This chapter surveys the current and emerging wireless communication standards and highlights the significance of Ultra Wide-Band (UWB) communications. A history of research in the field of UWB antennas are narrated followed by a description about advantages and applications of UWB communication. A description of the stimulus behind the present investigations is presented and the chapter is concluded with the organization of the present thesis.
1.1 Introduction

The antenna is an essential part of any wireless system as it is the component providing transition between a guided wave and a free-space wave. According to IEEE standard definitions for antennas [1], an antenna is defined as a means for radiating or receiving radio waves. During the period 1885-1900, some pioneers invented the antennas and the wireless systems.

The foundations for wireless communication research and industry were established in 1864, when James Clerk Maxwell predicted that the electric and magnetic fields will allow energy to be transported through materials and space at a finite velocity [2]. Heinrich Rudolf Hertz demonstrated Maxwell’s theory of electromagnetic radiation in 1888 by his classical spark transmitter. Hertz’s apparatus demonstrated the first transmission of regulated radio waves, the ‘new form of energy’ [3].

The great Indian scientist Jagadish Chandra Bose made a revolutionary attempt to demonstrate radio communication. In 1895, Bose gave his first public demonstration of electromagnetic waves. The wavelengths he used ranged from 2.5 cm to 5 mm. He was playing at 60 GHz over one hundred years ago! Bose's investigations included measurement of refractive index of a variety of substances. He also made dielectric lenses, oscillators, receivers, and his own polarization device.

Guglielmo Marconi, dubbed the father of the wireless communications, took the discoveries of Maxwell and Hertz to the outside world. It was in 1897 that Marconi demonstrated the practical applications of wireless communication, when he established continuous radio contact between the shore and ships traveling in the English Channel [4]. By mid December in 1901, Marconi took a much greater step by performing the first transcontinental
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wireless communication, between England and Canada. This achievement triggered the scientists and engineers all over the world towards wireless communication.

1.2 Over view of Antenna Research

Prior to World War II, most antenna elements were of wire types such as long wires, dipoles, helices, rhombuses etc., and were used either as single element or as arrays. In the year 1926 Yagi-Uda antenna was introduced [5], which received wide popularity due to the simple array structure and excellent radiation performance. It is still being used as home TV antenna.

World War II was the most flourishing period in antenna research. During and after World War II, many other radiators were introduced. Many of these were aperture type such as open ended waveguides, slots, horns, reflectors and lenses. They were employed for radar, remote sensing and deep space applications [6]. In 1950s a breakthrough in antenna evolution was created by V.H Ramsey [7] which extended the bandwidth as great as 40:1 or more. The structure is specified entirely by angles, instead of linear dimensions, they offered an infinite bandwidth and were popularly referred to as frequency independent antennas.

It was not until almost 20 years later that a fundamental new radiating element, which has received a lot of attention and many applications since its inception, was introduced. Microstrip antennas received considerable attention starting in the 1970s, although the idea of a microstrip antenna can be traced to 1953 [8]. Microstrip antenna is simple, lightweight, inexpensive, low profile and conformal to Aircraft, Missile etc. Major advances in millimeter wave antennas have been made in recent years, including integrated antennas where
active and passive circuits are combined with the radiating elements into one compact unit to form monolithic circuits [9].

There has been much interest in electrically small antennas. Antennas that are electrically small, efficient, and have significant bandwidth would fill many needs if antenna engineers could reconcile these usually contradictory requirements. This is especially true recently with increased uses of wireless technologies for communications and sensor networks. It is well known that small electric dipole antenna is an inefficient radiator, i.e., because it has a very small radiation resistance with very large capacitive reactance. Consequently, to obtain a high overall efficiency, considerable effort must be expended on a matching network that produces an impedance that is conjugately matched to the dipole’s impedance; i.e., it forces the total reactance to zero by introducing a very large inductive reactance which cancels the very large capacitive reactance of a small electric dipole, and that then matches this resonant system to a feed network. Recently, this problem has been overcome by introducing metamaterials in antennas. A metamaterial medium is introduced in antennas to obtain electrically small antenna element with good efficiency [10].

Research conducted on antennas is driven by several factors. The first factor deals with the increase of the bandwidth and shift of operational frequency to the higher bands. With the ever-increasing need for mobile communication and the emergence of many systems, it has become important to design broadband antennas to cover a wide frequency range. Modern wireless applications require the processing of more and more data in different forms, higher data rates, higher capacity and multi-standard abilities. There are numerous well-known methods to increase the bandwidth of antennas including designs with log-periodic profile, travelling-wave topologies, increase of the
substrate thickness and the use of a low dielectric substrate, various impedance matching and feeding techniques, multiple resonators and slot antenna geometry [11-14].

According to wireless applications and the associated devices, the type of antennas can be very different. For example, the main requirements for an antenna of a cellular mobile radio phone will be small type, low profile and broad/multi bandwidth. Last but not least, in modern wireless communication systems, complex signal processing techniques and digital routines are considered in order to build a device which is flexible enough to run every possible waveform without any restrictions on carrier frequency, bandwidth, modulation format, date rate, etc. This is the philosophy of future radio systems such as Software Defined Radio (SDR) and cognitive radio firstly introduced by Mitola [15,16]. In this context, the antenna becomes not only one of the most important parts in a wireless system but it is also flexible and “intelligent” enough to perform processing function that can be realized by any other device.

The antennas are becoming increasingly linked to other components (e.g., system-on-chip) and to other subject areas (such as digital signal processing or propagation channels). To accurately integrate the antenna performance into the design of the overall wireless system, specific models compatible with standard languages are highly desired. Such modeling allows the right design and optimization of wireless RF front-ends including antennas.

1.3 Short-Range Wireless Communications

Radio-based Short-Range Wireless (SRW) communication is an alternative class of emerging technologies designed primarily for indoor use over very short distances. It is intended to provide fast (tens or hundreds of megabits per second) and low cost, cable free connections to the internet and
between portable devices. SRW features transmission powers of several microwatts up to milliwatts, yielding a communication range between 10 and 100 meters. SRW provides connectivity to portable devices such as laptops, PDAs, cell phones and others.

Short-range communications standards fall into two broad but overlapping categories: Personal Area Networks (PAN) and Local Area Networks (LAN). Wireless PAN technologies emphasize low cost and low power consumption, usually at the expense of range and peak speed. In a typical wireless PAN application, a short wireless link, typically under 10 meters, replaces a computer serial cable or USB cable. Standards, such as Bluetooth and Home RF, have been created to regulate short-range wireless communications. Bluetooth has appeared recently in many mobile devices. Bluetooth can transmit data through solid nonmetal objects and supports a nominal link range of 10cm-10m at a moderate baud rate up to 720kb/s (raw data rate is 1Mb/s) [17]. An optional high power mode in the current specifications allows for ranges up to 100m. Because of the nature of radio, Bluetooth is a point to multipoint communication system, which supports connections of two devices as well as ad hoc networking between several devices. In order to prevent unauthorized access, Bluetooth requires sophisticated authentication and encryption mechanisms, which hamper fast connection establishment.

Therefore, Bluetooth is best for applications that require stable point-to-point or point-to multipoint connections for data exchange at moderate speeds, where mobility is a key requirement. Ultra-WideBand (UWB) is an emerging new technology that shows great potential for SRW applications. Unlike conventional wireless communications systems that are carrier-based, UWB-
based communication is baseband. It uses a series of short pulses that spread the energy of the signal from near DC to a few GHz.

Wireless LAN technologies, on the other hand, emphasize a higher peak speed and longer range at the expense of cost and power consumption. Typically, wireless LANs provide wireless links from portable laptops to a wired LAN access point. To date, 802.11b has gained acceptance rapidly as a wireless LAN standard. It has a nominal open-space range of 100m and a peak over-the-air speed of 11Mb/s. Users can expect maximum available speeds of about 5.5Mb/s. Other communication standards offer even higher data rates, like 802.11a and 802.11g.

### 1.3.1 Bluetooth

In 1994, Ericsson Mobile Communications, the global telecommunications company based in Sweden, initiated a study to investigate the feasibility of a low-power, low-cost radio interface between mobile phones and their accessories. The aim of the study was to find a way to eliminate cables between mobile phones and PC cards, headsets, desktops, and other devices. The study was part of a larger project investigating how different communications devices could be connected to the cellular network via mobile phones. The company determined that the last link in such a connection should be a short-range radio link. As the project progressed, it became clear that the applications for a short-range radio link were virtually unlimited [18]. The Bluetooth specification comprises a system solution consisting of hardware, software and interoperability requirements. The set of Bluetooth specifications developed by Ericsson and other companies answers the need for short-range wireless connectivity for ad hoc networking. The Bluetooth baseband protocol is a combination of circuit and packet switching, making it suitable for both voice and data.
Bluetooth wireless technology is implemented in tiny, inexpensive, short-range transceivers in the mobile devices that are available today, either embedded directly into existing component boards or added into an adapter device such as a PC card inserted into a notebook computer. Potentially, this will make devices using the Bluetooth specification the least expensive wireless technology to implement.

Bluetooth wireless technology uses the globally available unlicensed ISM (Industrial, Scientific, and Medical) radio band of 2.4 GHz. The ISM bands include three frequency ranges at 902—928 MHz and 2.4—2.484 GHz, which do not require an operator's license from the Federal Communications Commission (FCC) or any international regulatory authority. The use of a common frequency band means that devices using the Bluetooth specification can be used virtually anywhere in the world and they will be able to link up with other such devices, regardless of what country they are being operated in.

When it comes to ad hoc networking for data, a device equipped with a radio using the Bluetooth specification establishes instant connectivity with one or more other similarly equipped radios as soon they come into range. Each device has a unique 48-bit Medium Access Control (MAC) address, as specified in the IEEE 802 standards for LANs. For voice, when a mobile phone using Bluetooth wireless technology comes within range of another mobile phone with built-in Bluetooth wireless technology conversations occur over a localized point-to-point radio link. Since the connection does not involve a telecommunications service provider, there is no per-minute usage charge.

The radio link itself is very robust, using frequency-hopping spread-spectrum technology to mitigate the effects of interference and fading. As noted, spread spectrum is a digital coding technique in which the signal is taken
apart or "spread" so that it sounds more like noise to the casual listener. The coding operation increases the number of bits transmitted and expands the bandwidth used.

Using the same spreading code as the transmitter, the receiver correlates and collapses the spread signal back down to its original form. With the signal power spread over a larger band of frequencies, the result is a robust signal that is less susceptible to impairment from electromechanical noise and other sources of interference. It also makes voice and data communications more secure. With the addition of frequency hopping—having the signals hop from one frequency to another—wireless transmissions are made even more secure against eavesdropping.

The objective of the Bluetooth standard is to enable seamless communications of data and voice over short-range wireless links between both mobile and stationary devices. The standard specifies how mobile phones, Wireless Information Devices (WIDs), handheld computers, and Personal Digital Assistants (PDAs) using Bluetooth wireless components can interconnect with each other, with desktop computers, and with office or home phones. With its use of spread-spectrum technology, the first generation of the Bluetooth specification permits the secure exchange of data up to a rate of about 1 Mbps—even in areas with significant electromagnetic activity. With its use of Continuously Variable Slope Delta modulation (CVSD) for voice encoding, the Bluetooth specification allows speech to be carried over short distances with minimal disruption.

1.4 Ultra-Wideband (UWB) Technology

In the short-range application space, ultra-wideband radio technology (UWB-RT) can drive the potential solutions for many of today’s problems
identified in the areas of spectrum management and radio systems engineering. The novel and unconventional approach underlying the use of UWB-RT is based on optimally sharing the existing radio spectrum resources rather than looking for still available but possibly unsuitable new bands. This disruptive idea has recently received legal adoption by the regulatory authorities in the United States [19], and efforts to achieve this status have started in both Europe [20] and Asia, particularly Japan and Singapore. It is widely anticipated that UWB-RT will have a sizable impact on the multimedia-driven home networking and entertainment market, and will allow implementation of intelligent networks and devices enabling a truly pervasive and user-centric wireless world.

The bandwidth of UWB systems, as defined by FCC in [21], is more than 20% of a center frequency or more than 0.5 GHz. Clearly, this bandwidth is much greater than the bandwidth used by any current communication technology. UWB implementations can directly modulate an impulse that has a very sharp rise and fall time, thus resulting in a waveform that occupies several GHz of bandwidth. Fractional bandwidth is defined as

\[ B_f = \frac{f_h - f_l}{f_h + f_l} \]  \hspace{1cm} \text{(1.1)}

where, \( f_h \) and \( f_l \) are the highest and lowest cut-off frequencies (-10 dB point) of a UWB pulse spectrum respectively. The large bandwidth of UWB signals provide robustness to jamming and have low probability of detection properties. UWB devices usually require low transmit power, due to the control over duty cycle, thus supporting a longer battery life for hand-held devices.

This led to the emergence of UWB technology based applications for commercial high-data-rate, short-range communications, radar systems and measurement. They include high-speed file transfers and printing, high-definition
audio/video streaming and a myriad of other applications in the consumer electronics, personal computing and mobile communication arenas. The UWB systems should provide $\approx 50$Mbps through buildings within a range of at least 20m, as well as higher rates (up to 1Gbps) at shorter distances. UWB circuits need very little power to achieve these data rates (around tens of mW), which is between one tenth and one hundredth of the power required by devices such as mobile telephones and existing WLANs for the equivalent data rates, respectively, and are thus ideal for battery-powered devices [22].

If we have a fixed amount of energy, we can either transmit a great deal of energy density over a small bandwidth or a very small amount of energy density over a large bandwidth. This is measured in terms of the Power Spectral Density (PSD) which is defined as

$$\text{PSD} = \frac{P}{B}$$  \hspace{1cm} (1.2)

where $P$ is the power transmitted in watts (W), $B$ is the bandwidth of the signal in hertz (Hz), and the unit of PSD is watts/hertz (W/Hz) or dBm/Hz on a logarithmic scale. For UWB systems, the energy is spread out over a very large bandwidth (hence the name ultra wide band) and in general, is of a very low power spectral density. The maximum permitted power levels of the FCC approved UWB technology is low enough at 0.5mW over the entire 7.5GHz bandwidth (i.e. PSD = -41.3dBm/MHz, the same level as unintentional radiation from common electronics devices such as laptop computers). For wireless communications in particular, this allows UWB technology to overlay already available services such as the WiMAX and the IEEE 802.11 WLANs that coexist in the 3.1 to 10.6GHz.
The proponents of the ultra wideband technology have claimed that the system has the ability to utilize the frequency spectrum without causing any interference problem to other conventional communication systems, because it has a low power spectral density. Fig. 1.1 shows spectrum utilization of UWB system and conventional narrowband system.

![Fig.1.1. Illustration of spectrum utilization by UWB systems](image)

### 1.4.1 Overview of Ultra-Wideband Communications

In today’s world, although it is most common to use sinusoidal signals in wireless communication systems, the earliest electromagnetic communication systems were actually based on pulses [23].

The spark gap generator is known to be the first UWB radio that was used by Hertz and Marconi in the late 1800’s [24]. Heinrich Hertz used the spark gap to produce electromagnetic waves for his experiments in 1893. Similarly, Marconi used spark gap generator for electromagnetic data communications [25].
Marconi’s spark-gap transmission experiments in 1901 were one of the first experiments about impulse radio. Additionally, Sommerfeld first analyzed the diffraction of a short pulse by a half-plane which is known to be one of the fundamental problems in UWB wave propagation [26]. Therefore, it can be assumed that the first practical UWB systems and theoretical research on UWB radiation goes back to more than a century ago. Nevertheless, the signals generated by the spark-gap transmitters had low spectral efficiency and low bit rate but large bandwidth [27]. During that period, researchers could not utilize this issue and it was perceived as a failure. Therefore, the communications became mainly narrowband after 1910, and ultra wideband research did not get any more interest until the 1960s when the studies began again for time domain electromagnetics with the innovative work of Gerald F. Ross.

In his studies, Ross described the transient behavior of microwave networks through their characteristic impulse responses. Also around this time, the sampling oscilloscope was developed by Hewlett Packard and some techniques were built up for subnano second (baseband) pulse generation. This allowed the analysis of short duration signals in the time domain experimentally and provided the direct observation and measurement of the impulse response for microwave networks.

When the techniques for impulse measurement were developed also for designing wideband antenna structures, researchers recognized that short pulse radar and communication systems could be built up utilizing the same equipments.

Afterwards, the main interest moved towards the techniques for the development of radar and communication devices. Designing high power, short pulse generators for UWB radar systems was investigated by the military. In particular, radar got a lot of interest because it was possible to obtain results
with good accuracy. The low-frequency components were useful in penetrating objects, and ground penetrating radar was developed.

In the 1970s, ultra wideband communications started to get more attention [28]. Ross developed various applications for radar and communications at the Sperry Research Center. In April 1973, he was awarded the first UWB communications patent. Therefore, in the 1970s and 1980s, most of the research and development were in the military or in the works funded by the US Government.

One of the earliest applications of UWB technology was high power military radar. Also, low probability of intercept capability of UWB signals is utilized for covert communications and use of a very wide band of frequencies allowed detection of buried mines in ground penetrating radar applications. The term ultra-wideband was first applied around 1989 by the U.S. Department of Defense and this technology was earlier referred to as baseband carrier-free or impulse radar.

Small companies such as Multispectral Solutions, Inc., Aether Wire and Location, and Pulson Communications (Time Domain Corporation) also started basic research and development on communications and positioning systems, specializing in UWB technology, beginning in the late 1980s [29]. By the mid-1990’s, University of Southern California’s UltRa Lab was established. UltRa Lab lobbied FCC to allow commercializing the UWB technology.

In May 1998, a workshop sponsored by US Army Research Office and USC UltRa Lab was organized and soon after this conference, the companies working on UWB technology decided to band together and formed an informal industry association, Ultra-Wideband Working Group (http://www.uwb.org).

In the late 1990s, there has been a lot of interest regarding the application of UWB technology for wireless communications. Companies such as Time
Domain Corporation, US Radar, Zircon Corporation had requested for permission from FCC to develop a small number of commercialized UWB devices. At the same time, USC’s UltRa Lab acquired a license from FCC for experimental studies on UWB radio transmissions.

Since UWB signals occupy a large frequency range, they violate the frequency regulations assigned to other conventional narrowband systems all over the world. However, proponents of the technology in both industry and academia insisted that UWB emissions would not interfere with those other narrowband services. Then, after lengthy deliberations, the FCC issued its first report and order on UWB technology in April 2002[30]. In this ruling, it is specified that the UWB emission is allowed between the frequency ranges of 3.1 GHz and 10.6 GHz. Since the late 1990s, the research and development of ultra wideband technology have widely emerged and become a promising technology which came to be known as impulse radio.

1.4.2 UWB antenna characteristics

In 2003, a history of UWB antennas is presented by H.G. Schantz who emphasizes the relevant past works on UWB antennas and their important wide variety [31]: “Ultra-Wideband has its roots in the original spark-gap transmitters that pioneered radio technology. This history is well known and has been well documented in both professional histories and in popular treatments. The development of UWB antennas has not been subjected to similar scrutiny. As a consequence, designs have been forgotten and then re-discovered by later investigators”. Thus, in the recent years, a lot of UWB antenna designs have been reported and presented in the academic literature (32; 33; 34) and in some patents (35).
An antenna is a device that converts a signal transmitted from a source to a transmission line into electromagnetic waves to be broadcasted into free space and vice versa. An antenna is usually required to optimize or concentrate the radiation energy in some directions and to suppress it in the others at certain frequencies. A good design of the antenna can relax system requirements and improve overall system performance. In practice, to describe the performance of an antenna, there are several commonly used antenna parameters, such as impedance bandwidth, radiation pattern, directivity, gain, input impedance, and so on.

However, UWB antennas are firstly antennas! As a consequence, UWB antennas try to achieve the same goals, and are subjected to the same physical constraints (e.g., low cost, small size, integration capability, etc.) and the same electrical constraints (e.g., impedance matching, radiation pattern, directivity, efficiency, polarization, etc.) as in the case of narrowband antennas. Further, due to the large bandwidth, the electrical parameters become frequency dependent complicating the design and analysis. In addition to the conventional characterization parameters, some specific parameters must be examined in order to take into account the distortion effects, notably, critical for IR applications. These specific parameters include group delay, phase response and impulse response. The radiation pattern is desired to be constant within the overall operating frequency in order to guarantee the pulse properties to be same in any direction. The group delay is given by the derivative of the unwrapped phase of an antenna. If the phase is linear throughout the frequency range, the group delay will be constant for the frequency range. This is an important characteristic because it helps to indicate how well a UWB pulse will be transmitted and to what degree it may be distorted or dispersed.
The specifications of the antenna design will be a trade-off of these parameters taking into account not only the expected application but also the technique of transmission (multiple narrow bands or pulsed operation) to be used. Some parameters have to be declared more important than others. Two types of requirements can be distinguished. The physical constraints arise when one strives to develop antennas of small size, low profile and low cost (materials, maintenance and fabrication), and with embeddable capability. The electrical constraints arise while designing antennas with wideband impedance bandwidth covering all sub-bands (for MB-OFDM) or the bandwidth where most of the energy of the source pulse is concentrated (for IR), steady directional or omni-directional radiation patterns, constant gain at directions of interest, constant desired polarization.

UWB antennas may be categorized into different types according to their radiating characteristics: frequency independent antennas, multi-resonant antennas, travelling wave antennas and small element antennas.

1.4.2.1 Frequency independent antennas

Frequency independent antennas, such as biconical, spiral, conical spiral and log periodic antennas are classic broadband and UWB antennas. They can offer real constant impedances and consistent pattern properties over a frequency bandwidth greater than 10:1. There are two principles for achieving frequency independent characteristics.

The first one was introduced by V.H Rumsey in the 1950s. Rumsey’s principle suggests that the pattern properties of an antenna will be frequency independent if the antenna shape is specified only in terms of angles. Infinite biconical and spiral antennas are good examples whose shapes are completely described by angles. For the log periodic antennas, the entire shape is not solely specified by angles rather it is also dependent on the length from the origin to
any point on the structure. However, the log periodic antennas can still exhibit frequency independent characteristics. Fig. 1.2 illustrates the geometry of spiral, log periodic and conical spiral antennas.

The second principle accounting for frequency independent characteristics is self complementarities, which was introduced by Mushiake in the 1940s derived from the Babinet’s principle in optics. Mushiake discovered that the product of input impedances of a planar electric current antenna (plate) and its corresponding “magnetic current” antenna was the real constant $\frac{\eta^2}{4}$, where $\eta$ is the intrinsic impedance of free space. Hence, if an antenna is its own complement, the frequency independent impedance behavior is obtained. In Fig. 1.2 (a), if the lengths W and S are the same, i.e., the metal and the air regions of the antenna are equal; the spiral antenna is self-complementary. Fig. 1.2 (d) shows the geometry of a logarithmic spiral antenna.

![Fig. 1.2(a) Spiral antenna; (b) Log periodic antenna (SAS 510-7 from A.H. Systems Inc); (c) Conical spiral antenna; (d) Logarithmic spiral antenna.](image-url)
Although the frequency independent antennas can operate over an extremely wide frequency range, they still have some limitations. Firstly, to satisfy Rumsey's requirement, the antenna configuration needs to be infinite in principle but, in practice, it is usually truncated in size. This requirement makes the frequency independent antennas quite large in terms of wavelength. Secondly, the frequency independent antennas tend to be dispersive because they radiate different frequency components from different parts of the antenna, i.e., the smaller-scale part contributes higher frequencies while the large-scale part accounts for lower frequencies. Consequently, the received signal suffers from severe ringing effects and distortions. Due to this drawback, the frequency independent antennas can be used only when the waveform dispersion may be tolerated.

1.4.2.2 Multi-resonant antennas

Multi-resonant antennas are composed of an arrangement of multiple narrowband radiating elements. This type of antenna includes log periodic antennas, Yagi antennas (Fig. 1.2(b)). Planar versions of these antennas also exist. Although these antennas are UWB, yet they are not convenient for IR-UWB systems because their phase centers are not fixed in frequency and therefore exhibit dispersion.

1.4.2.3 Travelling wave antennas

Travelling wave antennas include horn antennas, tapered slot antennas and dielectric rod antennas. These antennas feature a smooth and gradual transition between a guided wave and a radiated wave, and have good properties for UWB. Horn antennas constitute a major class of UWB directional antennas and these are commonly used for measuring radiation patterns or for ground penetrating radar applications. They consist of rectangular or circular waveguides which are inherently broadband. Their bandwidth is relatively large, i.e., 50% - 180%. These antennas present very good polarization, very low dispersion and
very low variation in phase center versus frequency. Fig. 1.3 (a) shows a double ridge horn antenna as an example.

The Tapered Slot Antenna (TSA) is another important class of UWB directional antennas. A typical TSA consists of a tapered slot that has been etched in the metallization on a dielectric substrate. The profile of tapering may take different forms: linear tapered slot antenna (LTSA), constant width slot antenna (CWSA), broken linearly tapered slot antenna (BLTSA) or exponentially tapered slot antenna (Vivaldi) as shown in Fig. 1.3 (b). The TSAs are adapted to a wide bandwidth of 125% - 170%. Their radiation pattern is unidirectional in the plane of the substrate and has a low level of cross-polarization. The directivity increases with frequency and the gains achieved by these antennas can go up to 10 dBi depending on the type of profile.

1.4.2.4 Small element antennas

Small-element antennas include Lodge’s biconical and bow-tie antennas, Mater’s diamond dipole, Stohr’s spherical and ellipsoidal antennas, and Thomas’s circular dipole. These antennas are direct evolution of monopole and the basic dipole (doublet of Hertz). Antenna engineers discovered that, starting from a dipole or monopole antenna, thickening the arms results in an increased
bandwidth. Thus, for a thick dipole or monopole antenna, the current
distribution is no longer sinusoidal and where this phenomenon hardly affects
the radiation pattern of the antenna, there this strongly influences the input
impedance too. This band widening effect is even more severe if the thick
dipole takes the shape of a biconical antenna.

1.4.3 UWB Transmission Schemes

Although the FCC has regulated the spectrum and transmitter power
levels for a UWB, there is currently no standard for a UWB transmission
scheme. Various pulse generation techniques have been proposed to use the 7.5-
GHz license-free UWB spectrum. Generally, UWB transmission approaches
can be categorized into two main approaches: single-band and multiband.
Figure 1.4 illustrates UWB signals in the time and frequency domains when
single and multiband approaches are employed.

Essentially, UWB communications comes in one of two types,

**Single Band**: Impulse radio falls in the category of single band UWB system
and is based on sending very short duration pulses to convey
information. In impulse radio, the signal that represents a symbol
consists of serial pulses with a very low duty cycle. The pulse width
is very narrow, typically in nanoseconds. As a result it has a better
resolution of multi path in UWB channels. The small pulse width
gives rise to a large bandwidth as shown in Fig.1.4(a). The high
instantaneous power during the brief interval of the pulse helps to
overcome interference to UWB systems, but increases the possibility
of interference from UWB to narrow band systems. Simple I-UWB
systems can be very inexpensive to construct as it eliminates the need
for up and down conversion and allows low-complexity transceivers.
**Multi Band:** Since UWB can be any technique that generates signals occupying at least 500MHz of bandwidth within the spectrum mask placed by FCC, the UWB systems can also be classified as multiband based. Here, the 7500MHz of unlicensed spectrum can be considered to provide a number of UWB “bands” as shown in Fig.1.4(b) and can be exploited in many ways like by using multi-carrier (MC) or OFDM modulation with Hadamard or other spreading codes. MC-UWB is particularly well-suited for avoiding interference because its carrier frequencies can be precisely chosen to avoid narrow band interference to or from narrow band systems.

![Spectrum of a Gaussian Doublet](image1.png)

**Fig. 1.4:** Comparison of (a) Impulse and (b) Multi carrier UWB spectrums.
Impulse radio faces the very important challenge of coexisting with existing narrowband systems. To mitigate the effects of narrow band interferers, notch filters are required in impulse radios. However, use of such filters may distort a received signal. Multi banded UWB on the other hand, can avoid transmitting on the frequency bands where other wireless systems like 802.11a are present by not using those frequency bands. This approach has the additional benefit of being able to adapt to the different regulatory requirements of various countries due to the flexibility of multi band allocation.

Short duration of the pulses in impulse radio presents several technical challenges as well. The generation of pulses that fit into the spectral mask imposed by regulatory bodies is difficult and their short duration makes them more susceptible to timing jitter. Supporting higher data rates will involve increasing the pulse PRF either by using higher-order modulation or by using spread spectrum technology. The first option makes the system more vulnerable to ISI. The second would increase the peak-to-average power ratio and impose greater linearity requirements on the circuits. The last option requires careful selection of the properties of the codes.

In multi banded UWB, the pulses are not as short. So, the PRF can be lower than that of impulse radio at the same peak power, diminishing the effects of ISI and timing jitter. This approach also eases the requirements of pulse shaping filters and avoids the use of notch filters. Scaling can be achieved by simply adding more bands. Furthermore, more multiple access schemes like FDMA and CDMA are available.

The longer duration of the pulses in a multi banded system lead to milder ISI and equalization requirements, but may also require the suppression of adjacent channel interference. In addition, the number of resolved multipath
components increases as the bandwidth increases. Thus, the number of rake fingers needed for the impulse-based approach is around ten times more than the multi banded approach for a given Signal to Interference Ratio (SIR), leading to a more complex receiver.

These challenges faced by impulse radios have made UWB solution providers and developers to look toward to a multiband approach for their systems. This approach has much greater flexibility in coexisting with other wireless systems and is based on more conventional technology.

1.4.4 UWB regulation and standards

In USA, the FCC approved a UWB spectral mask specified 7.5 GHz of usable spectrum bandwidth between 3.1 GHz and 10.6 GHz for communication devices and protected existing users operating within this spectrum by limiting the UWB signal’s EIRP level of -41.3 dBm/MHz (known as Part 15 Limit). In this restriction, the limitation of the power spectral density (PSD) measured in a 1 MHz bandwidth at the output of an isotropic transmit antenna to a spectrum mask is shown in Figure 1.5 for indoor and outdoor environments, respectively.

The FCC issued in April 2002 UWB Regulations, under Part 15 of the Commission’s rules, permitting ultra-wideband intentional emissions subject to certain frequencies and power limitations that will mitigate interference risk to those sharing the same spectrum. UWB signals may be transmitted between 3.1 GHz and 10.6 GHz at power levels up to -41 dBm/MHz, with higher degree of attenuation required for the out of band region for outdoor communication.
Introduction

Although UWB currently is legal only in the United States, international regulatory bodies are considering possible rules and emission limits that would help it enable worldwide operation of UWB devices. Fig. 1.6 shows the graph of the worldwide spectrum mask that is defined now for UWB communication devices. There is difference in EIRP levels among USA, Europe, Japan and Singapore. In some countries, there is an exclusive obligation to protect the existing communication systems. Countries that have a sole obligation to protect existing users tend to be much more conservative in international fora that are designed to achieve spectrum harmonization, such as the international Telecommunication Union (ITU). Therefore, it is extremely necessary to gain compromises and agreement among all of them for making the international UWB policy because UWB is not only a new technology but also a new regulatory paradigm. In the processes of the compromise for UWB policy, there are two useful technologies to prevent the interference with other signal. One is Detect and Avoid (DAA) and the other is Low Duty Cycle (LDC). The former
is a technology to mitigate interference potential by searching for broadband wireless signals and then automatically switching the UWB devices to another frequency to prevent any conflict. The latter reduces interference with other signal by using the UWB signal with very low duty cycle.

Fig. 1.6 The worldwide spectrum masks for UWB communication devices

1.4.5 Advantages and Limitations of UWB

The main advantages and benefits of UWB systems can be summarized as follows:

In military communications, there are many potential threats about the security of the signal. Ultra wideband signals are usually at noise floor level due to the very large spreading factor. Therefore they provide low probability of detection for military communication and cannot be detected using conventional receivers.
Also, UWB signals immune to jamming and interference from other radio systems because of the large spreading factor.

In UWB communication system, the pulses can easily penetrate walls, doors, and other objects. Since UWB signals contain significant low frequency components, it has the ability to penetrate materials that are normally more resistive to higher frequencies.

The extremely high transmission bandwidth of an UWB signal provides very accurate timing information to be resolved. Accurate range measurements and positioning can be achieved due to the resolving capability of multipath. This ability combined with the penetration through materials makes UWB suitable for accurate positioning applications.

Multiple users can transmit simultaneously on the same frequency range as long as they use different spreading codes. Due to the very large spreading gain of UWB systems, it can enable multiple access capability and a large number of users can be fitted in a UWB system.

Since the UWB technology is the transmission and reception of baseband signals, its complexity is relatively low and it provides inexpensive implementation compared to conventional narrowband systems. UWB systems do not require RF modulators and demodulators in the transmitter and receiver design. The absence of RF & IF stages, linear amplifiers, and the required filters reduces the complexity and the cost of the system.

Another advantage of UWB transmission for communications is its high data rate. Higher data rates can enable new applications and devices. The extremely large bandwidth occupied by UWB gives this potential.
The main disadvantages and limitations of UWB systems can be summarized as follows:

UWB antennas need to be optimized over a wide range of frequencies such that the antennas employed in UWB systems are required to efficiently radiate electromagnetic signals over several gigahertz bandwidth. This makes the design procedure more complicated than for other conventional narrowband antennas. The transmission range of an UWB radio is very limited without use of a power amplifier. Designing small-size, efficient wideband power amplifiers and directional antennas is still a challenge even though medium-range communications using low-power UWB signals is claimed to be possible.

Since UWB extends over an extremely wide bandwidth, many other wireless systems would be affected and need to be convinced that UWB will not cause too much interference to their existing services. Although it has been claimed that the interference between UWB and other systems is minimal, a large amount of UWB transmissions could still cause a problem for systems such as GPS. Moreover, if higher power UWB signals are used for longer range transmissions, the interference problem may arise.

1.4.6 UWB Applications

FCCs First Report and Order permits the marketing and operation of certain type of new products incorporating ultra-wideband technology. Depending on the operational characteristics and the potential for causing interference to other services, each system is allowed to operate in their allocated frequency bands. According to these restrictions, the FCC report categorizes UWB devices into following categories: imaging systems, communications and measurement systems, and vehicular radar systems.
Ground penetrating radar systems (GPRs), wall imaging systems, through wall imaging systems, and medical systems can be included in the imaging systems.

GPRs are used for detecting the buried objects. The operational frequencies are required to be below 960 MHz or in between 3.1-10.6 GHz. Law enforcement, fire and rescue, scientific research institutions, mining companies, and construction companies are placed in this category.

Medical systems are used for health care applications to observe the location or movement of objects inside the body of a human or animal. These systems must operate in the frequency band 3.1-10.6 GHz. Operation must be carried out under the guidance of licensed health care practitioners.

Communication and measurement systems include devices that are subject to certain frequency and power limitations under the Part 15 of the FCC’s rules. UWB high-speed home and business networking devices, storage tank measurement can be included in this group. The operational frequency band is 3.1-10.6 GHz.

Vehicular radar system devices are used to detect the location and movement of objects near a vehicle. They operate in 24 GHz band using directional antennas on terrestrial transportation vehicles. The center frequency of the emission and the frequency at which the highest radiated emission occurs are greater than 24.075 GHz.

1.5 Motivation for the work

The UWB technology has undergone remarkable achievements during the past few years. In spite of all the promising prospects featured by UWB, there
are still challenges in making this technology fulfill its full potential. One particular challenge is the UWB antenna.

In recent years, many varieties of UWB antennas have been proposed and investigated. They present a simple structure and UWB characteristics with nearly omni-directional radiation patterns. However, for some space-limited applications, UWB antennas need to feature a compact size while maintaining UWB characteristics. Therefore, miniaturization of UWB antennas becomes an interesting research topic and deserves a comprehensive investigation and analysis.

The issues concerning interference between wide band devices with other existing narrow band communication networks can be sorted by implementing filters to notch out the required frequency bands. However, since additional filters would increase the size of the devices, embedded filters on the antenna is preferred.

Consumer electronics like wireless USB & next G bluetooth applications requires narrow planar antennas with a width of \( \approx 11 \) to 24mm. However, with the reduction of antenna size, impedance bandwidth degrades. Since compact antennas show significant ground plane length/shape effects on its performance, it is important to design antennas resistant to it. The conflicting requirements of good performance and compact size make the design of such antennas challenging.

The aim of the thesis is to investigate the requirements for a wide band behavior of compact planar antenna designs. This work looks in detail the wide band performance of the monopole and slot antennas and identifies the design parameters of the same. Several novel designs on commercially available
microwave substrates are proposed that could be successfully implemented in consumer electronics applications. It is important to characterize the designed UWB antennas in terms of their transient performance. To throw light on their suitability for pulse communications, their time-domain behavior is studied in the final part of the thesis.

The shortcoming of the planar antenna designs, usually reported, is that they are based on the lengthy trial and error method that involves computationally intensive full wave electromagnetic simulations. When one decides to design an antenna using a different dielectric substrate, the time consuming design process has to be fully repeated. In such circumstances, the designers are interested in having simple design formulas that provide a very good approximation to the final design when sophisticated EM analysis and design software packages are applied. This thesis addresses this issue and provides simple design formulas, which are suitable for the antennas designed. It is shown that the antenna design parameters obtained using the equations developed in this thesis do not differ much from the optimized values obtained using the commercial software.

1.6 Thesis Organization

Chapter 1 gives the introduction of the thesis. This chapter gives basic information about UWB technology and also the history of research in the field of UWB antennas. The motivation of the work and thesis organization is also included in this chapter.

Chapter 2 starts with the methodology used for developing the antennas reported in this thesis. Measurements in the frequency domain such as return loss, radiation pattern, gain are explained. The relevant theory behind the time domain characterization of the antenna, are deduced from the measurements,
are explained. Then a detailed literature review about monopole UWB antennas is conducted.

Chapters 3 & 4 concentrate on UWB Monopole and Slot antennas respectively. In this section, a common approach is followed for the antenna development. The chapters begin with a detailed literature review of the available designs belonging to this broad category, followed by a description on the evolution of the antennas. The proposed antenna designs are simulated and their resonant modes are identified. The antennas are CPW-fed for easy fabrication and better integration with monolithic microwave circuits except in some cases where it is microstrip-feed. The surface current and field distributions on the antenna at the resonant modes and their corresponding radiation patterns are analyzed in detail.

The results of the analysis along with the parametric studies have enabled to deduce their design equations and design methodologies on any substrate for the desired operating frequencies. The measured results of the fabricated antennas are then plotted with their corresponding simulated results which are found to conform well in all cases. Further, to notch out selected narrow band frequencies in the wide operating band, thin slot resonator is embedded in the serrated monopole antenna.

There are two novel compact designs of planar monopole antennas presented in chapter 4: a ground modified antenna and a serrated antenna. These antennas perform well in terms of its impedance match and gain, over a wide band and easily comply with the FCC UWB frequency band of 3.1 to 10.6GHz. The radiation patterns are omni-directional but in case of ground modified antenna they are distorted at the higher end of the spectrum. This is overcome a little bit by the serrated antenna which has the advantage of a compact size as
well. A band notched serrated antenna to notch out the 5.8GHz WLAN band by etching a inverted U slot from the patch is also presented. Electronic reconfiguration of the notch band by integrating a PIN diode across \( \lambda/2 \) inverted ‘U’ slot is also demonstrated. A CPW fed serrated monopole antenna is also developed and presented.

The triangular slot antenna developed in chapter 4 overcomes the problem of pattern deterioration at higher frequencies observed in the case of monopole antennas. Antenna structure is compact and covers the FCC specified UWB band. To reduce the interference with the conventional WLAN, a notch band is also introduced.

In the final sections of chapters 3&4, the influence of the antenna on radiation of a UWB pulse to confirm their suitability for I-UWB applications is investigated. The transfer function measurements are performed in the azimuthal plane and their impulse responses are deduced. The influence of the antenna on pulse transmissions is evaluated by convoluting the impulse response with a UWB pulse. The time domain distortions for the different designs are then characterized in terms of mathematically tractable parameter Fidelity.

Finally the thesis is concluded in Chapter 5, by compiling the overall work and their results along with a brief description on the scope for future study.
References


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