{BW}, \tag{2.26}$$

where N_{points} is the number of measurement points used in one sweep and BW is the bandwidth selected. We use 1601 points and 500 MHz of bandwidth in our system, providing a maximum delay detectable of 3.2 μs, this value is big enough and covers almost all indoor environments.

Another parameter that should be taken into account is the frequency shift, Δf, which is a function of the propagation time, t_{tr} (time of flight), the frequency span (S), and the sweep time, t_{sw}, as defined by the following expressions:

$$\Delta f = t_{tr} \left(S/t_{sw} \right), \tag{2.27}$$

The Intermediate Frequency (IF) bandwidth should be greater than Δf. With 500 MHz S, a sweep time of 800 ms, and not expecting to detect components after 2 μ s, we require an IF bandwidth greater than 1.25 kHz.

Radio White Spaces Measurement Method

The setup corresponding to white space measurements is described in this section. In this case two different setups are used in order to aim different objectives. The first setup is focus on calibration whereas the second setup is intended to study the minimum distance between the WSD and the TV receiver. Papers 7 and 8 contain a deeper explanation of these measurement setups.

The aim of the first setup is to determine the minimum D/U ratio for single and multiple WS channels located around the primary TV channel. The setup is illustrated in Figure 2.11. The R&S SMU200A was used as a WSDs generator. The DTV signal is the broadcast signal captured from the local TV transmitter. The DTV and WSD signals are combined and sent to the R&S FSQ26 signal analyzer and to a commercial DTV receiver. Based on the TV display we can quantify the quality of the TV signal for different WSD transmitted power and collect the WSD received power in the signal analyzer. Knowing the DTV signal power and the WSD received power, we compute the D/U ratio.

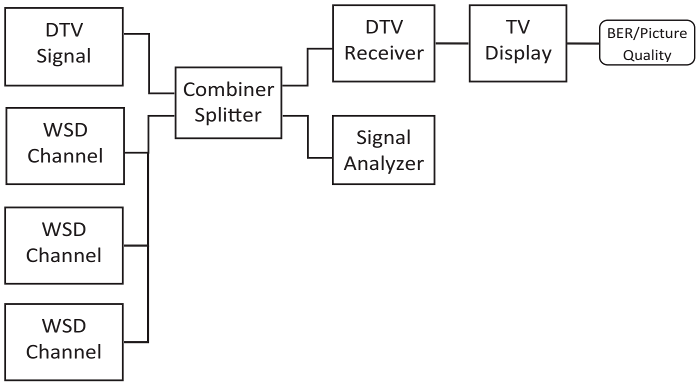

Figure 2.11: Measurement setup for D/U ratio calculation.

The parameters used to generate the secondary users and the characteristics of the DTV receiver are shown in Table 2.2.

Table 2.2: Measurement parameters

WSD Signal Bandwidth (W):	8 MHz
WSD Wireless Interface:	OFDM
WSD Modulation Scheme:	QPSK
WSD Maximum Output Power:	10 dBm
WSD Duplex Scheme:	TDD
WSD Maximum Antenna Gain:	16 dBi
TV Set-top Antenna 1: Panel (Low Directivity)	4 dBi (Main Lobe Gain) 0 dB (Back Lobe Gain)
TV Set-top Antenna 2: Yagi (High Directivity)	8 dBi (Main Lobe Gain) -10 dB (Back Lobe Gain)
TV Rooftop Antenna Gain:	6 dBi
TV Signal:	-55 dBm (Strong Signal) -75 dBm (Weak Signal)

The measurement method is described as follows:

1. Capture the DTV-B channel N.
2. Create a white space channels with characteristics shown in Table 2.2.
3. Combine the signals and send them to the TV and spectrum analyzer.
4. Quantify the minimum power of the white space channel that causes degradation to the picture quality of the TV channel N.
5. Obtain the maximum power received from the spectrum analyzer
6. Move the WSD channel to another channel, as shown in Figure 2.12.

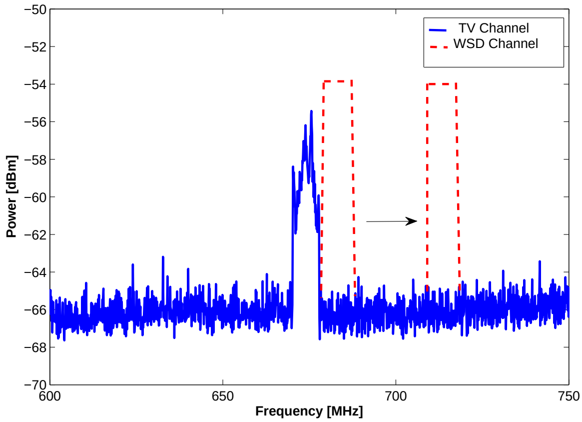

Figure 2.12: TV and WSD channels.

The second measurement setup is aimed at obtaining the minimum separation distance between the WSD and the DTV receiver, as illustrated in Figure 2.13. The WSD generator, the signal analyzer and the digital TV are the same as in the first measurement setup. In this case two commercial antennas are used with the parameters described in Table 2.2. The distance between the WSD and the DTV antenna is changed by placing the WSD at different locations. For each location, the number of available WS channels is different, we calculate this number by observing the picture quality of TV channel N.

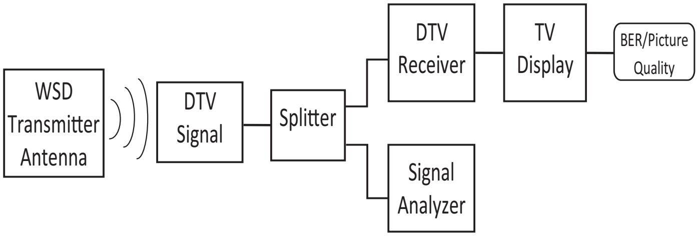

Figure 2.13: Measurement setup separation distance WSD and DTV receiver.

2.4 Conclusions

To summarize, this chapter presented the theoretical background and the measurement setups used in the following chapters. We described the APD as a tool for impulsive interference analysis. In the second part of this chapter, we explained how to determine multipath quantitative parameters from the frequency response of the channel. In the third part of the theory, new models that limit the maximum power of secondary users were defined. Finally, we include a section with the description of the different measurement setups that were used during our measurement campaigns.

Chapter 3

Characterization of Industrial Environments

3.1 Introduction

Today, the number of new industrial wireless applications keeps growing and we can expect a bright future for these technologies given the great potential that lies ahead. Wireless technologies provide increased flexibility and productivity for the industry. However, this places heavy demands on wireless technologies within these harsh environments, which may contain excessively high or low temperatures, high humidity, intense vibrations, and excessive electromagnetic noise caused by large motors, industrial processes and conductors.

In general, the wireless technologies currently used in industry are based on off-the-shelf technologies which are not optimized for industrial environments. It is important to note that these wireless technologies are vulnerable to electromagnetic interference. In fact, there are no specific wireless standards for industrial or factory applications. Some standard organizations are working to develop future standards, such as the case of European Telecommunications Standards Institute (ETSI).

Manufacturers of wireless technologies must confront the choice between capacity and robustness. Capacity implies having as many users as possible and a high data rate, while robustness implies having non-disruptive communications and low delay, which are important for achieving critical safety and security in the case of industrial applications. In particular, robust systems are needed to address high levels of radiated electromagnetic interferences present in industrial environments.

Moreover, industrial environments have special building structures that include a high amount of metallic material. This creates reflections between the transmitter and the receiver leading to delayed multipath components. Time distortion can degrade the communication due to the introduced ISI. On the other hand, some industrial environments present opposite properties, absorbent material can considerably reduce the multipath propagation, resulting in a coverage problem.

The need for non-disruptive communications with high reliability is, therefore, important in industrial environments. Thus, interference problems must be handled when they occur. Furthermore, in the planning process of new wireless applications in an industrial environment, care must be taken to choose the right frequency bands and communication technologies so that the risk for interference problems is minimized. In order to cope with interference problems, an electromagnetic characterization of industrial environments must be performed.

This part of the thesis addresses the characterization of the electromagnetic environment within three industrial environments: a paper mill, a steel mill, and a freight train marshalling yard. The objective is to highlight potential safety issues caused by RF interference in emerging wireless communication systems. In this part, electromagnetic interference measurements using the amplitude probability distribution (APD) are performed in combination with traditional electric field versus frequency measurements. Additionally, multipath measurements are conducted to characterize and classify the different industrial environments.

Most of the material in this chapter is included in Papers 1 through 5. In the next section some notable communication incidents in industrial environments are presented. Section 3.3 provides experimental results during the measurement campaigns in the industry. The chapter ends with a summary of the measurement results including comparison and analysis of all the different environments.

3.2 Incidents in Industrial Environments

In this section, we report incidents that are related directly or indirectly with the use of wireless communications in industrial environments. The following is a list of problems identified during our measurement campaigns caused by electromagnetic disturbances:

- Inability to use digitally enhanced cordless telecommunications (DECT) in certain industrial environments due to electromagnetic interference generated by industrial processes.

- High disturbance levels in the frequency band of 400 to 450 MHz cause errors in the train communication link. The signature of these disturbances is similar to the Syledis navigation communication system. Syledis is a 420 to 450 MHz frequency land-based radio positioning system which is said to be shut down several years ago [42].

- The disturbance of critical radio systems for a cargo crew were disturbed caused by leaky signals from cable TV. A temporary solution was to move the TV to another channel.

- Inability to move remote-controlled cranes as intended. In other case, cranes using wireless local area networks (WLAN) experience downtime due to disturbances.

- Problems with the door opener in an industrial hall, operating in the 26 to 30 MHz band, possibly caused by a traverse crane that was using electromagnet to lift steel reels.

- Wireless equipment used for real-time monitoring exhibits excessive delays in data transmission, resulting in process stops.

- Dysfunctional locking of cars with a remote-control at one shopping center near an industrial plant. The owners were forced to tow their cars some distance away to open the doors.

- Inability of security personnel in an industrial plant to lock their cars in certain areas due to remote-control locks were unintentional disturbed. It was subsequently demonstrated that there was a strong intelligent signal operating in the same frequency as the locks.

- Dysfunctional operation of radio systems for fire fighters in areas with industrial processes and high-voltage installations. These systems stopped functioning or exhibited a short operating range of only 20 meters.

Moreover, we have registered some related problems caused by wireless communications:

- Personnel at the cargo rail yard reported severe cross talk problems between channels in their voice intercom radios. The voice intercom is an essential safety function for staff working in the train yards, where the marshalling of trains is primary solo work. The crosstalk was early suspected to be originated from inter modulation (IM) in the repeater stations. Therefore, starting with IM calculations with frequencies according to a new channel plan, the problem was solved.

- WLAN problems with cell dragging were also reported to cause transportation dysfunction in an industrial area. The problem could be solved with a better cell planning.

- Communication problems caused by the reflective and absorbent characteristics of industrial environments have also been observed.

So far, such incidents have only incurred economic costs, but such incidents should be seriously considered to prevent human accidents in the future. Incidents and performance limitations in industrial environments clearly demonstrate the need to control the electromagnetic interference to improve the robustness of wireless systems.

3.3 Interference and Multipath Measurements in Industrial Environments

In this section, we present the measurement and analysis results from multiple environments. Channel characterization of the electromagnetic interferences and time dispersion within industrial environments are the main focus. These results are used to assess the vulnerability of different wireless technologies according to different types of interference and extreme values of delay spread. The measurement campaigns have been conducted in three industrial contexts: paper mill, steel mill and freight train marshalling yard. The results are presented in this chapter; for a more detail, see Papers 1 through Paper 5.

Channel characterization can be divided in two big groups, namely, indoor and outdoor environments. Usually, indoor industrial environments are classified as reflective environments due to their metallic structure and building dimensions. During our measurement campaign, we observed that this classification is too general, and rather, it should be divided in three categories, high, medium and low reflective.

Interference and Multipath Analysis of Indoor Environments

In this section, we present measurements and simulation regarding different indoor industrial environments, ranging from high reflective with strong interference and long delays in the receipt multipath components, to low reflective environments with no interference and few components with short delay.

High Reflective Environments

High reflective environments have large amount of interference and high levels of time dispersion. These interferences are often produced by industrial machinery whereas time dispersion is caused by the building dimensions and the metallic materials found in industrial environments. Figure 3.1 shows two reference locations where measurements were conducted. The locations are factory halls that have a high number of metallic objects and structures composed by metallic walls, floors and ceiling.

Figure 3.1: Reference locations for high reflective environment at paper mill.

To study these environments, an electromagnetic characterization for a wide band spectrum was performed. Figure 3.2 (left) shows that the majority of the impulsive interferences occur in low frequency regions. The frequency of theses impulsive interferences is located within the band of 20 MHz to 1 GHz, where the majority of the wireless communications in the industry occur. DECT is a system used for voice and data communications in industries and it works at the 1.8 GHz frequency band. In high reflective environments, we detected the presence of interferences affecting DECT communication, see Figure 3.2 (right).

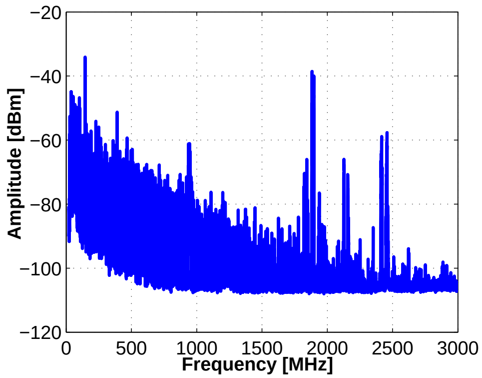

Figure 3.2: Electromagnetic interferences at low frequencies (left) and disturbances on the DECT band (right).

Once the interference is located in the frequency spectrum, a time domain measurement is performed to determine the statistical properties of the signal and interference. Figure 3.3 shows the APD of the captured signal in the DECT band. For example, if a system tolerates a maximum error probability of 10^{-3} then the signal received power should be higher than -80 dBm for this case.

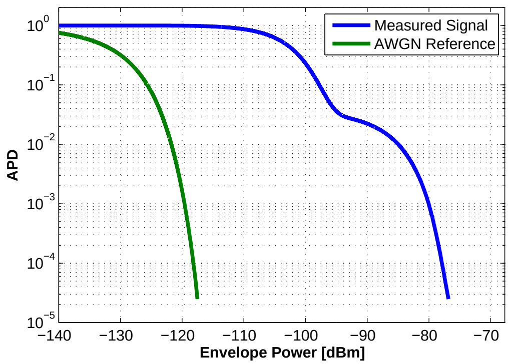

Figure 3.3: Amplitude Probability Distribution at 1888 MHz.

Using the time dispersion measurement the PDP can be determined for these environments. The results show that the channel introduces a high level of time dispersion to the signal. Figure 3.4 presents the power delay profiles for three different frequency bands in one of the locations in Figure 3.1. We can see that the rms delay for high reflective environment is more than 290 ns in some cases.

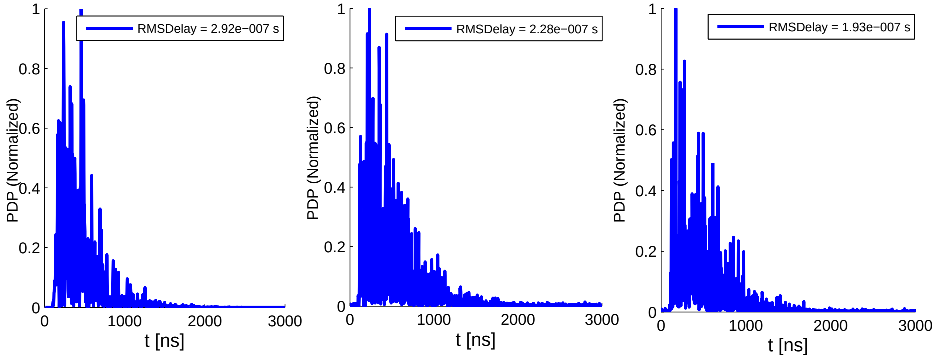

Figure 3.4: PDP at 433 MHz (left), at 1890 MHz (center) and at 2450 MHz (right), NLoS case.

Figure 3.5 represents the CDF of the PDP for NLoS case. 10% of the received energy arrives after 750 ns.

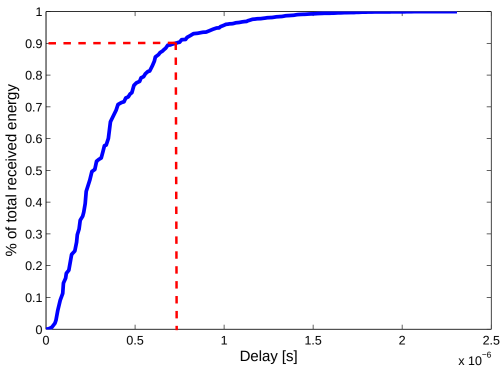

Figure 3.5: Percentage of total received energy for high reflective environments.

Additionally from the PDP, some quantitative parameters can be calculated according to the expressions in (2.21) and (2.22). Table 3.1 presents some results extracted from the measurements. The number of components in the PDP corresponds to the number of paths that the signal takes from transmitter to receiver. We can observe high values of rms delay as well as maximum excess delay.

Table 3.1: PDP parameters for high reflective environments

	LoS	NLoS
Nº Components	60-223	102-230
τ_{rms} [ns]	178	251
M_D [ns]	244	1020

Medium Reflective Environments

Medium reflective environments represent typical industrial environments, where the building has large dimensions and there are metallic objects present. Photographs of two factory halls are shown in Figure 3.6, including a production hall in a steel mill and a steel finished-product warehouse. The actual structure are composed of metallic walls, concrete floor, and large cranes hung from the metallic ceiling. The dimensions of the halls are in the same range as the high reflective environments but in this case the amount of metallic objects present is considerably lower. Interference and multipath propagation in these medium reflective environments are studied in Papers 1 and Paper 4.

Figure 3.6: Large industrial halls at steel mill.

Most of the disturbances detected in this environment are present at low frequencies as in the high reflective scenario but with lower strength and at narrower frequency band. Figure 3.7 (left) is an example of electromagnetic interferences located in low frequency regions. Figure 3.7 (right) shows an example of disturbances in the 433 MHz industrial, scientific and medical (ISM) band captured at one of the locations of Figure 3.6.

Figure 3.8 shows PDP for three different frequency bands. In these environments the maximum excess delay is lower than 380 ns at distances of 28 m for NLoS case.

In Table 3.2, the number of multipath components, the rms delay and the maximum excess delay for this type of environment are presented. The number of multipath components is considerably reduced compared with high reflective environments. Similarly, the maximum excess delay shows lower values than in the high reflective environment for LoS and NLoS cases.

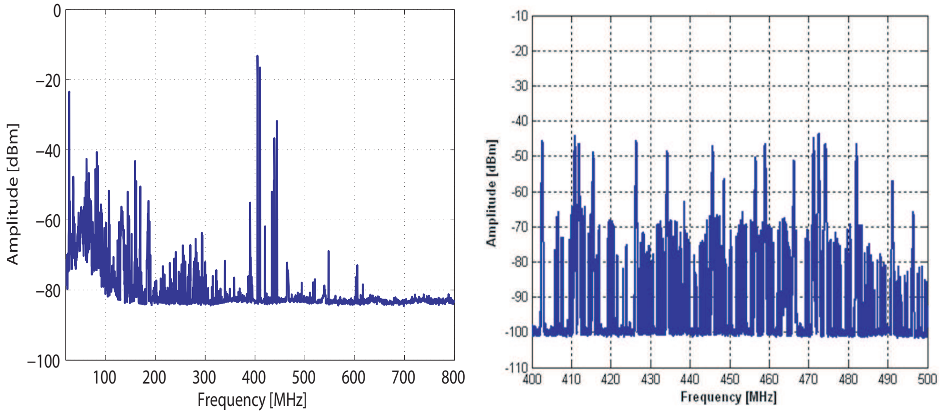

Figure 3.7: Electromagnetic interference at low frequencies (left) and interferences at 400-500 MHz band (right), in an industrial hall at steel mill.

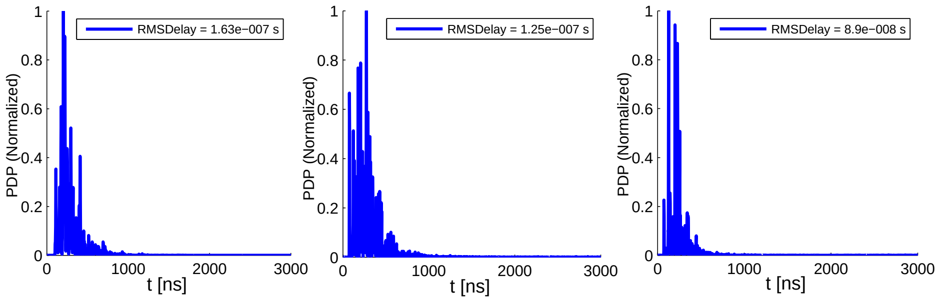

Figure 3.8: PDP at 433 MHz (left), at 1890 MHz (center) and at 2450 MHz (right), NLoS case.

Table 3.2: PDP parameters for medium reflective environments

	LoS	NLoS
N° Components	43-108	86-114
τ_{rms} [ns]	96	139
M_D [ns]	132	547

Low Reflective Environments

This section explores non-reflective or highly absorbent industrial environments. This type of environment has been investigated in Paper 3, which describes measurements and simulations associated in the paper warehouse.

In particular, we examined a finished-product warehouse at the paper mill, see Figure 3.9 (left). The paper rolls (i.e., finished products) are stacked in blocks that are separated by corridors, and the diameter of each paper roll varies between 1.25 and 1.70 m. The storage plan has an area of 85 x 150 m and ceiling height of 8 m. The walls and ceilings are constructed of prefabricated concrete, and the floor is made of concrete.

Ray tracing software is a good tool to simulate the propagation characteristics of an environment where it is not possible to perform measurements. We have simulated and performed measurements in the real environment to verify the correct behaviour of the software in industrial scenarios. The virtual building and its surrounding environment are designed in a manner similar to the real measurement location. Reflecting the actual location of the transmitter and the receivers, Figure 3.9 (right) shows the simulated environment.

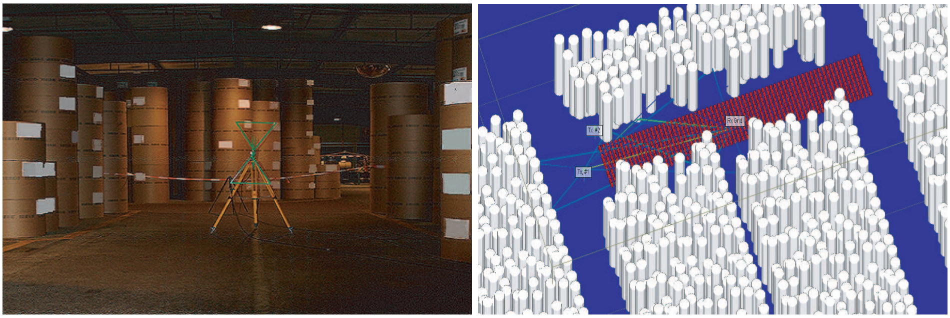

Figure 3.9: Paper rolls warehouse at paper mill (left) and simulated environment at the same location (right).

Electric field strength measurements were conducted in this environment in the frequency band of 20 MHz to 3 GHz. No electromagnetic interferences were detected.

Multipath measurement results show the absence of reflections in this environment. The PDPs for three different frequency bands in the paper rolls warehouse are presented in Figure 3.10. For the 2450 MHz frequency band, we observe a difference in the noise floor, we find that the signal to noise is low even at a distances of 6 meters between the transmitter and the receiver in the NLoS case. Only one main component and a few small reflections were observed. The rms delay spread calculated is smaller than the typical values for indoor environments such as offices.

Measurements and simulation results regarding time dispersion in highly absorbent environment are shown in Figure 3.11 (left). We noted the similarities in both of the PDPs. In Figure 3.11 (right), the simulation results obtained with a higher number of receivers provide insight into the rms delay spread distribution in the environment.

Table 3.3 shows some quantitative parameters related to the time dispersion. We identify less than 30 components in the PDPs. The maximum excess delay is not greater than 43 ns for the NLoS cases.

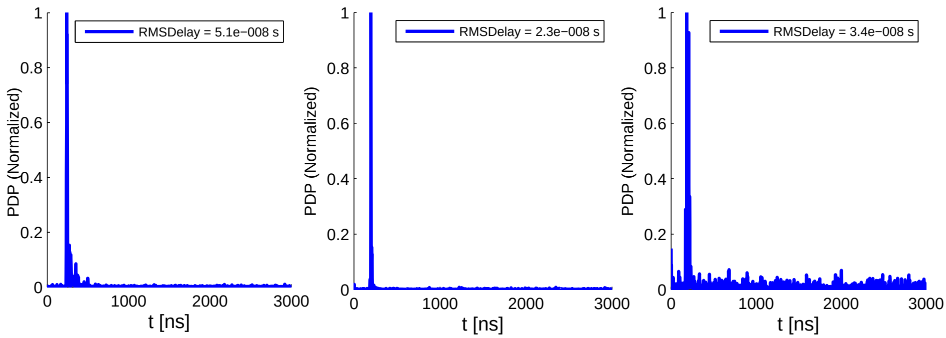

Figure 3.10: PDP at 433 MHz (left), at 1890 MHz (center) and at 2450 MHz (right), NLoS case.

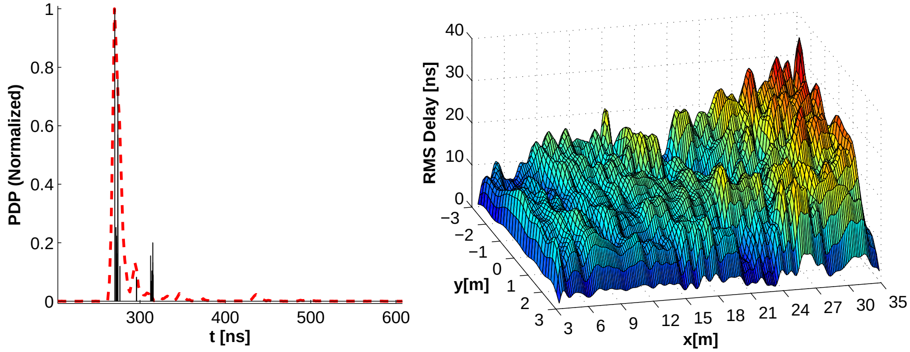

Figure 3.11: Measured and simulated PDP for 433 MHz for the LoS (left) and distribution of rms delay spread in the receiver simulated grid (right).

Table 3.3: PDP parameters for absorbent environments

	LoS	NLoS
Nº Components	9-27	5-19
τ_{rms} [ns]	11	28
M_D [ns]	16	31

Interference Analysis in Outdoors Environments

Electromagnetic interference measurements were conducted in the train yards in Borlänge, Göteborg, Luleå, Hallsberg and Stockholm. Disturbances in railway wireless communication systems can limit the successful functioning of wireless control technologies, leading to the failure of critical locomotive functions and loss of control. Figure 3.12 shows two examples of railway freight environments.

Figure 3.12: Two railway freight environments.

The electric field strength and APD measurements at the marshalling yards are investigated in Paper 5. For example, in Figure 3.13 we observe interference from 420 to 450 MHz that could correspond to Syledis, which is an old navigation system that has not been in use since 1995. This interference is located in a frequency band that is used to control the railway system.

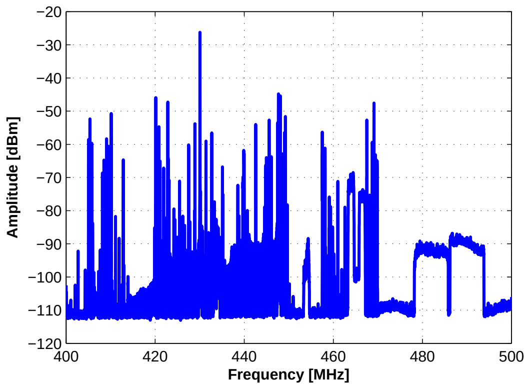

Figure 3.13: Interference measurement in Borlänge.

Interference Analysis from Other Sources in Industrial Environments

Transportation and repair activities in industrial environments may generate electromagnetic interferences in wireless communication systems. In this section, we focus on interference caused by trains, mopeds and welding processes. Paper 2 address the problems related to transportation and repair work in industrial environments.

The interference measurements involving railway freight train were conducted in the marshalling yards in Luleå, Borlänge and Stockholm. In the case, of moped and repair work, the measurements were performed at different locations in the paper and steel mill. Figure 3.14 shows two examples of vehicles, a train cabin and a four-wheeled motorcycle.

Figure 3.14: Freight train in Borlänge (left) and four-wheeled motorcycle in steel mill (right).

The measurement results shown in Figure 3.15 correspond to a train driven by an electric power line. We have simulated whether the train is loaded or unloaded by turning the brakes on or off. The electric train driven takes the energy from the overhead power

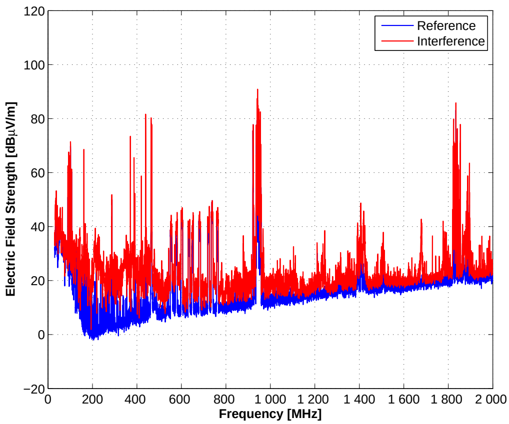

Figure 3.15: Electric train without brakes and with brakes, in Borlänge.

lines by the use of a pantograph. The design involves the use of inverters that contribute considerably to the measured noise. From the results we observed that during the breaking process, the impulsive noise covered a frequency band from 20 MHz to 2 GHz. The noise floor grew between 5 dB and 20 dB, depending on the frequency, and some impulsive peaks reached 60 dB with respect to the reference measurement.

With the introduction of modern transportation using mopeds and four-wheel motorcycles, new disturbances have appeared within the existing wireless communication systems in industrial environments. The results captured during the measurement campaign are shown in Figure 3.16 (left). We note that these interferences mainly cover a band of 20 MHz to 1 GHz. The impulsive interferences are more than 15 dB higher than the noise floor, and therefore, communication systems operating in this band could experience serious problems in the proximity of moped vehicles.

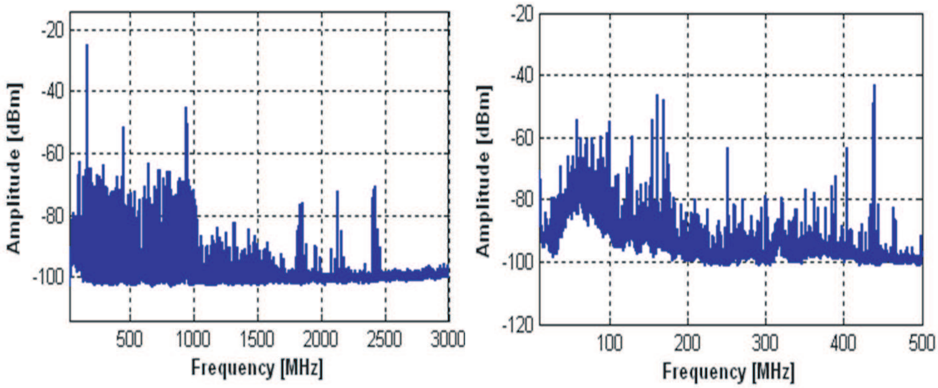

Figure 3.16: Disturbances generated by a moped in paper mill (left) and electromagnetic interferences from MIG welding (right).

In industrial environments, welding is an activity common used as a repair work and in industrial process. During the measurements, we captured impulsive interferences produced by welding work. Figure 3.16 (right) shows measurements related to maintenance work in which metal inert gas (MIG) welding is used, the resulting interference is located at low frequencies.

3.4 Conclusions

This chapter presents results from measurement campaigns conducted in multiple industrial environments. These results are required to understand the characteristics of the environment before developing and deploying a new wireless system. Measurements must be done to characterize these complex environments.

We have divided industrial environments into three types: high, medium and low reflective environments. We also present results from an outdoor environment and measurements of electromagnetic interference from transportation and repair work activities. Based on these extended measurement studies, we developed Figure 3.17 which provides an overall characterization of industrial environments based on interference and multipath propagation. Industrial Processes 1 and 2 correspond to industrial environments with sim-

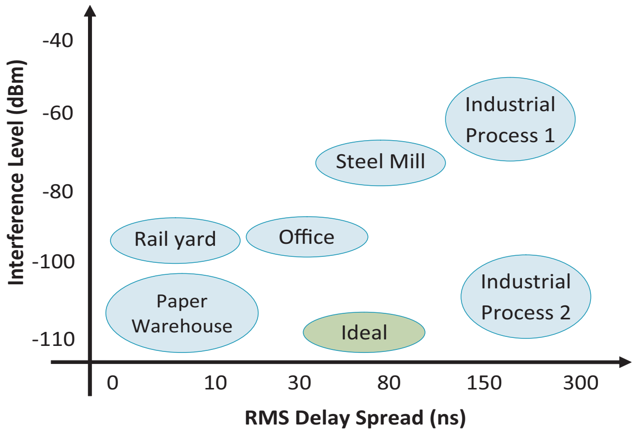

Figure 3.17: Interference and multipath classification of multiple industrial environments.

ilar dimensions and structure characteristics but with different production processes. The dense presence of metallic objects in both of these environments produces a high level of rms delay. However, Industrial Process 1 has higher interference levels than Industrial Process 2 due to the more recent installation of the process. The paper warehouse has larger dimensions than Industrial Processes 1 and 2, but the material stored is paper rolls. These paper rolls absorb the signals, and therefore mitigate the strength of possible interference. However, at the same time, the paper rolls produce a radio coverage problem, eliminating the possibility of using systems that take advantage of multipath propagation effects.

We use typical office environment as a reference; in these environments, interferences are not severe and the structure of the building is concrete. The ideal environment for a wireless system would probably lack interference and have a medium level of time dispersion.

In general, industrial environments are considered to be high reflective with multiple noise sources. The steel mill is a representative case of this type of environment. However, base on the results of our measurements, we can conclude that it is not possible to generalize that industrial environment are reflective. To illustrate this, in Figure 3.18 we compare the total received energy for a high reflective, office and absorbent environment.

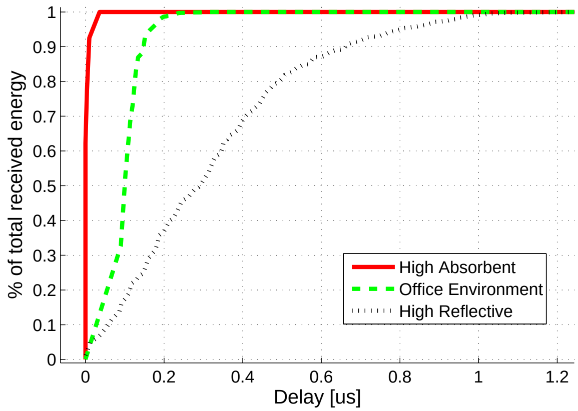

Figure 3.18: Percentage of total received energy for high reflective, office and high absorbent environments.

Chapter 4

Hospital Environments

4.1 Introduction

Wireless communication for medical applications is a promising market nowadays, and customers are demanding the use of wireless systems for multiple services. The deployment of new wireless systems should ensure that medical devices work perfectly in the presence of electromagnetic noise from different hospital activities, electrical equipments, infrastructure and existing wireless communication systems. It is important to also be aware that many medical devices are widely used outside of hospitals and are sometimes implanted in patients.

The basic construction of a hospital consists of various usage rooms, including operating rooms, X-ray tomography, computer labs, as well as ordinary hospital rooms. Usually, there is a hollow space in the walls that has various uses, and may include electric cabling, water pipes, conducts for medical gases or ventilation ducts. This leads to an inhomogeneous wall structure that can have strongly varying electromagnetic properties. In hospital environments, medical devices may be affected by electromagnetic interference from a number of sources, including infusion pumps, syringe pumps, artificial ventilators, dialysis equipments, pulse oximetry, cerebral blood flow measurement equipments, electrocardiogram (ECG), ultrasonography, defibrillators and telemetry systems. In general, we can identify two important sources of interference:

1. Radiated electromagnetic energy from wireless communication systems; and
2. Electromagnetic noise generated by the power supply, installed electronic equipment and medical processes.

In the case of disturbances from wireless systems, note that almost all employees, hospitalized patients, visiting patients and other persons who are in the hospital use some mobile communication system, both for communication and for entertainment. Nevertheless all types of mobile communication equipments transmit electromagnetic signals. Therefore, sensitive medical equipment is exposed to electromagnetic interference from portable nearby mobile handsets [43–45]. In large hospitals with a large number of medical devices, the demand for electricity is high. This means that most of the magnetic field strength is generated inside the hospital. In addition, some areas of a hospital for example clinical laboratories, diagnostic areas, special treatment sections and intensive care units have a high density of medical equipment that can produce interference noise. Other sources of interference that are worth mentioning in a building include air-conditioners, elevator motors, generators, welders and microwave ovens in staff rooms.

In this chapter, we present a preliminary study of electromagnetic interference in a hospital environment. We start by reporting medical incidents identified in the literature. In the second section of this chapter, we discuss the interference generated by microwave ovens, which operate in the 2.4 GHz ISM band. This is followed by an analysis of electromagnetic interference measurements from several locations in a hospital environment. The chapter ends with a discussion and conclusions.

4.2 Medical Incidents

This section presents some examples of problems that may arise when radiated electromagnetic energy interacts with the sensitive electronics contained in medical devices [43, 45].

- GSM mobile phones produce problems with pacemakers. Switching mobile phones on and off produces 2.2 Hz bursts, which in turn affect pacemaker functioning. Therefore patients should avoid to place phones near a pacemaker.
- Failure of an infusion pump caused by a mobile phone placed near a patient, which caused the patient to be poisoned by an overdose of epinephrine.
- An infusion pump changed its rate when a cellular phone was placed on the instrument stand.
- Experiments have shown that 1800 MHz mobile system interferes with ECGs. As consequence, many hospitals have prohibited the use of cellular phones in some areas.
- Apnoea monitors, which are used to monitor patient breathing during sleep, have been affected by electromagnetic interferences from FM transmission. Effectively, this interference mimic human breathing, preventing the apnoea monitor from properly generating alarm.
- TETRA handsets can mimic the effect of cellular phones inside of a hospital.
- Anaesthetic machines have displayed incorrect oxygen values when mobile phones were used 1 m or less away.
- Experiments have shown that electromagnetic interference from an Apple iPod potentially to affects the operation of implanted pacemakers.

- Electromagnetic interferences from electro-surgical equipment disturb real-time video images from an endoscope used during surgery.
- A plastic welding machine that was used during an operation caused the disruption of a monitoring and control system, which failed to identify that the circulation had stopped in a patient's arm, which later had to be amputated.
- An electric powered wheelchair suddenly turned off course as it passed near a radio antenna mast, leading to injury to the occupant.

Given all of the reported incidents involving medical equipment malfunctions caused by electromagnetic interference, individual health associations and hospitals tend to recommend restrictions on the use of mobile phones in hospitals. However, there are no clear guidelines that can be applied to all hospitals. Usually, health associations and hospitals recommend shielding to handle the interference generated by electrical equipment, hospital processes or hospital infrastructure (e.g., ventilation systems). However, the effectiveness of shielding medical devices depends on the enclosure material. Medical devices with plastic shielding have lower electromagnetic interference thresholds than those with metal shielding. Even with metal shielding, there may be holes or slots for connections that allow electromagnetic waves propagate to the devices.

Extensive laboratory test and other research have shown that many medical devices can be susceptible to problems caused by electromagnetic interference and researchers are constantly working on finding solutions. However, the key to deal with EMI problems in hospital environments is not only the device itself but also the environment in which it is used. Indeed, given the variety of people entering a hospital, any type of device may come into this environment. In any case, a solution requires knowledge of the environment, which can be derived by characterizing these environments.

4.3 Microwave Ovens Interferences in the 2.4 GHz ISM band

WLAN systems are becoming widely implemented in hospitals. It is possible to find them in high traffic patient areas such as emergency rooms, intensive care wards, nursing stations, doctor's office and patient waiting areas. For some applications, WLAN technology is not the best option for monitoring devices, because the power consumption is high. In this case, system designers may choose Bluetooth technology, which provides better performance.

However, these two wireless systems may interfere with medical equipment, and the equipment can also be affected by other devices such as microwave ovens. Most microwave ovens emit signals within the 2.4 GHz frequency band that WLAN and Bluetooth use. Therefore, electromagnetic interference from microwave ovens can cause delays and lower throughput on WLAN and Bluetooth communications [44]. In cases which interfering signals are particularly strong, clients may not be able to access the wireless systems for some time.

In this section we focus on the disturbances that microwave ovens generate.

The measurements presented in Figure 4.1 were performed in an office inside the building of the university of Gävle, namely, the break room. We used a laptop with MetaGeek hardware and channel analyzer software, together with a commercial microwave oven operating at 800 watts. In these two figures we can see clearly, the electromagnetic noise created by the microwave oven when it is in operation. Figure 4.1 shows a three dimensional view of the power with respect to frequency and time. From the captured data we note that only WLAN signals are received in Figure 4.1 (left), where three WLAN channels are working. Once the microwave oven is turned on, the interference levels increase to more than 40 dB above the WLAN channels, see Figure 4.1 (right).

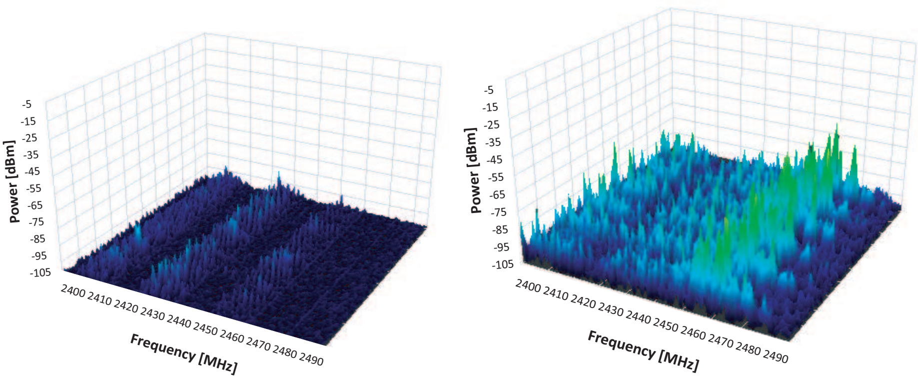

Figure 4.1: WLAN system (left), WLAN and microwave oven interference (right).

Since WLAN and Bluetooth share the spectrum with microwave ovens, both systems must work in the presence of interference. To design more robust systems, one option may be to improve the communication protocol, which would include additional mechanisms for error checking and correction so that corrupt packets would be resent. This solution may not always be adequate. In that case, physical solutions should be implemented to increase the distance from the interference source or to provide additional shielding.

4.4 Interference Analysis in the Hospital of Gävle

The interference measurements were performed in three representative spaces at Gävle hospital:

1. Entrance of the hospital which is a public hall where many wireless systems can be present;

2. ECG room where a Bluetooth system is used for monitoring and storing ECG data from patients; and

3. Telemetry room where many telemetry devices operating in the frequency 438.325 to 438.450 MHz are used.

   Figure 4.2 shows a photograph of the hall entrance, ECG room and the telemetry room.

Figure 4.2: Entrance of the hospital (left), ECG room (center) and telemetry room (right).

The procedure and equipments to perform the interference measurements in the hospital were similar to those used in industrial environments. In each location in the hospital, a broadband scan of the frequency was performed, and after selecting the interested frequency, a time domain measurement was performed. From the collected data, an analysis was conducted, obtaining the APD and the Middleton parameters that model the measured interference.

Figure 4.3 shows the broadband spectrum data in the entrance hall of the hospital. In

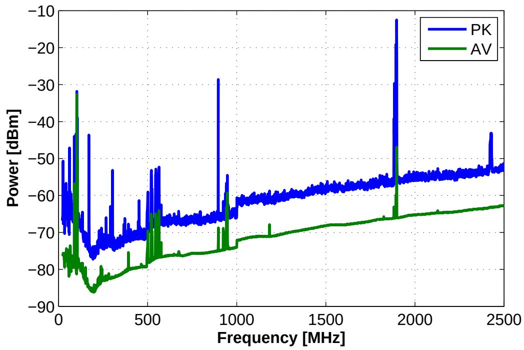

Figure 4.3: Spectrum at the entrance of the hospital for peak and average detectors.

this case, common radio signals, as well as the telemetry signals from the telemetry room were captured.

The telemetry room is an area where patients are under intensive care. The status of the patients is monitored using telemetry devices that send the signals to a central station. This telemetry system has an assigned frequency band from 438 to 439 MHz. In Figure 4.4, we can observe a frequency scan in the telemetry band, where three telemetry devices are captured with high level of impulsive signals.

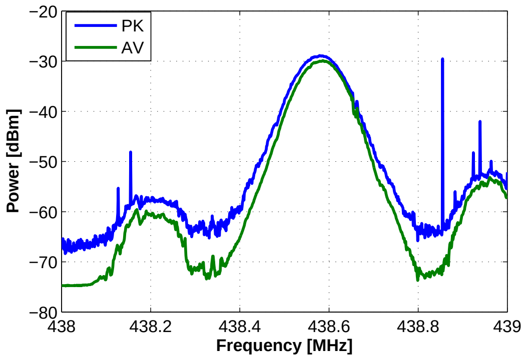

Figure 4.4: Spectrum from 438 to 439 MHz in the telemetry room for peak and average detectors.

After performing time domain measurements, we could determine the APD and Middleton parameters. Figure 4.5 shows the measured disturbance signal at 2438 MHz in the ECG room. The top figure corresponds to the time domain measurement and the bottom figure displays the statistical APD calculated based on the measured data and the Middleton APD approximation.

The estimated Middleton APD parameters were calculated by setting the threshold to -65 dBm and splitting the components in two groups, Gaussian and Impulsive components. Table 4.1 contains the Middleton estimated parameters extracted. From the table, we could observe that the impulse part, σ_I^2, of the measured signal was 17 dB higher than the σ_G^2 Gaussian part. The value A close to 0.1 told us that 10% of the measured data was above the threshold.

Table 4.1: Middleton estimated parameters

σ_I^2	$2.55 \cdot 10^{-9}$ W	-55.93 dBm
σ_G^2	$4.61 \cdot 10^{-11}$ w	-73.36 dBm
Γ	0.0181	17.43 dB
λ	0.8541/s	
Emission length	0.1145 s	
A	0.0978	

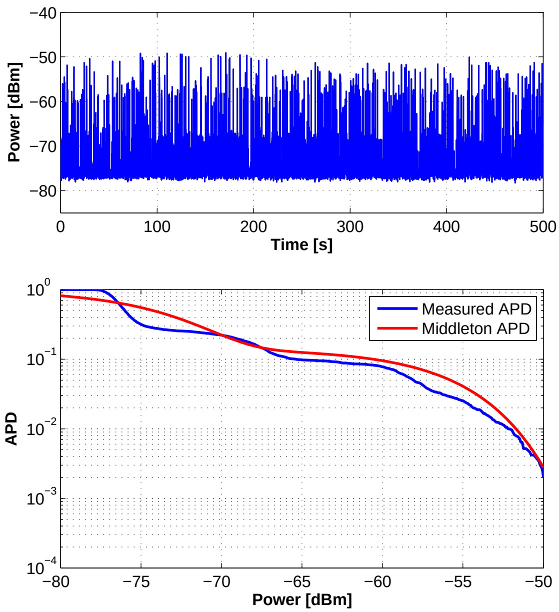

Figure 4.5: Time domain measurements (top), APD of measured data and Middleton approximation (bottom) at 2438 MHz in the ECG room.

4.5 Conclusions

In this chapter, we have performed a preliminary study to characterize hospital environments. We have measured significant levels of electromagnetic interference caused by the interaction between multiple wireless systems and specific medical instruments. These interferences have been analyzed by calculating their statistical properties and Middleton Class A parameters. The results can be used when formulating future standards to ensure that electronic medical equipment is immune from electromagnetic interference.

Chapter 5

Home Environments - TV White Space

5.1 Introduction

The apparition of cognitive radio brings a new way to share spectrum in the context of wireless communications. This new technology aims to solve the problem of poor spectrum utilization. This problem is common in many frequency bands, including ultra high frequency (UHF) TV bands from 470 to 790 MHz. By sensing the spectral environment, a cognitive radio is capable of adapting transmission parameters to dynamically reuse the available spectrum in industrial, hospital and home environments. However, it will require some time until the technology is adequately developed for widespread use.

Observing the digital TV channels used in the proximity of Gävle as shown in Figure 5.1, we can appreciate that from a total of 40 available frequency channels, only 5 frequency channels are used. This leaves 87,5% of the spectrum unused. Obviously, spectrum efficiency is not optimal in this case.

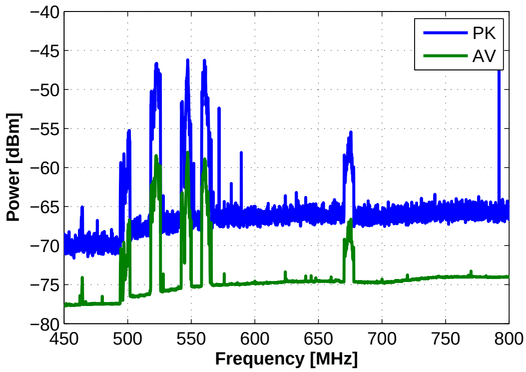

Figure 5.1: DTV broadcast frequency band for Peak and Average detectors.

One approach to affront this problem is to deploy wireless networks within the UHF TV band that use the white spaces in the spectrum. White spaces in the TV spectrum are referred to frequency channels that are not used by local TV transmitters or other licensed users in a given area. This frequency band has good propagation characteristics because radio signals suffer less attenuation than in higher frequencies.

However, the spectrum capacity offered by white spaces depends both on the use of the band by the primary services, as well as on the harmonization of the sub-band for white space devices (WSDs). WSDs should be able to detect and avoid the frequencies used by primary users, and this should be reflected not only in the detection threshold of the devices but also on the characteristics of the environment.

In this chapter, we verify a prediction model that calculates the maximum desired power-to-undesired power D/U ratio as given in (2.23) and (2.24). In addition, we investigate the effect of multiple secondary users in the D/U ratio. The spectrum reuse opportunities for WSDs are determined by analyzing the interference of that WSDs produce to the DVB-T receiver. Paper 7 contains the information regarding D/U measurement, and Paper 8 addresses the aggregate adjacent channel interference in the case of multiple WSDs.

This chapter first describes the environment where the measurements were performed. The second section of this chapter presents some of the measurements and simulation results. The final part provides the concluding remarks of this chapter.

5.2 Measurement Environments

The measurement campaign was conducted in two environments:

1. Gävle university laboratory

2. Home environment

The laboratory room dimensions were 9.5 m x 6.5 m x 3 m. A photograph of the laboratory is shown in Figure 5.2 (left). Note the presence of office materials such as tables, shelves and electronic instruments, which are stored in racks. The home environment consists of two apartments, one located in a suburban area with a weak TV signal strength and the other located in the city center with a strong TV signal strength. The floor plan of the second apartment is illustrated in Figure 5.2 (right). The red arrows in the figure represent the WSD antenna locations, we consider the worse-case scenario by pointing those antennas towards the set-top TV antenna.

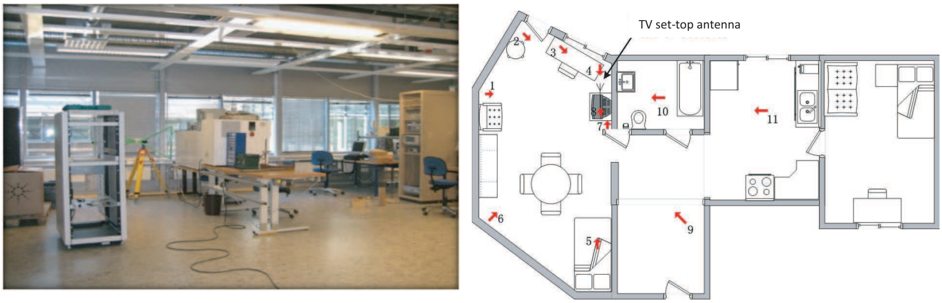

Figure 5.2: Laboratory environment (left) and floor plan of the second apartment (right).

5.3 Measurement Results

This section provides some results regarding the limitations of WSDs that transmit in a primary user spectrum. We start by considering one WSD working within the primary user band and we continue by extending the experiment with the presence of multiple WSDs transmitting at the same time.

Base on the measurements at the laboratory we obtained the minimum D/U threshold for adjacent channel rejection, this threshold limits the transmitting power of a single WSD. In Figure 5.3 we can observe the results from the reference simulated data [29] and the measurements using high and low TV signal strength.

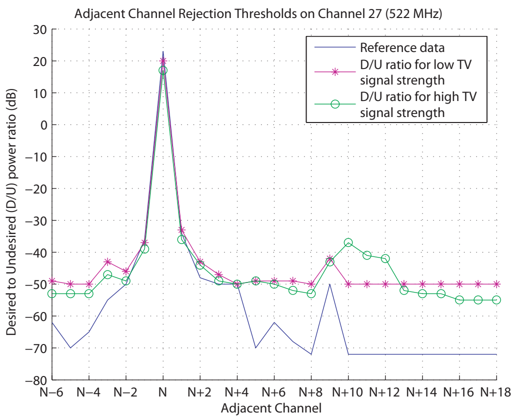

Figure 5.3: Adjacent channel rejection thresholds on channel 27 (522 MHz).

In the home environment we determined the minimum distance that a WSD should be placed to avoid disrupting the primary user. From the measurement campaign, we found that the number of available channels for secondary usage depends on the distance between the TV antenna and the WSD. Using the D/U threshold from Figure 5.3, we estimated the number of available channels and found that it is in line with previous simulation results, see Figure 5.4. Note that the number of available channels grows as the distance between the WSD antenna and set-top TV antenna is increased.

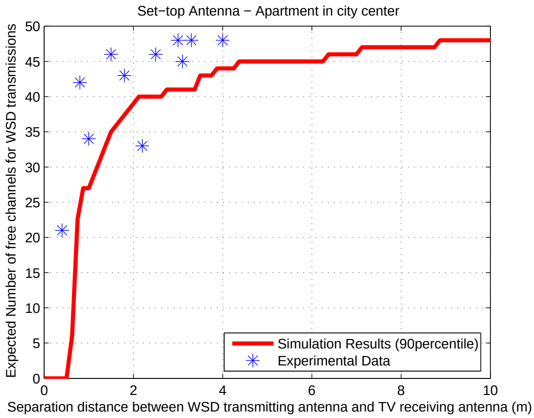

Figure 5.4: Expected number of available channels for one WSD versus the distance between TV antenna and WSD antenna.

The single WSD case is extended to account for multiple WSDs transmitting at the same time. The adjacent channel interference (ACI) should not only fulfill the threshold established in Figure 5.3, but should also stay below certain power level. This power level is the result of the weighted sum of the total ACI in the primary channel. In other words, to maintain particular D/U ratio, the maximum power tolerable for the WSDs should decrease as more secondary users join the system. The measurements and theoretical results from the model formulated in (2.25) are shown in Figure 5.5.

Based on Figure 5.5, we note that the assumptions and the parameter settings of the proposed model are reasonable. Moreover, the overall performance predicated by the model reasonably matches our measurement results.

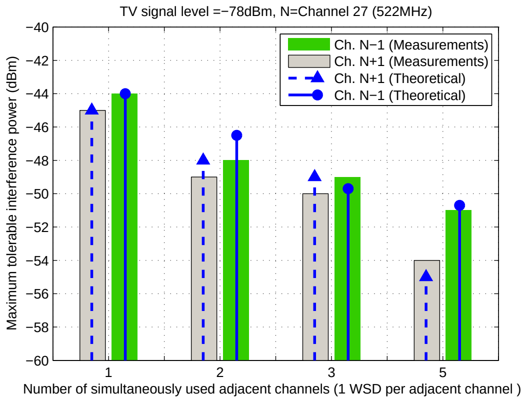

Figure 5.5: Maximum interference power level versus the number of simultaneous WSD in use.

5.4 Conclusions

Spectrum efficiency can be improved by reusing TV white spaces. The addition of secondary users to the primary user frequency can create harmful interference with the TV signal. In this chapter, we have proposed and verified models of AACI to restrict the interference of the secondary user into the primary user. The maximum power of a white space channel depends on four factors: the frequency separation between the WSD channel and the primary channel; the surrounding environment; the spatial distance from the WSD to the TV antenna; and the number of WSDs transmitting at the same time. We have demonstrated that the assumptions and parameter settings of the proposed models are reasonable and that the overall performance predicted by the model matches the measurement results.

Chapter 6

Discussion and Conclusions

6.1 Industrial Environments

Industrial environments can exhibit severe electromagnetic interference caused by electrical systems, production processes and repair work. Most of the wireless communication systems used in industry are developed for office or outdoor environments, and therefore, they are not optimized to handle disturbances of impulsive character. To improve the wireless technologies that are used in these radio hostile environments, the electromagnetic interference and related channel characteristics must be properly characterized.

In this thesis, we have developed measurement methods to characterize electromagnetic interference and multipath propagation in complex environments such as industry. Through intensive measurement campaigns, we have characterized multiple industrial environments, including paper mill, steel mill and freight train yard. One of our motivations for conducting these measurements was the observation of number of serious incidents reported in the literature. Our results show three categories of environments that can have a large impact on critical wireless communications in industrial applications:

- High reflective environments with a significant amount of metal structures produce multipath propagation that is different from office or outdoor environments. These environments can be vulnerable to critical wireless communications since present commercial systems do not have equalization adapted to cope with these multipath properties.
- Medium reflective environments refer to large industrial halls with multiple metal objects. Most of the disturbances are generated from electric motors, switched power supplies, frequency converters and repair work. The frequency range of such interference is mainly located at low frequencies, typically below 400 MHz. These environments show less time dispersion than high reflective environments, however the time dispersion is still higher than in offices.
- Highly absorbent environments strongly limit the radio coverage, problem that can not be handled by present commercial wireless systems. Additionally in these en-

vironments, all reflective components are absorbed which makes multiple-antenna solutions become useless for communication performance improvement.

Additionally, we have shown that trains, mopeds and four-wheel motorcycles in industrial environments as well as repair work involving welding generate electromagnetic interferences of impulsive character.

6.2 Hospital Environments

Electromagnetic interference in hospital environments arises from computers, electrical power supplies, electronic systems, maintenance work, elevators, microwave ovens, fan systems, external sources and medical equipment. When a serious incident occurs caused by wireless communication problems, the difference between hospital environments and office environments is that in the former, patients could be in danger. Remote controlled radio systems used in medical devices are often critical for safety. Therefore, non-disruptive communications with high reliability are essential for such applications. Thus, it is critical to characterize these environments before and after the deployment of any wireless system.

In this thesis, a preliminary study aimed at such characterization is presented based on electromagnetic interference measurements in a hospital. We show that conventional measurements of electric field strength versus frequency can be combined with APD measurements to determine the information needed to evaluate the interference impact of wireless systems in medical applications. This approach makes possible to distinguish different interference waveforms so that a more valid value of the interference impact can be determined regarding the performance degradation of wireless links.

The purpose of our study was to inspire interest among other research groups to develop a single research orientation towards the issue of electromagnetic interference in hospital environments. General guidelines should be imposed in all hospitals, for example, to limit the usage of mobile phones in some critical zones of the building, particularly in the case of the new generation of phones equipped with multi-wireless systems (e.g., WLAN and Bluetooth systems), which could interfere with sensitive equipment.

6.3 Home Environments - TV White Space

Future wireless systems for commercial or public services that aim to support multiple users and higher data rates require better frequency planning. However, we are already experiencing spectrum scarcity at frequencies that may be economically profitable to use wireless communication. It is necessary to find new ways to use the spectrum, and one promising possibility is through cognitive radio. By using cognitive radio, wireless systems can modify their frequency, power and modulation schemes when a specific problem is found. The use of cognitive radio can be great advantage in complex environments such as industrial and hospital, and it can help to fulfill the oncoming data rate.

In this thesis, we have verified two models for the characterization of WSD interference with primary receivers on UHF TV bands from 470 to 790 MHz using measurements from laboratory and real home environments. The results show that the distance between the WSD and the TV receiver should be considered when WSD power is selected. In addition, the number of WSDs and the frequency allocation with respect to the primary user should also be considered to avoid harmful interference with the primary user.

6.4 Future Research

In the future, we will continue working in industrial environments. To this point, we have characterized and classified multiple industrial environments.

We plan to elaborate a time dispersion prediction model for industrial environments which should predict the time dispersion based on the dimensions and materials of a building.

In the near future, we would like to improve the design of current wireless technology making it more robust against impulsive interferences. Space diversity can be an improvement in industrial applications. Therefore, we plan to investigate the minimum antenna distances for low correlation in high and medium reflective environments.

This thesis can be extended by a deeper analysis of impulsive interference and multipath propagation with respect the performance of various industrial wireless systems. This can be implemented by the following:

- Obtaining the statistical properties of impulsive interference from the measurements. We hope to study the performance of different modulation schemes, including, for example, the relationship between the percentage of impulsive samples and the error floor of different modulations.

- Quantifying the effect of a high delay spread on the BEP for several modulation schemes and select an optimal equalization algorithm for this case,.

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