PERFORMANCE ANALYSIS OF ULTRA WIDE BAND INDOOR CHANNEL

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DECLARATION

We hereby declare that this thesis is based on the results found by ourselves. Materials of work found by other researcher are mentioned by reference. This thesis, neither in whole nor in part, has been previously submitted for any degree.

Signature of Supervisor	Signature of Authors

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We feel deepest admiration to our Department for giving us the honor to perform the thesis as a partial fulfillment of the requirement for the degree of Bachelor of Science (BS) in Electronics and Communication Engineering.

Last but most important, we would like to thank our parents and family members. Without their continuous support and blessings, this thesis will never come to an end. We would also like to thank our friends for their inspiration to do this thesis.

THESIS ABSTRACT

Research on wireless communication system has been pursued for many years, but there is a renewed interest in ultra-wideband (UWB) technology for communication within short range, because of its huge bandwidth and low radiated power level. This emerging technology provides extremely high data rate in short ranges but in more secured approach. In order to build systems that realize all the potential of UWB, it is first required to understand UWB propagation and the channel properties arise from the propagation. In this research, the properties of UWB channel for indoor industrial environment was evaluated. A few indoor channel models have been studied so far for different environments but not for indoor industrial environment and various data rates are obtained according to wireless channel environments. Therefore, an accurate channel model is required to determine the maximum achievable data rate. In this thesis, we have proposed a channel model for indoor industrial environment considering the scattering coefficient along with the other multipath gain coefficient. This thesis addresses scattering effect while modeling UWB channel. Here, the performance of UWB channel model is analyzed following the parameters, such as power delay profile and the temporal dispersion properties which are also investigated in this paper.

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1. INTRODUCTION

Wireless communication systems have evolved extensively over the last two decades. The explosive growth of the wireless communication market is expected to continue in the future, as the demand for all types of wireless services is increasing. New generations of wireless mobile radio systems aim to provide flexible data rates (including high, medium, and low data rates) and a wide variety of applications (like video, data, ranging, etc.) to the mobile users while serving as many users as possible. This goal, however, must be achieved under the constraint of the limited available resources like spectrum and power. As more and more devices go wireless, future technologies will face spectral crowding and coexistence of wireless devices will be a major issue. Therefore, considering the limited bandwidth availability, accommodating the demand for higher capacity and data rates is a challenging task, requiring innovative technologies that can coexist with devices operating at various frequency bands [1].

Ultra wideband (UWB), which is an underlay (or sometimes referred as shared unlicensed) system, coexists with other licensed and unlicensed narrowband systems. The transmitted power of UWB devices is controlled by the regulatory agencies [such as the Federal Communications Commission (FCC) in the United States], so that UWB system does not affect narrowband system in a large extend and vice versa. However, UWB offers attractive solutions for many wireless communication areas, including wireless personal area networks (WPANs), wireless telemetry and tele-medecine, and wireless sensors networks. With its wide bandwidth, UWB has a potential to offer a capacity much higher than the current narrowband systems for short-range applications. Fig. 1.1 shows the comparison of narrowband (NB), spread spread spectrum (SS) and ultra-wideband (UWB) signal concepts.

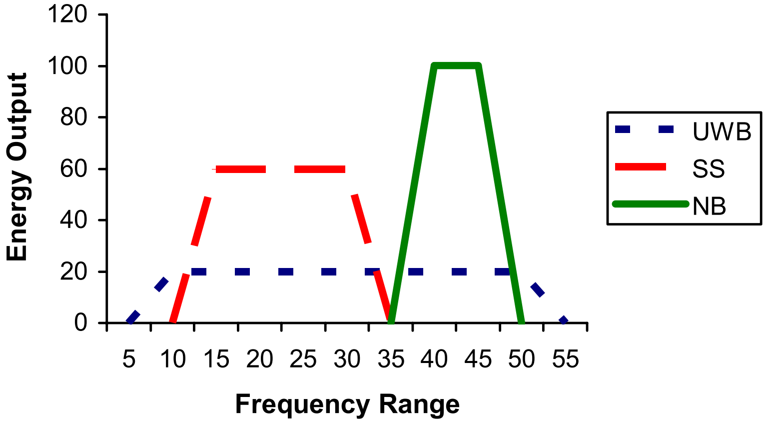

Fig. 1.1: Comparison of narrowband (NB), spread spectrum (SS) and ultra-wideband (UWB) signal concepts

According to the modern definition, any wireless communication technology that produces signals with a bandwidth wider than 500 MHz or a fractional bandwidth greater than 0.2 can be considered as UWB. A possible technique for implementing UWB is impulse radio (IR), which is based on transmitting extremely short (in the order of nanoseconds) and low power pulses. Rather than sending a single pulse per symbol, a number of pulses determined by the processing gain of the system are transmitted per symbol. The processing gain serves as a parameter to flexibly adjust data rate, bit error rate (BER), and coverage area of transmission. Pulses can occupy a location in the frame based on the specific pseudo random (PN) code assigned for each user (as in the case of time-hopping UWB). Other implementations, such as direct sequence spreading, are also popularly used with impulse radio-based implementations. Impulse radio is advantageous in that it eliminates the need for up- and down-conversion and allows low-complexity transceivers. It also enables various types of modulations to be employed, including on–off keying (OOK), pulse-amplitude-modulation (PAM), pulse-position-modulation (PPM), phase-shift-keying (PSK), as well as different receiver types such as the energy detector, rake, and transmitted reference receivers [1].

Another strong candidate for UWB is multicarrier modulation, which can be realized using orthogonal frequency division multiplexing (OFDM). OFDM has become a very popular technology due to its special features such as robustness against multipath interference, ability to allow frequency diversity with the use of efficient forward error correction (FEC) coding, capability of capturing the multipath energy efficiently, and ability to provide high bandwidth efficiency through the use of sub-band adaptive modulation and coding techniques. OFDM can overcome many problems that arise with high bit rate communication, the most serious of which is time dispersion. In OFDM, the data-bearing symbol stream is split into several lower rate streams, and these sub-streams are transmitted on different carriers. Since this increases the symbol period by the number of non-overlapping carriers (sub-carriers), multipath echoes affect only a small portion of neighboring symbols. Remaining intersymbol interference (ISI) can be removed by cyclically extending the OFDM symbol [1].

1.1 Background

UWB characterizes transmission systems with instantaneous spectral occupancy in excess of 500 MHz or a fractional bandwidth of more than 20%. (The fractional bandwidth is defined as B/fc , where $B = f_H - f_L$ denotes the -10 dB bandwidth and center frequency $fc = (f_H + f_L)/2$ with f_H being the upper frequency of the -10 dB emission point, and f_L the lower frequency of the -10 dB emission point. According to [2], UWB systems with $fc > 2.5$ GHz need to have a -10 dB bandwidth of at least 500 MHz, while UWB systems with $fc < 2.5$ GHz need to have fractional bandwidth at least 0.20.) Such systems rely on ultra-short (nanosecond scale) waveforms that can be free of sine-wave carriers and do not require IF processing because they can operate at baseband. As information-bearing pulses with ultra-short duration have UWB spectral occupancy, UWB radios come with *unique advantages* that have long been appreciated by the radar and communications communities. Despite the attractive features, interest in UWB devices prior to 2001 was primarily limited to radar systems, mainly for military applications. With bandwidth resources becoming increasingly scarce, UWB radio was “a midsummer night’s dream’’ waiting to be fulfilled.

Fig. 1.1.1 shows the fractional bandwidth comparison between narrowband and ultra wideband systems.

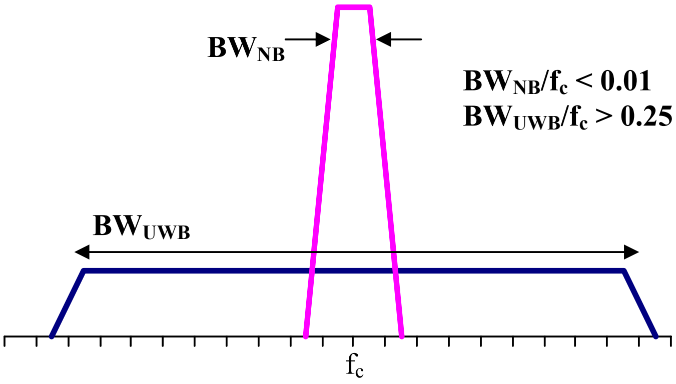

Fig. 1.1.1: Fractional bandwidth comparison

Although receiving a renascence, ultra wideband transmissions are not new. The concept of ultra wideband communication originated with Marconi, in the 1900s, when spark gap transmitters induced pulsed signals having very wide bandwidths. Spark transmissions created broadband interference and did not allow for coordinated spectrum sharing, and so the communications world abandoned wideband communication in favor of narrowband, or tuned, radio transmitters that were easy to regulate and coordinate [3].

In the mid-1980s, the FCC encouraged an entirely new type of wideband communications when it allocated the Industrial Scientific and Medical (ISM) bands for unlicensed spread spectrum and wideband communications use. This revolutionary spectrum allocation is most likely responsible for the tremendous growth in Wireless Local Area Networks (WLAN) and Wi-Fi today, as it led the communications industry to study the merits and implications of wider bandwidth communications than had previously been used for consumer applications [3]. Fig. 1.1.2 and Fig. 1.1.3 shows the FCC mask for indoor communications and outdoor communications.

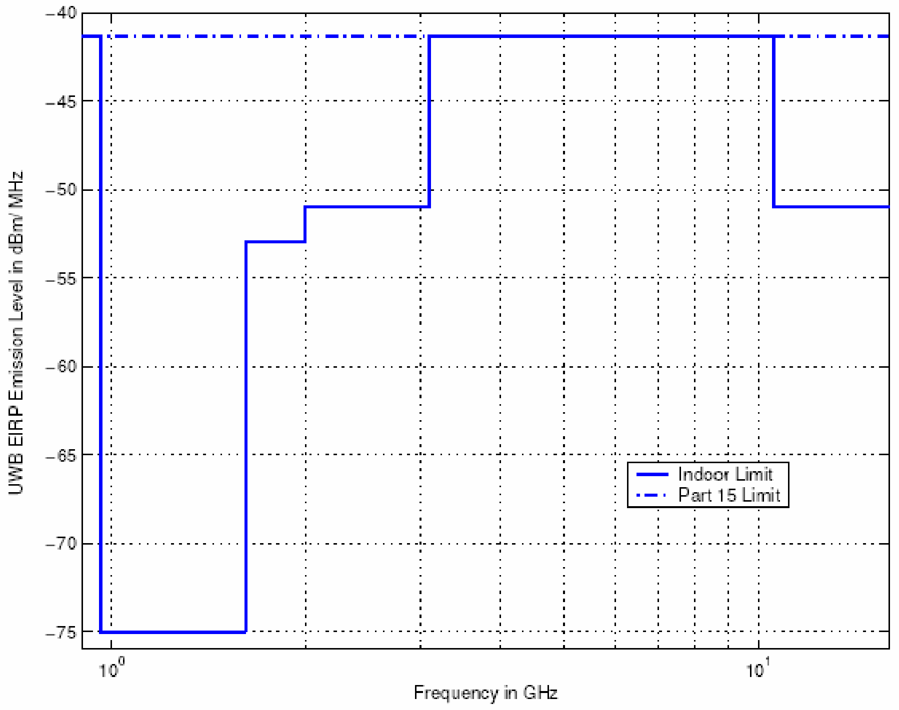

Fig. 1.1.2: FCC mask for indoor communications

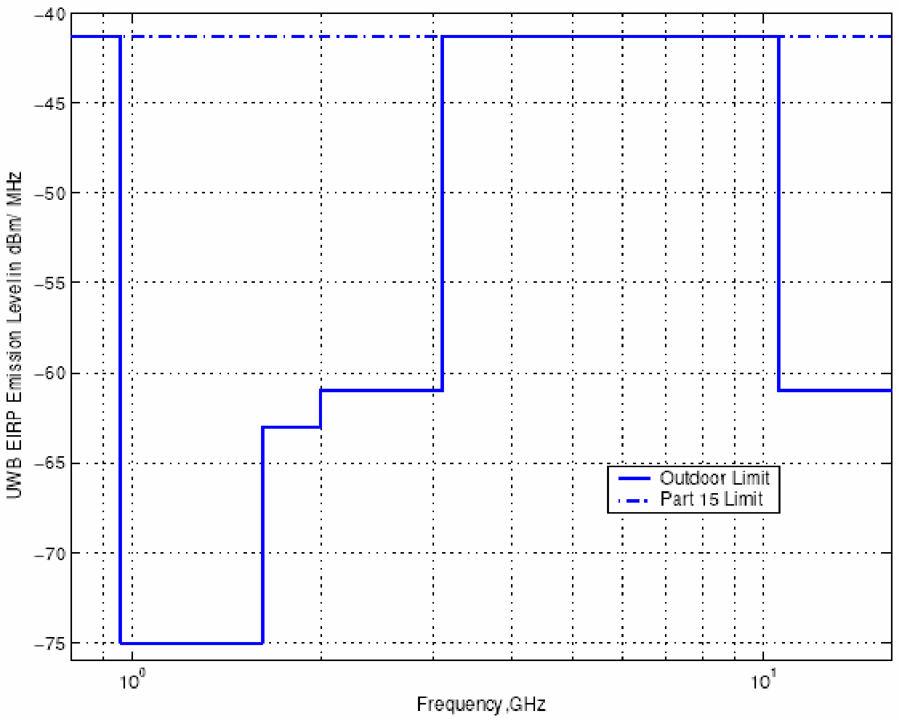

Fig. 1.1.3: FCC mask for outdoor communications

On February 14, 2002, the FCC amended the Part 15 rules which govern unlicensed radio devices to include the operation of ultra wideband (UWB) devices. The use of UWB under the FCC guidelines [2] offers tremendous capacity potential (several Gbps) over short ranges (less than 10 meters) at low radiated power (mean EIRP of -41.3 dBm/MHz), which allows UWB technology to overlay already available services such as the global positioning system (GPS) and the IEEE 802.11 wireless local area networks (WLANs) that coexist in the 3.6-10.1 GHz band. Although UWB signals can propagate greater distances at higher power levels, current FCC regulations enable high-rate (above 110 MB/s) data transmissions over a short range (10-15 m) at very low power. In the table 1.1.1, FCC requirements for indoor and handheld UWB systems are shown and Fig. 1.1.4 and 1.1.5 shows the frequency allocation for different wireless communication systems and Range and throughput comparison of wireless technologies respectively.

Table 1.1.1
FCC requirements for indoor and handheld UWB systems

<table>
<tr><th colspan="2">Operating Frequency Range 3.1 to 10.6 GHz</th></tr>
<tr><th colspan="2">Average radiated emissions limit</th></tr>
<tr><th>Frequency Range (MHz)</th><th>Mean EIRP in dBm/MHz (Indoor/handheld)</th></tr>
<tr><td>960-1610</td><td>-75.3/-75.3</td></tr>
<tr><td>1610-3100</td><td>-53.3/-61.3</td></tr>
<tr><td>3100-10600</td><td>-41.3/-61.3</td></tr>
<tr><td>Above 10600</td><td>-51.3/-61.3</td></tr>
<tr><th>Peak emission level In band</th><th>60dB above average emission level</th></tr>
<tr><th>Max. unacknowledged transmission period</th><th>10 seconds</th></tr>
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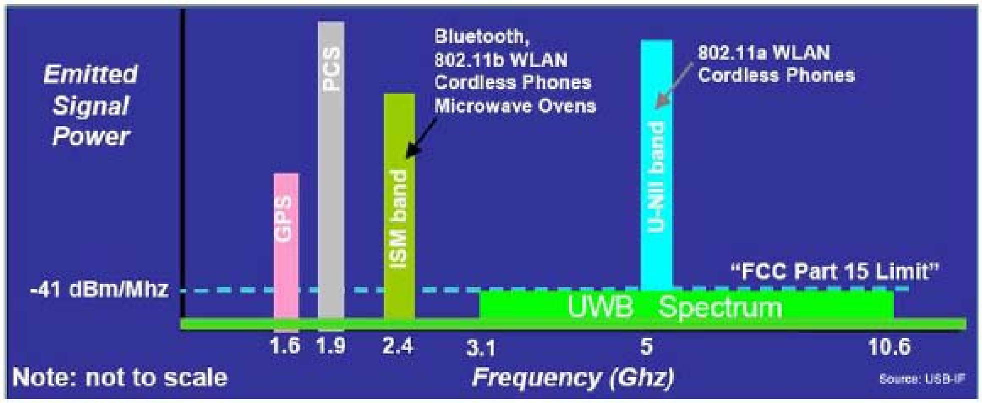


Fig. 1.1.4: Frequency allocation for different wireless communication systems.

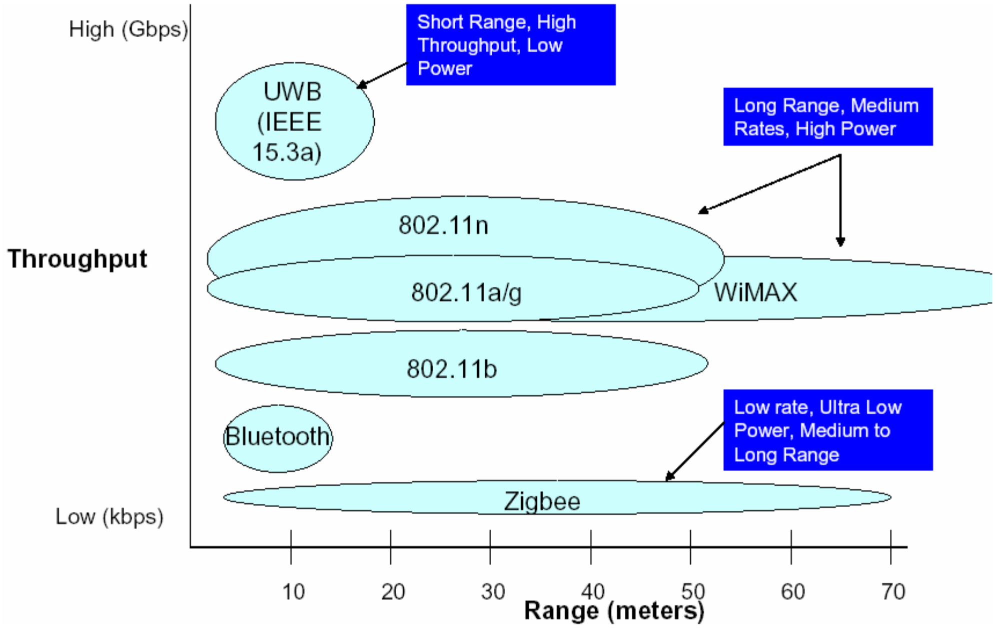


Fig. 1.1.5: Range and throughput comparison of wireless technologies.

The FCC rules provide the following definitions for UWB signaling:

- *UWB bandwidth:* UWB bandwidth is the frequency band bounded by the points that are 10 dB below the highest radiated emission, as based on the complete transmission system including the antenna. The upper boundary is designated f_h and the lower boundary is designated f_l. The frequency at which the highest radiated emission occurs is designated f_m.

- *Center frequency:* The center frequency f_c is the average of f_l and f_h, that is,

$$f_c = \frac{f_l + f_h}{2} \tag{1.1}$$

- *Fractional bandwidth* (FB): The fractional bandwidth is de.ned as

$$FB = 2(\frac{f_h - f_l}{f_h + f_l}) \tag{1.2}$$

- *UWB transmitter:* A UWB transmitter is an intentional radiator that, at any point in time, has a fractional bandwidth equal to or greater than 0.20 or has a WB bandwidth equal to or greater than 500 MHz, regardless of the fractional bandwidth.
- *Equivalent isotropically radiated power* (EIRP): EIRP is the product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna. EIRP refers to the highest signal strength measured in any direction and at any frequency from the UWB device.

The first set of FCC key regulations for all UWB systems are as follows:

- No toys, and no operation on an aircraft, ship or satellite.
- Emissions from supporting digital circuitry is considered separately from the UWB portion, and is subject to existing regulations, not new UWB rules.
- The frequency of the highest emission, f_m, must be within the UWB bandwidth.
- Other emissions standards apply as cross-referenced in the UWB rules, such as conducted emissions into AC power lines.
- Emissions below 960 MHz are limited to the levels required for unintentional radiators.
- Within a 50 MHz bandwidth centered on *fm*, peak emissions are limited to 0 dBm EIRP.
- UWB radar, imaging and medical system operation must be coordinated. Dates and areas of operation must be reported, except in the case of emergency. These systems must also have a manual

switch (local or remote) to turn the equipment off within 10 s of actuation [4].

1.2 Applications of UWB Technology

This huge “new bandwidth” opens the door for an unprecedented number of bandwidth-demanding position-critical low-power applications in wireless communications, networking, radar imaging, and localization systems [5]. It also explains the rapidly increasing efforts undertaken by several research institutions, industry, and government agencies to assess and exploit the potential of UWB radios in various areas. These include short-range, high-speed access to the Internet, accurate personnel and asset tracking or increased safety and security, precision navigation, imaging of steel reinforcement bars in concrete or pipes hidden inside walls, surveillance, and medical monitoring of the heart’s actual contractions.

Here are some applications that are of great interest for UWB communications:

- *Wireless PC peripheral connectivity:* For wireless PC peripheral connectivity, UWB technology can take the performance and ease-of-use found in USB to the next level. Presently, wired USB has significant market segment share as the cable interconnect of choice for the PC platform (Fig. 1.2.1). But the cable can get in the way. Bluetooth Technology has resolved this issue to some degree, but it has enjoyed little success so far due to performance limitations and interoperability problems. A UWB-enabled WUSB solution provides the performance users have come to expect from wired USB without the cable. Enabling un-tethered USB connectivity, UWB has the possibility of gaining significant volume in the PC peripheral interconnect market segment. The recently announced Wireless USB Working Group objective is to define a specification that delivers on this promise by providing speeds up to 480 Mbps—equivalent to wired USB 2.0—within a 10-meter range. With WUSB, a user can bring a mobile device, such as a portable media player (PMP), in proximity to a content source, like a PC, laptop, or external hard disk drive, and, once authentication and authorization are complete, video files can be streamed onto the PMP for later viewing [6].

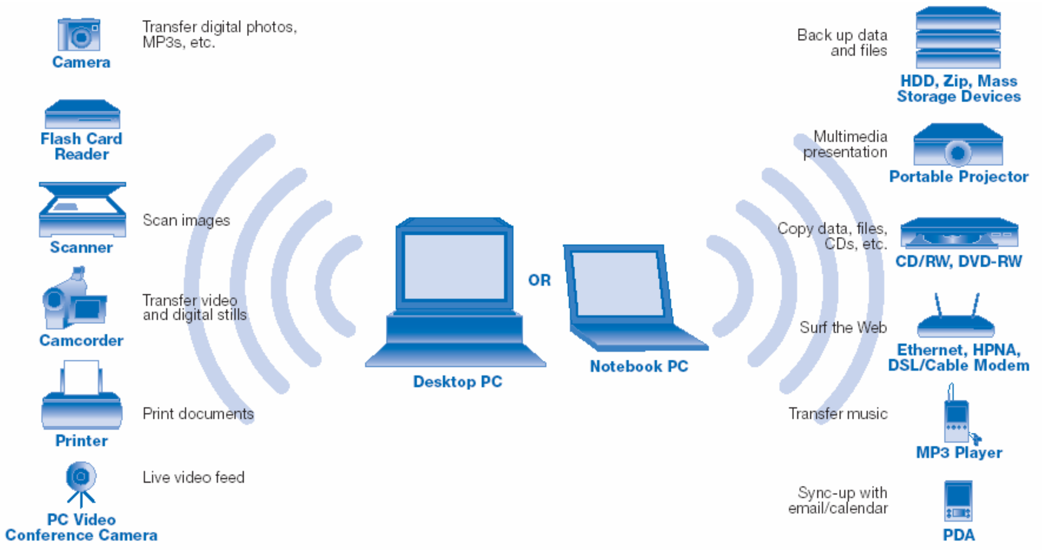
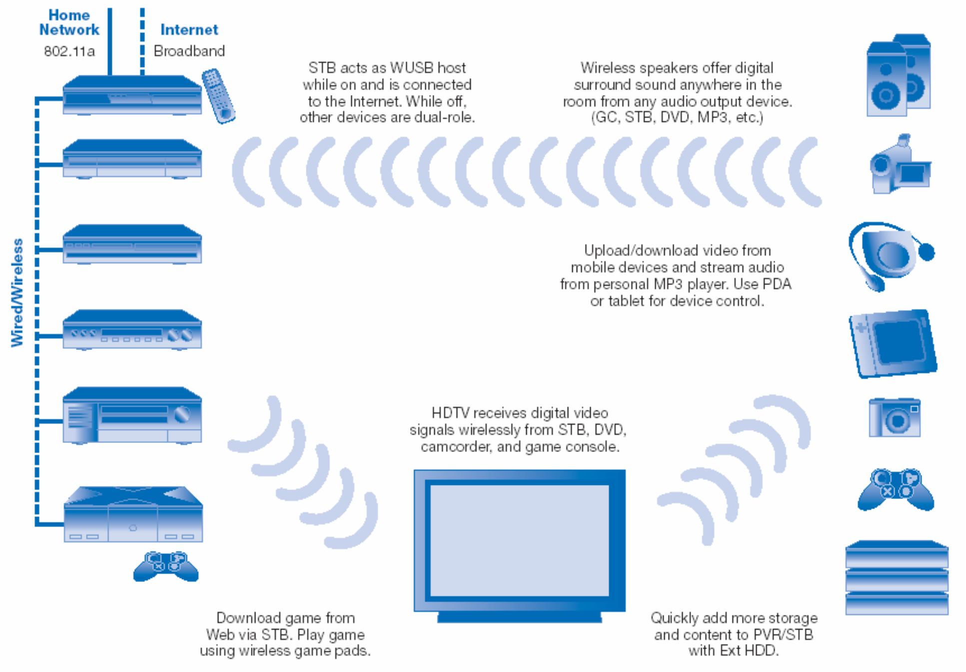


Fig. 1.2.1: PC clusters interconnected through USB

- *Wireless multimedia connectivity for AV CE devices:* Closely related to PC peripheral connectivity is wireless multimedia connectivity for audio and video consumer electronics (AV CE) devices. The benefits are similar to those of PCs and peripherals; wireless ease-of-use and data transfer performance are key advantages. The variety of devices within the entertainment cluster (Fig. 4) is wide: digital video disc players (DVDs), HDTVs, STBs, personal video recorders (PVRs), MP3 players and stereos, digital camcorders and digital cameras, and other CE devices found throughout the home. For example, UWB could connect a wall-mounted plasma display or HDTV to an STB or DVD player, without annoying and unaesthetic cables. UWB can also enable multiple streams to multiple devices, simultaneously. This would allow picture-in-picture functionality or the ability to view the same or different content on multiple devices throughout the home. UWB can also connect devices between the PC and entertainment clusters, such as a digital camcorder to a media PC for digital video editing or to a large LCD for viewing. Connect a digital camera to a mobile notebook PC for editing, compiling, and sending pictures via e-mail to a family member while sitting at a public hotspot. UWB offers key benefits for these kinds of uses. With UWB-enabled WPANs, once the devices are within proximity, they recognize each other, and streaming occurs when the user presses the Play button. Portable AV CE devices, such as digital camcorders, digital still cameras, portable MP3 players, and emerging personal video players are expected to create the sweet spot of the early UWB mainstream market [6].



STB acts as WUSB host while on and is connected to the Internet. While off, other devices are dual-role.

Wireless speakers offer digital surround sound anywhere in the room from any audio output device. (GC, STB, DVD, MP3, etc.)

Upload/download video from mobile devices and stream audio from personal MP3 player. Use PDA or tablet for device control.

HDTV receives digital video signals wirelessly from STB, DVD, camcorder, and game console.

Download game from Web via STB. Play game using wireless game pads.

Quickly add more storage and content to PVR/STB with Ext HDD.

Fig. 1.2.2: Entertainment cluster

- *Wireless personal area networks (WPANs):* An important application of UWB is personal area networks (PANs), which is also known as in-home networks. WPANs address short-range (generally within 10-20 m) ad hoc connectivity among portable consumer electronic and communication devices. They are envisioned to provide high-quality real-time video and audio distribution, file exchange among storage systems. UWB technology emerges as a promising physical layer candidate for WPANs, because it offers high-rates over short range, with low cost, high power efficiency, and low duty cycle.

- *Cable replacement and network access for mobile computing devices:* For users of multiple mobile devices, cable management can be a large inconvenience when devices need to communicate with each other. Many devices, such as personal digital assistants, connect through USB ports, but others, like 3G cellular phones, might require a special connector or adapter for a USB cable. UWB technology allows these devices to interoperate—without cables—as soon as they are in proximity. UWB could also be used to enable high-speed, low-power network access within hotspot locations. Hotspot Internet coverage is generating a great deal of market interest for broadband Internet access for mobile computing devices at remote locations. Today, two technologies enable hotspots: 802.11a/g WLAN and Bluetooth Technology-based WPAN. Both have limitations for addressing the combined needs for high bandwidth connectivity: high spatial capacity for serving many users in a given space and low power consumption. UWB promises to help overcome these challenges and could provide a significantly improved user experience once this segment matures [6].
- *Wireless Body Area Networks (WBAN):* WBANs are another example of how our life could be influenced by UWB. Probably the most promising application in this context is medical body area networks. Due to the proposed energy efficient operation of UWB, battery driven handheld equipment is feasible, making it perfectly suitable for medical supervision [7]. Moreover, UWB signals are inherently robust against jamming, offering a high degree of reliability, which will be necessary to provide accurate patient health information and reliable transmission of data in a highly obstructed radio environment. The possibility to process and transmit a large amount of data and transfer vital information using UWB wireless body area networks would enable tele-medicine to be the solution for future medical treatment of certain conditions. In addition, the ability to have controlled power levels would

provide flawless connectivity between body-distributed networks. UWB also offers good penetrating properties that could be applied to imaging in medical applications; with the UWB body sensors this application could be easily reconFig.d to adapt to the specific tasks and would enable high data rate connectivity to external processing networks (e.g. servers and large workstations).

- *Sensor networks:* Sensor networks consist of a large number of nodes spread across a geographical area. The nodes can be static, if deployed for, e.g., avalanche monitoring and pollution tracking, or mobile, if equipped on soldiers, firemen, or robots in military and emergency response situations. Key requirements for sensor networks operating in challenging environments include low cost, low power, and multifunctionality. High data-rate UWB communication systems are well motivated for gathering and disseminating or exchanging a vast quantity of sensory data in a timely manner. Typically, energy is more limited in sensor networks than in WPANs because of the nature of the sensing devices and the difficulty in recharging their batteries. Studies have shown that current commercial Bluetooth devices are less suitable for sensor network applications because of their energy requirements [8] and higher expected cost [9]. In addition, exploiting the precise localization capability of UWB promises wireless sensor networks with improved positioning accuracy. This is especially useful when GPSs are not available, e.g., due to obstruction.
- *Imaging systems:* Different from conventional radar systems where targets are typically considered as point scatterers, UWB radar pulses are shorter than the target dimensions. UWB reflections off the target exhibit not only changes in amplitude and time shift but also changes in the pulse shape. As a result, UWB waveforms exhibit pronounced sensitivity to scattering relative to conventional radar signals. This property has been readily adopted by radar systems) and can be extended to additional applications, such as underground, through-wall and ocean imaging, as well as medical diagnostics and border surveillance devices [10, 11]. Some forms of imaging will be applicable

in Surveillance Systems (i.e.Wall Imaging and Through-wall Imaging Systems or Intrusion Protection). Another example of imaging is a specialized Government application using UWB for GPR (Ground Penetrating Radar). This application was employed after the terrorist disaster on September 11th in New York to try and find survivors in the rubble. Other Military examples of UWB have been used to locate enemy objects behind walls and around corners in the battlefield. Imaging applications applied to commercial use find value in Medical Systems where X-ray Systems may be less desirable [12].

- *Vehicular radar systems:* UWB-based sensing has the potential to improve the resolution of conventional proximity and motion sensors. Relying on the high ranging accuracy and target differentiation capability enabled by UWB, intelligent collision-avoidance and cruise-control systems can be envisioned. These systems can also improve airbag deployment and adapt suspension/braking systems depending on road conditions. UWB technology can also be integrated into vehicular entertainment and navigation systems by downloading high-rate data from airport off ramp, road-side, or gas station UWB transmitters.
- *Emergency Communications:* Another important application is emergency communications, communications by fire departments and law enforcement agencies, and military radio [13]. These application spans most of the environments defined above, but also include communication through snow (e.g. emergency communications after avalanches), through rubble (e.g. communications with victims after an earthquake) etc [14].

1.3 Advantages of UWB Technology

UWB system shows a good number of uniquely attractive features in the wireless communication systems. Some of the potential advantages of UWB systems over narrowband and wideband systems are reduced system complexity (and thus cost), large information rates, support for a large number of users in a multiple access environment, low power spectral densities resulting in low interference to narrowband systems operating in overlapping frequency bands and low probability of detection (LPD) by hostile systems, immunity to multipath fading, large number of resolvable multipath components that can be exploited using a Rake receiver, and combined services such as communications, radar, and precision location.

One of the advantages claimed by some UWB proponents is that the transmitter and receiver hardware can be produced less expensively than traditional communications equipment. The generated pulses can be transmitted directly (or filtered and then transmitted) eliminating the need for oscillators, mixers, and other costly RF hardware. If the pulses are transmitted directly, a baseband system results where the signal occupies frequencies near DC to the highest frequency of the pulse (possibly in the gigahertz range). However, to transmit only in a higher frequency band or to more tightly control the spectral shape of the signal, the pulses can be filtered before they are radiated. This type of filtering can be used to meet specific spectrum masks such as those mandated by the FCC or to intentionally avoid certain bands (such as GPS) to prevent interference to other systems. The antennas can also act as a filter or source of distortion for signals of such a large bandwidth and must be accounted for in determining the radiated spectrum. The pulses can also be modulated by a carrier to achieve a desired center frequency and frequency range, but then oscillators and mixers become necessary, increasing the complexity and thus the cost of the system [15].

From Shannon's theory of channel capacity,

$$C = B\log_2(1+\frac{P_0}{N_0}) \tag{1.3}$$

Where, C is the channel capacity in bits/sec, B is the bandwidth in Hz, P_o is the signal power spectral density in W/Hz, and N_o is the noise power spectral density in W/Hz. For UWB the signal bandwidth is much larger than the information bandwidth and therefore, the system can operate at low signal to noise ratios (SNR = P_o/N_o) and relatively high data rates (compared to more narrowband systems). For these low SNR values, the capacity of the system increases almost linearly with power [16].

Since the energy is spread over such a large bandwidth in UWB, the power spectral density can be very low, often on the same order as the noise spectral density as discussed above. A narrowband system that operates in a band that overlaps a small portion of a band within which a UWB device is operating will experience some interference. However, the UWB interference will only raise the noise floor slightly (this assumes a Gaussian approximation for the UWB interference which results $P_{inter} = P_0W \approx N_0W$). As more UWB devices are operating simultaneously, the interference power will be additive.

With a low power spectral density, the signal is also inherently more covert to hostile interceptors and detectors. It was shown that UWB signals are less detectable than wideband signals being detected by a wideband radiometer with some basic knowledge of the signal being detected [17]. The level of covertness was quantified using a metric that measures the probability of detection as a function of distance. However, while the radiometer is the optimum detector for CW signals, a modified detector can improve the detection for impulse radio, exploiting the unique features of UWB signals such as high peak-to-average ratio and small duty cycle [18, 19]. However the UWB signals detected by the improved system were still shown to be more covert than some wideband DSSS systems [19].

In traditional wideband DSSS systems, frequency diversity can be exploited through the use of a Rake receiver. Multipath components of the signal that are delayed in time by more than a chip duration are resolvable as they appear uncorrelated. The Rake receiver correlates with each of the delayed versions of the signal and combines them to increase the signal to noise ratio. This is possible because the delayed versions of the signal are close to orthogonal in code (delayed versions of the spreading code are nearly uncorrelated). For pulse based UWB systems, the multipath components that are delayed by more than the pulse duration are orthogonal in time (for low duty cycle signals) and can also be combined using a Rake receiver. Since the pulse duration is typically very short (on the order of the inverse of the bandwidth), a large number of resolvable multipath components may be present for many different channel types. For example, in outdoor channels, Rake receivers are often used to exploit multipath diversity in wideband CDMA systems where the delay between multipath components is large (relative to the chip duration), because the scatterers in the outdoor channel are spaced at large distances (mountains, buildings, etc.). However, in the indoor channel, the delay between multipaths is much less (indoor scatters, such as walls, furniture, etc. are spaced much closer) and therefore for traditional wideband systems, a Rake receiver is ineffective because the multipaths are not resolvable. But, if the UWB pulse duration is less than the typical delay between multipath components, the time diversity can be exploited using a Rake receiver even in an indoor environment.

Since more of the multipath components are resolvable, it has been speculated that less paths contribute toward each resolvable component. In this case, some of the traditional models for multipath fading are not valid as they assume a large number of physical paths arrive at the same delay. Also, traditional fading models are based on CW signals that have a clearly defined phase term. UWB pulses do not have phase in the same sense that sinusoidal signals do. There has not been any research published that explores the theoretical basis for multipath fading in UWB. However, since many of the multipath components are expected to be resolvable, the fading variation of each component has been expected by some to be less severe than in more narrowband systems [20].

1.4 Thesis Organization

Chapter 2 presents the basic propagation mechanisms of the transmitted signal, classification of UWB channel model, different channel sounding techniques and the channel characteristics.

Chapter 3 illustrates the proposed UWB channel model with necessary equations and descriptions. The model is a modified version of S-V model, where scattering effect is considered along with other multipath gain coefficients.

Chapter 4 discusses the simulated results of the proposed UWB channel model indoor industrial environment, which shows the impact of scattering on the channel characteristics.

Chapter 5 contains the concluding remarks and discussion about the results obtained form the proposed UWB channel model.

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2. UWB CHANNEL

2.1 Basic Propagation Mechanisms

The signal arrival at the receiver is in general a summation of both direct LOS and several multipath components (MPCs). Multipath occurs due to the three basic multipath propagation mechanisms, namely reflection, diffraction and scattering of the transmitted signal. All three of these phenomenon cause radio signal distortions and give rise to signal fades, as well as additional signal propagation losses in a wireless communication system. The relative importance of these propagation mechanisms depends on the particular environments. For example, if there is a LOS between terminals, the reflection dominates the propagation, while if the mobile is in a heavily cluttered area with no LOS path, scattering and diffraction play major role.

2.1.1 Reflection and propagation

The abrupt change in direction of a wave front at an interface between two dissimilar media so that the wave front returns into the medium from which it originated is called *reflection*. Reflection may be *specular* (mirror-like) or *diffuse* (i.e. not retaining the image, only the energy) according to the nature of the interface. Depending upon the nature of the interface (i.e. dielectric–conductor or dielectric–dielectric) the phase of the reflected wave may or may not be inverted. Reflection is a very important propagation process and transmission through dielectric or conductive objects and this shows frequency dependency.

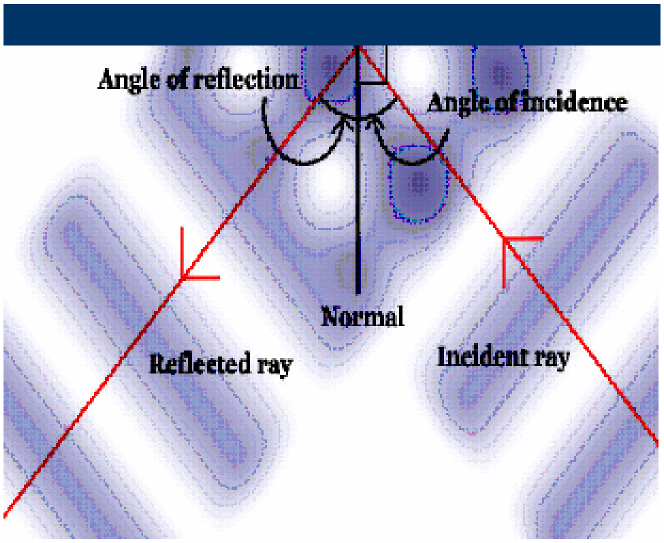

Fig. 2.1.1.1: Reflection

2.1.2 Diffraction

Diffraction is the *spreading out* of waves. All waves tend to spread out at the edges when they pass through a narrow gap or pass an object. Instead of saying that the wave spreads out or bends round a corner, we can say that it diffracts around the corner.

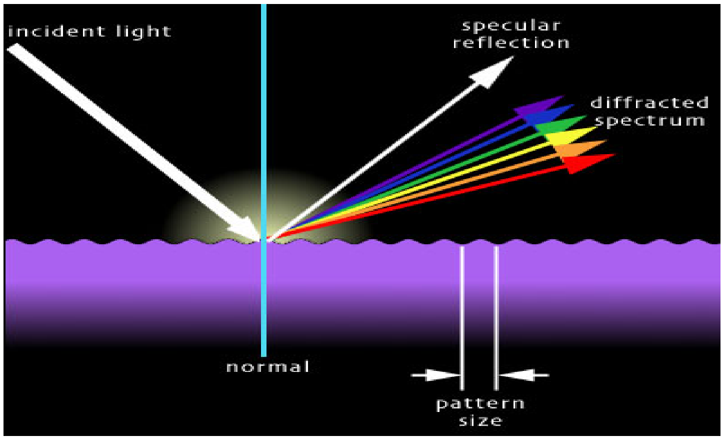

Fig. 2.1.2.1: Diffraction

A narrow gap is one which is about the same size as the wavelength of the electromagnetic wave or less. The longer the wavelength of a wave, the more it will diffract. Actually, a strong frequency dependence is shown by another effect is diffraction at the edge of a screen or wedge. It is clear that the diffraction loss increases with increasing frequency. An example is the canonical problem of diffraction by a half-plane.

2.1.3 Scattering

Scattering plays a major role if the mobile is in a heavily cluttered area with NLOS path. When a radio wave imposes on a rough surface, the reflected energy is spread out in all direction due to scattering. Small objects like the peak of this stand tend to scatter energy in all direction. Scattering is obvious in such a factory hall or any other cluttered area. We have considered scattering as a major propagation mechanism in the proposed model.

Fig. 2.1.3.1: Scattering

The scattering coefficient can be defined as:

$$\rho_l = \rho_{obj} e^{-2(2\pi \frac{f}{c_0} \sigma \sin \varphi_0)} \tag{2.1}$$

Where, ρ_{obj} depends on the material of the object.

σ = standard deviation
φ_0 = angle of incidence
f = frequency
c_0 = light velocity

2.2 Classification of UWB Channel Models

Many different types of wireless propagation channels already have been proposed. But one reason for the abundance of modeling approaches is the complex phenomena encountered by a transmitted signal. The transmitted signal will usually arrive at he receiver via several paths like multipaths, where the signal encounters various propagation mechanisms. Many different types of simplifications and approximations are necessary in order to obtain a simple yet reliable model for wireless communication channel. Signal propagation theory is well established for both narrowband and wideband systems. Generally, the UWB propagation channel model can be classified into Deterministic and Statistical model.

2.2.1 Deterministic model

An electromagnetic tool such as ray tracing techniques is applied to obtain nearly exact propagation characteristics for a specified geometry in deterministic model. These models can explain the propagation mechanisms such as path loss, diffraction, reflection, and scattering. Ray tracing models are based on exact computations making use of a detailed data base of the geometry of the specific physical environment. Actually the accuracy of ray tracing models relies on the accurate and detail of the site-specific representation of the propagation medium. For example, indoor channel modeling usually relies on the availability of the three-dimensional database. In addition to the geometry, the electromagnetic parameters of the materials also need to be included in the database. The major advantage of these models is that they offer great accuracy with site-specific results. Any site can be modeled if its physical characteristics are available, and any parameter can be calculated by adjusting these models. However, these models have several disadvantages such as the topographical and building data is always tied to a particular site and thus a huge amount of such data is required in order to obtain a comprehensive set of different propagation environments.

Moreover, they are usually computationally intensive, especially when the environment is complex.

A huge number of UWB channel models have been developed under deterministic model. For example, the ray tracing approach is combined with the uniform theory of diffraction to model the received signal as superposition of rays. This model has the advantage of being versatile and of general validity. However, it has high complexity in the channel modeling which leads to a high computational load. Another UWB channel model based on UTD techniques consists of three basic ray mechanisms of geometrical optics and time domain uniform theory of diffraction. This signal can determine both the signal attenuation and the waveform distortion in terms of pulse shape and pulse duration.

2.2.2 Statistical model

Statistical models can provide sufficiently accurate channel information and Statistical models are normally less complex than the deterministic models. These models attempt to generate synthetic channel responses that are representative of real propagation channels. Typically, such models can be tuned to imitate various propagation environments by setting appropriate values for the channel model parameters. Note that fixed parameter settings do not produce identical outputs on each simulation run but stochastic processes are used to create variability within a fixed environment type. For example, a particular set of parameters might generate a representative set of propagation scenarios found in indoor environments. Statistical models may be formed based on the basic principles of wave propagation for random communications channels and by assuming statistical distribution of the channel parameters, and computing the required statistical moments from the data collected from the real-time measurements. This category of models has the ability to provide accurate statistical information, without the complexity of detailed deterministic approaches.

Several statistical-based UWB channels have been proposed recently. For example, Foerster and Li[21] proposed a statistical-based multipath channel model based upon measurements collected in a condominium in the frequency range 2-8 GHz. Ghassemzadeh et al.[22] proposes a model based on the frequency domain channel measurements results in 23 residential environments (based on extensive propagation studies in 23 homes). Measurements were conducted in the frequency range 4.375-5.625. a path loss model and a second order auto-regressive model are proposed for frequency response generation of the UWB indoor channel. Probability distributions of the model parameters for different locations and time-domain results such as root mean square delay spreads and percentage of captured power will be discussed later. Three channel models were considered namely the Rayleigh tap delay line model, the Δ-k model, and the Saleh-Valenzuela (S-V) model. The comparison shows that the S-V model gives the best fit to the measured channel characteristics such as the mean excess delay, mean RMS delay spread and the mean number of significant paths within 10 dB of the peak multipath arrival. In addition the log-normal was proposed to model the amplitude distribution which was shown to give a better fit than the Rayleigh distribution. Chong et al. [23] proposed a statistical-base UWB channel model which incorporates the clustering of MPC phenomenon observed in the measurement data collected in the frequency band 3-10 GHz in various types of high-rise apartments in Korea. Both the large-scale and small-scale channel statistics were characterized. The large-scale parameters included the distance and frequency dependency of path loss as well as the shadowing fading statistics. The small-scale parameters included the temporal domain parameters, the distribution of clusters, and MPCs, clusters, and MPC arrival statistics. A new distribution named mixtures of two position processes was proposed to model the ray arrival times. Again, the small-scale fading amplitude statistics as well as the temporal correlation between adjacent path amplitude were also investigated in the model.

2.3 Different Channel Measurement Techniques

The most direct method of studying radio wave propagation and verifying propagation theory can be obtained by measuring channel. This can then provide invaluable input to the development of realistic channel models. In general, there are two possible techniques to perform the UWB channel measurements and they are discussed in the following.

2.3.1 Frequency domain sounding technique

A vector network analyzer is used to control a synthesized frequency sweeper, and the bandwidth centered around the frequency of interest is scanned by the synthesizer through discrete frequencies. To measure the sampled frequency response of the channel an *S*-parameter test is used and

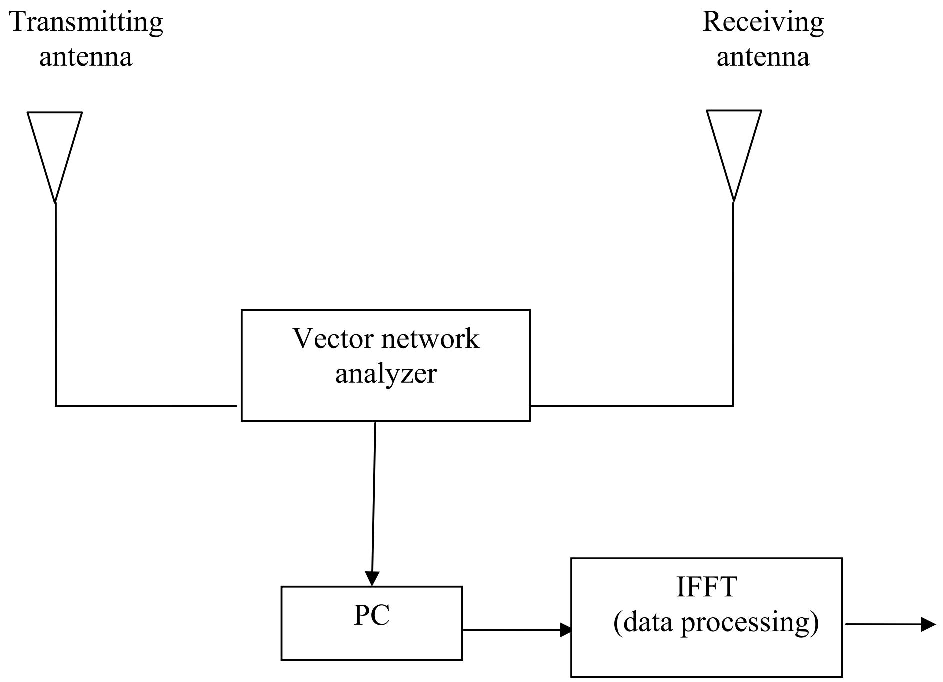

Fig. 2.3.1.1: Frequency-domain measurement technique based on frequency sweeping.

for each frequency step a known sinusoidal signal is transmitted and detailed information about the magnitude and phase of the received signal are obtained. The channel impulse response is obtained using the inverse Fourier transform (IFT). Several UWB channel measurements have been performed using this technique.

2.3.2 Time domain (pulse) sounding technique

In this technique a narrow pulse is employed to probe the channel. The measurement resolution is equal to the width of transmitted pulse. The pulse repetition period should be carefully chosen to allow observation to the time varying response of individual propagation paths, and at the same time to ensure that all multipath components are received between successive pulses. The advantage of this technique is that the environment does not need to be static within the recordings, but as long as the coherence time assumptions is still valid. The corresponding train of impulses can also be generated using a conventional direct sequence spread spectrum-based measurement system with a correlation receiver. However, the main drawback in this system is that it needs very high chip rates to achieve bandwidths over several GHz. Fig. 2.3.1.2 illustrates the time –domain measurement technique. This technique is used for several UWB measurements.

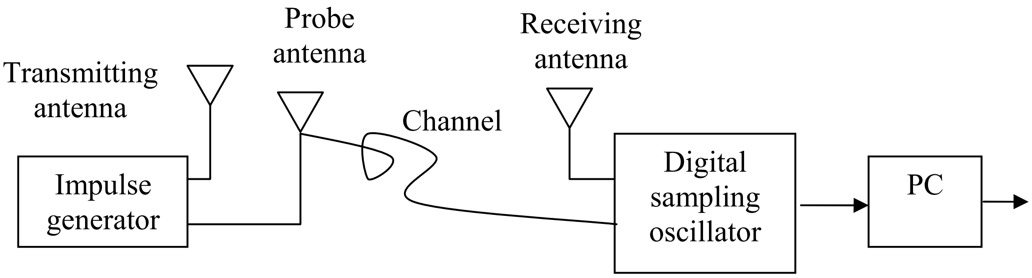

Fig. 2.3.1.2: Time-domain measurement technique based on pulse transmission.

2.4 UWB Channel Characteristics

The received signal in any communications system is an attenuated, delayed, and possibly distorted version of the signal that was transmitted plus noise and (possibly) interference. The relationship between the received signal and the transmitted signal is typically called the "channel." In order to evaluate and design wireless systems, we must create models of the channel. In the following sections, we will discuss how the channel is modeled for UWB systems. We should make a careful distinction about the type of modeling being examined. In general, there are two prevalent types of modeling of wave propagation. The first is what might be termed "site-specific modeling" or "deterministic modeling," and attempts to model the exact interaction of the wave in the specific environment of interest. A second type of modeling attempts to model the relevant statistics of the received signal and may be called "statistical modeling." Statistical modeling, discussed in this chapter, is particularly useful in communication system development where the system must work in a wide variety of environments.

2.4.1 Channel impulse response

Channel Impulse response is a wideband channel characterization and contains all information necessary to simulate or analyze any type of radio transmission through the channel. It can be used to predict and compare the performance of different mobile communication systems.

UWB channel can be described by its time variant impulse response $h(t,\tau)$, which can be expressed as

$$h(t) = \sum_{n=1}^{N(t)} \alpha_n(t)\delta(t-\tau_n(t))e^{j\theta_n(t)} \tag{2.2}$$

Where the parameters of the n^{th} path α_n, τ_n, θ_n and *N* are amplitude, delay, phase and number of relevant multipath components respectively.

2.4.2 RMS delay spread

RMS delay spread is the multipath channel parameter that can be determined from a power decay profile. It can be used to compare different multipath channels. RMS delay spread seems to follow a normal distribution. It is defined as

$$\sigma_\tau = \sqrt{(\tau^2) - (\overline{\tau})^2}$$
$$\overline{\tau^2} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)} \tag{2.3}$$

Typical values for the multipath delay spread of indoor channels have been reported to be between 15 nsec in a residence to over 100 nsec in an office to a 150 nsec in a commercial building [24]. Other measurements at 10 meter distances suggest RMS delay spreads of 19-47 nsec [25]. In addition, the multipath delay spread has been found to increase as the separation distance between the receiving and transmitting antenna is increased. Table 2.4.2.1 shows some of the published RMS delay spread numbers that have been suggested for the indoor channel (both industry adopted models and published academic papers).

Table 2.4.2.1
Suggested RMS delay spread for the indoor channel

Application	Delay spread	Comments
WPAN (ITU P.1238)	RMS values: 70 nsec for Residential 100 nsec for office 150 nsec for commercial	WSSUS model with tap-delay line and Gaussian distributed taps
802.11 LAN for evaluating HRb proposals	25 nsec 100 nsec 250 nsec	WSSUS model with tap-delay line and Gaussian distributed taps with zero mean (Rayleigh fading)
IEEE 802.15.3 High rate PAN	25 nsec minimum	WSSUS model with tap-delay line and Gaussian distributed taps with zero mean (Rayleigh fading)
Indoor at distances up to 30 meters (results here for 10 meters)	< 20 nsec for LOS < 70 nsec for NLOS for 2.4 GHz	Delay spreads for 2.4 GHz tends to be higher than 11.5 GHz. Delay

		spread increase with distance separation.
Indoor at ~ 1.5 GHz	Ave. rms delay spreads: Brick: 26-30 ns Concrete: 28-29 ns Office: 25 & 50 ns LOS factory: 96 ns OBS factory: 105 ns	Max rms delay spreads: Brick: < 70 ns Concrete: < 70 ns Office: 50 & 218 ns LOS factory: 300 ns OBS factory: 300 ns
UWB propagation indoor < 10 meters	Delay spreads on the order of 100 nsec observed	Suggests ray tracing not feasible for UWB. Number of dominant paths is much greater than 5 and < 50.
UWB propagation at 6, 10, and 17 m separation	--	Multipath energy varies by at most 5 dB (suggests fading is not of Rayleigh type)
900 MHz in office building environment. Paths were mostly OBS. Distances varied from 1-100 ft.	Mean RMS delays of 16, 40, 55 nsec for 3 different office buildings	Max. RMS delays of 48, 55, 146 nsec. Temporal variations followed closely to lognormal dist. Rather than Rayleigh.
12,000 measurements in 2 office buildings in frequency band of 900-1300 MHz	Mean values between 20-30 nsec for 5-30 m antenna separations, values of 11-20 nsec for 10 m separation.	Results agreed with a value of 26 nsec and 25 nsec.
870 channel realizations (LOS and NLOS) in a condo setting using 2-8 GHz frequency band)	Mean RMS delay spread of 12.94 nsec, and mean excess delay of 13.59 nsec.	
300,00 channel realizations collected in 23 homes using 4.375-5.625 GHz frequency band)	Mean RMS delay spread of 8.2 nsec, and mean excess delay of 4.2 nsec.	
906 UWB channel soundings in an office using a 2 GHz center freq. With 1.5 GHz bandwidth pulse.	Mean RMS delay of 5.22 nsec	

These results, and trying to stick with those published in [26] and [27], suggest that a fairly conservative RMS delay spread of 25 nsec would be a good initial starting point for PAN type applications with antenna separations of about 10 meters or less. Shorter RMS delay spreads could be considered for shorter ranges (5 meters or less). Results in [27] (few measurements have been done with such short range), found average RMS delay spreads of around 17 nsec at these short ranges. As a result of this wide variation, the final multipath model should consider a range of RMS channel delay spreads.

2.4.3 Excess delay spread

Excess delay spread is also the multipath channel parameter that can be determined from a power decay profile. It can be used to compare different multipath channels. It is defined as

$$\bar{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)} \tag{2.4}$$

2.4.4 Power decay profile

Power decay profile shows the amount of energy collected at the receiver and delays associated with this reception. It decreases exponentially with excess delay.

2.4.5 Number of multipath components

Multipath means multiple versions of the transmitted signal at the receiver. Signals may arrive at the reciever from different directions with different propagation delays, phase and angel of arival. They are vectorically summed up at the receiver, which can cause the signal to distort or fade. Even when the receiver is stationary, received signal may fade due to movement of surrounding objects. Naturally, multipath occurs in NLOS path. But it still occurs in LOS path due to reflections from the ground and surrounding objects. Multipath causes rapid fluctuation in signal strength over a small distance or time interval. It also causes random frequency modulation due to varying doppler shifts on different multipath signals. So the number of multipath components plays a major role in any channel modeling.

Fig. 2.4.5.1: Multipath components (MPCs)

3. PROPOSED UWB CHANNEL MODEL

Our proposed UWB channel model is based on S-V model. Here we consider the log-normal distribution instead of rayleigh distribution to model the multipath gain magnitude. The estimated parameters value for 4-10m distance is taken from the measured channel impulse response which is shown in table 3.1. Estimation of these parameters from the measured impulse responses has been conducted in a similar fashion described in [29]. In this paper, we demonstrate scattering effect in modeling UWB channel as it is more pronounced in a heavily cluttered area with non line of sight (NLOS) path.

Table 3.1
Predicted Parameter Value for Distance of 4-10m

Parameter	**Value**
Λ	0.0667
λ	3
Γ	17
γ	12
σ_x	4.8

The UWB channel can be described by the discrete time impulse response, which can be expressed as

$$h(t) = \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l} \delta(t - T_l - \tau_{k,l}) \tag{3.1}$$

where,

L= number of clusters;
K_l = number of multipath components (number of rays) in the l^{th} cluster;
$\alpha_{k,l}$ = multipath gain coefficient of the k^{th} ray in the l^{th} cluster;
T_l = arrival time of the first ray of the l^{th} cluster;

$\tau_{k,l}$ = delay of the k^{th} ray within the l^{th} cluster relative to the first path arrival time, T_l

By definition, we have $\tau_{0l} = 0$ and we set $T_0 = 0$. The cluster and rays form a Poisson arrival process with distributions given by:

$$p(T_l | T_{l-1}) = \Lambda e^{[-\Lambda(T_l - T_{l-1})]}, l > 0 \tag{3.2}$$

$$p(\tau_{k,l} | \tau_{(k-1),l}) = \lambda e^{[-\lambda(\tau_{k,l} - \tau_{(k-1),l})]}, k > 0 \tag{3.3}$$

Where,

Λ = cluster arrival rate;

λ = ray arrival rate.

The multipath gains are defined as follows:

$$\alpha_{k,l} = p_{k,l}\xi_l\rho_l\beta_{k,l} \tag{3.4}$$

In the above equation, ξ_l and ρ_l reflects the fading and scattering effect associated with the l^{th} cluster, and, $\beta_{k,l}$ corresponds to the fading associated with the k^{th} ray of the l^{th} cluster. With $p_{k,l}$ = +/-1 representing signal inversions due to reflections. In the original S-V model the amplitudes of each arrival are assumed to be Rayleigh distributed with:

$$E\left[\left|\xi_l\beta_{k,l}\right|^2\right] = \Omega_0 e^{-T_l/\Gamma} e^{-\tau_{k,l}/\gamma} \tag{3.5}$$

Where, $\Omega_0 = E[\beta^2(T_l = 0, \tau_{k,l} = 0)]$ is the average power of the first ray of the first cluster, that is, both the clusters and rays having amplitudes which decay exponentially with time, and are characterized by:

Γ = cluster decay factor;
γ = ray decay factor.

For the wideband channel we follow [30] and assume a log-normal distribution for the multipath gains given by:

$$20\log10(\xi_l\beta_{k,l}) \propto \text{Normal}(\mu_{k,l}, \sigma_1^2 + \sigma_2^2) \tag{3.6}$$

Or,

$$\begin{gathered} \left|\xi_l\beta_{k,l}\right| = 10^{(\mu_{k,l}+n_1+n_2)/20} \\ n_1 \propto \text{Normal}(0, \sigma_1^2), n_2 \propto \text{Normal}(0, \sigma_2^2) \end{gathered} \tag{3.7}$$

where, n_1 and n_2 are independent, $\mu_{k,l}$ is now given by:

$$\mu_{k,l} = \frac{10\ln(\Omega_0) - 10T_l/\Gamma - 10\tau_{k,l}/\gamma}{\ln(10)} - \frac{(\sigma_1^2 + \sigma_2^2)\ln(10)}{20} \tag{3.8}$$

In [30] the clusters are assumed to fade independently of rays. For example, each multipath arrival would have a fading term associated with the cluster arrival and a fading term associated with the ray arrival.

If the propagation is in a heavily cluttered area with NLOS path, scattering and diffraction play a major role. We designed the channel for a factory hall, where there are lots of obstacles in the NLOS paths. For this reason, while modeling the channel, the scattering coefficient should be considered along with the other multipath gain coefficient. The scattering coefficient can be defined as:

$$\rho_l = \rho_{obj} e^{-2(2\pi \frac{f}{c_0} \sigma \sin \varphi_0)} \tag{3.9}$$

Where, ρ_{obj} depends on the material of the object.

σ = standard deviation

φ_0 = angle of incidence of the l^{th} cluster

f = frequency

c_0 = light velocity

4. RESULTS AND DISCUSSION

Channel impulse response (CIR) which is important to characterize UWB channel, is depicted in Fig. 4.1. Other desired parameters are the power decay profile (PDP) and the temporal dispersion properties. The temporal dispersion properties include mean excess delay, τ_m, rms delay spread (RDS), τ_{rms} and number of multipath components (MPCs).

Power decay profile demonstrates the average power decay which is shown in Fig. 4.6 obtained from our UWB channel model. It shows that the power is decreasing exponentially. The double exponential decay function means two exponential decays, one for the clusters and the other for the rays shown in figure is due to the strong scattering effect in a factory hall. The time decay constant (TDC) of the exponential function seems to follow a lognormal distribution.

In order to compare different multipath channels and to develop some general design guidelines for wireless systems, temporal dispersion parameters are used, which grossly quantify the multipath channel. We calculated the mean excess delay, RMS delay spread and the number of MPCs from the CIR of our UWB channel model. The excess delay and the RMS delay spread follow the normal distribution with higher value of mean and variance for the case of our model. Fig. 4.2 and Fig. 4.3 shows the distribution of the excess delay and the RMS delay spread respectively. We demonstrated two distributions of the normalized amplitude of the MPCs in Fig 4.4 and Fig. 4.5, one is greater than 10dB from peak and other one is greater than 85% of captured energy. The cluster and ray arrival rates of the NLOS channels are significantly very high because of scattering. This is consistent with the temporal parameters from the measured data, which indicates the NLOS channels have many more significant MPCs.

The simulation results are compared with the *IEEE 802.15.3a Model* [31]. The comparison results are shown in Table 4.1 which proves that scattering mechanism affects the channel characteristics.

Table 4.1
Results and Comparison

Channel Characteristics	**Results from the IEEE 802.15.3a Model**	**Results from our model**
Mean excess delay (nsec) (τ_m)	22.198	22.2556
RMS delay (nsec) (τ_{rms})	19.835	19.5468
NP_{10dB}	50.840	45.7400
NP (85%)	99.86	101.6300

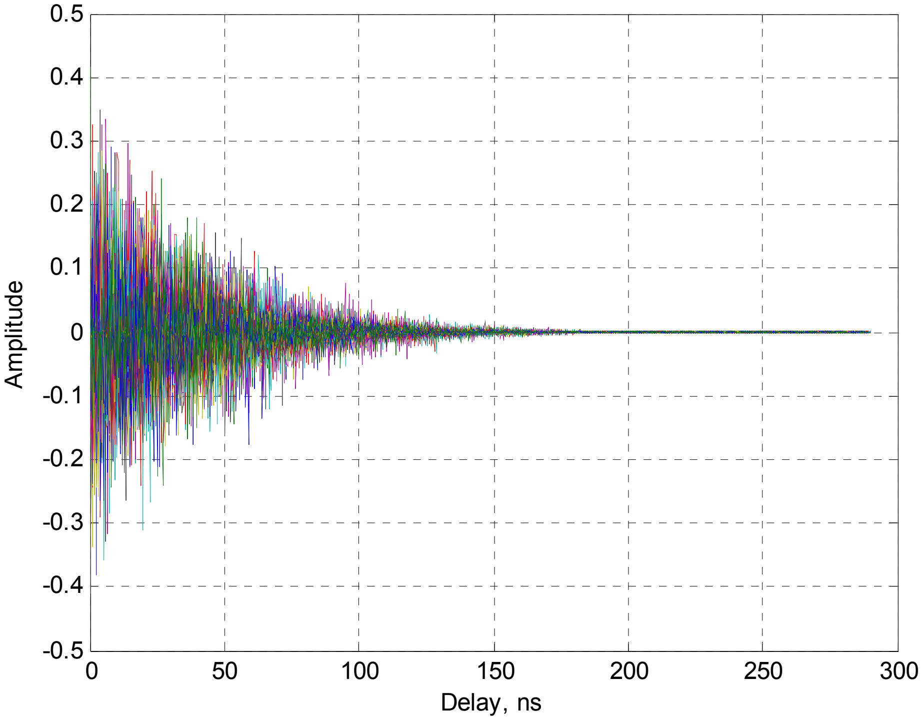

Fig. 4.1: Impulse Response Realization

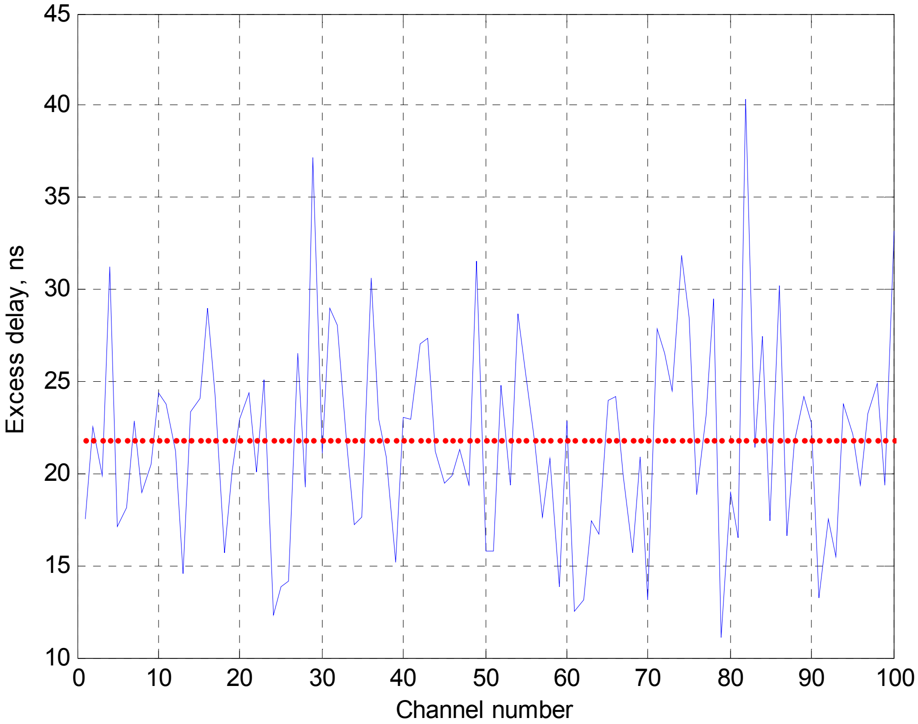

Fig. 4.2: Excess Delay

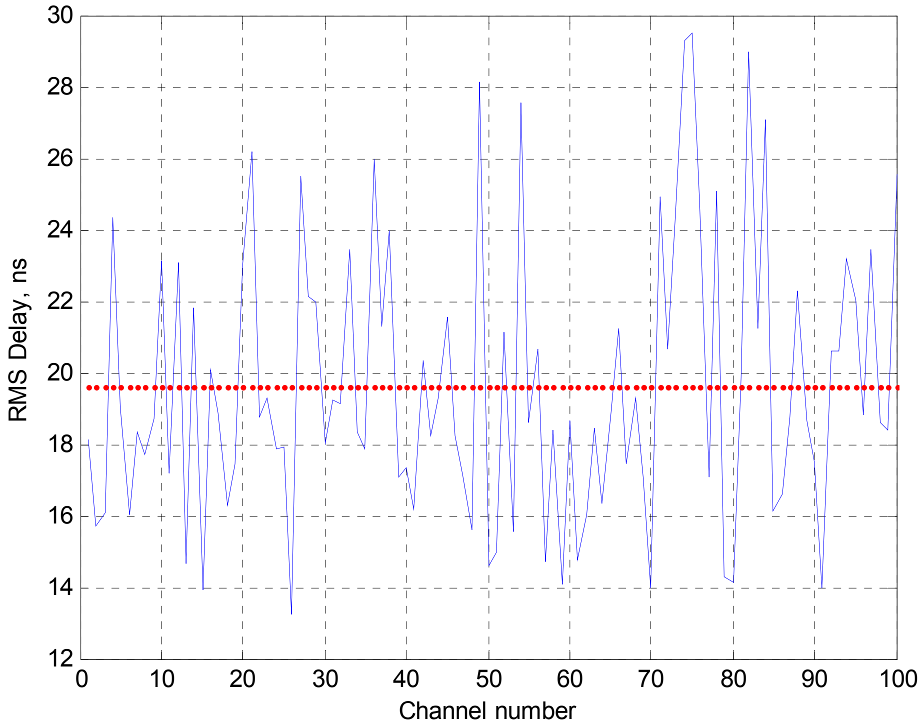

Fig. 4.3: RMS Delay

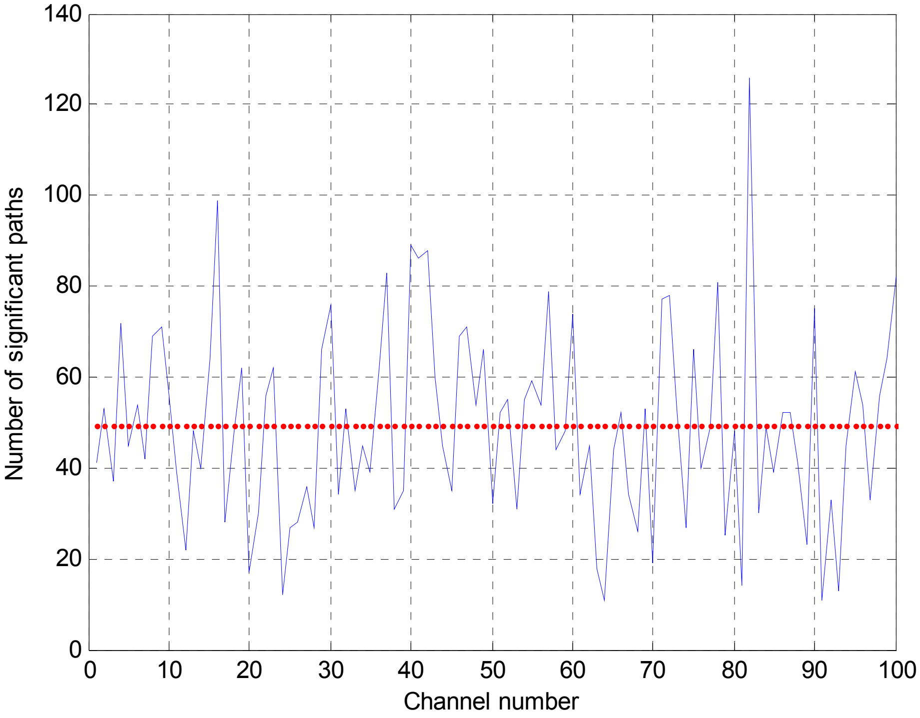

Fig. 4.4: Number of Significant paths >10 dB from peak

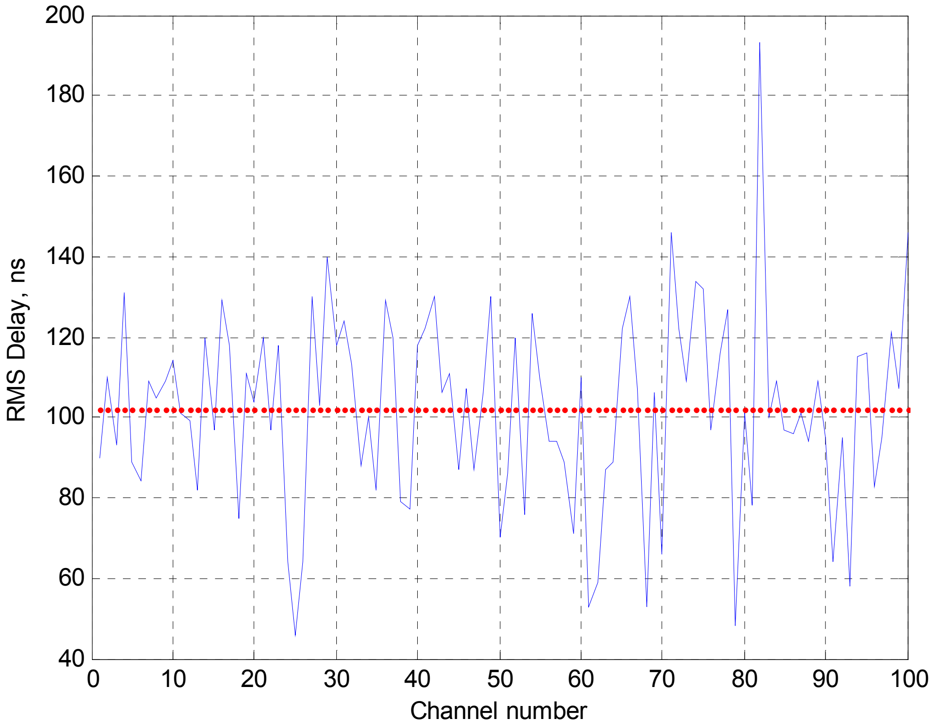

Fig. 4.5: Number of significant paths capturing >85% energy

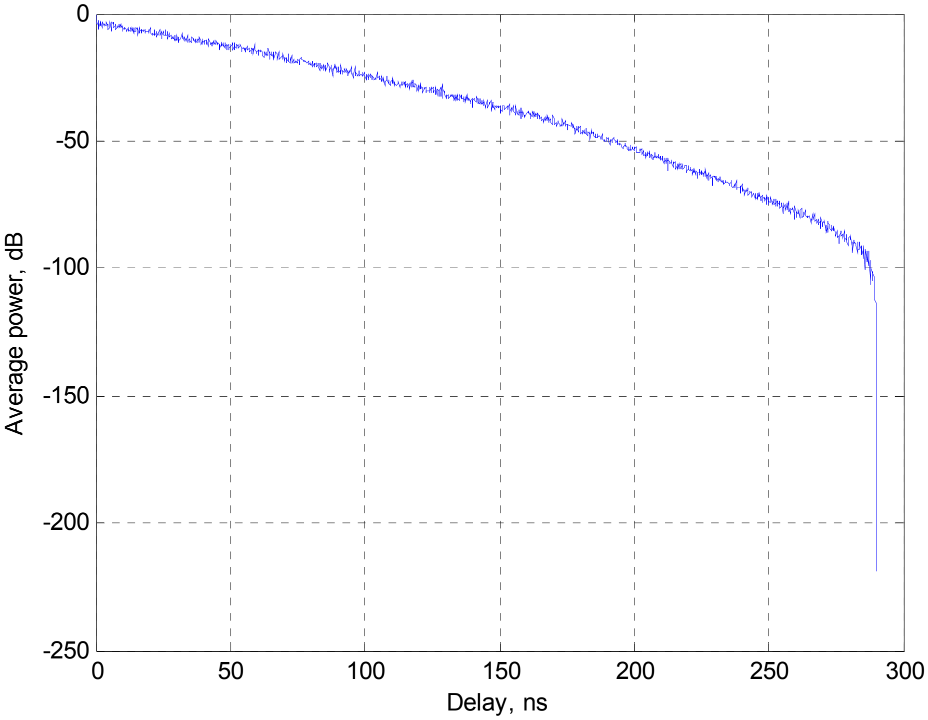

Fig. 4.6: Average Power Decay Profile

5. CONCLUSION

The objective of this thesis was to evaluate the performance of UWB channel for indoor environment. This paper illustrated a variety of topics related to ultra-wideband communications. Significant work characterizing the indoor UWB channel was presented. Based on those findings, issues in the design and performance of UWB receivers were also presented.

In this paper, scattering effect has been considered for accurate channel modeling. Simulated results show that the received UWB signal power decreases exponentially following double exponential function. The RMS delay spread, excess delay and MPCs follow normal distribution and they have higher value of mean. These results arise for the existence of strong scattering object in a heavily cluttered area.

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