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UWB antennas: design and modeling

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1. Introduction

1.1 Brief history of antennas and their evolution

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 the IEEE standard definitions of terms for antennas (IEEE, 1993), 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 wire antennas were inaugurated in 1842 by the inventor of telegraphy, Joseph Henry who had also discovered electromagnetic waves and had even formulated the idea that light waves were of this type. About forty years later, the antennas and the first wireless systems emerged. In 1885, Edison patented a communication system using vertical, top-loaded and grounded antennas. In 1887, Hertz launched, processed and received radio using a balanced or dipole antenna as a transmitter and a one-turn loop containing a spark gap as a receiver. The invention of antenna is credited to Popov who proposed a device capable of detecting electromagnetic waves in the atmosphere and introduced the concept of antenna in 1895. The initial concepts of phase arrays were proposed in 1889. Several advances in antennas were patented in 1897 by Lodge and these contributions yielded matching, tuning, and addition of the word "impedance" to the language. Finally, the first most significant application was the telegraph of Marconi patented in 1900.

Many decades after these early investigations, the antenna has drawn a lot of attention over the years and has remained a subject of numerous challenges. Although dipole and loop antennas are still widely used for various radio systems, yet the antennas have been evolved remarkably with respect to both their topologies and usages. 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 (Walter, 1990; Agrawal et al., 1997; Amman & Chen, 2003a; Islam, 2009).

The second factor deals with field pattern and the ways to control it. One method is to use a multitude of identical radiating elements to form an array. The elementary antennas are fed from a single source through a network of transmission line and/or waveguides. In such systems, the shape of the radiation pattern is governed by the field pattern of the elementary antenna (which is chosen to be as simple as possible), the power distribution among the elements and geometric details of their arrangement. Many examples are available in the literature (Chang, 1997). Even if the arrays were initially designed for high power purposes using bulk antennas, but their developments in planar and integrated forms using microstrip patches are more attractive (Munson, 1974). The third factor deals with isotropic behavior, i.e., the ability of antennas to radiate equally in all directions. Indeed in the context of wireless sensor networks, radio frequency identification or millimetre-length communications, the random and time-varying orientations of the devices with respect to each other cause strong variations of the transmitted signal due to the radiation anisotropy and polarization mismatches of antennas. Ad-hoc sensor networks for human motion capture systems based on wearable sensors as well as the localization of mobile objects are typical upcoming applications requiring quite constant received power whatever be the orientations of devices relative to each other (Puccinelli & Haenggi, 2005). Directions of departure and arrival of a beam can totally change while in use and fall into antenna radiating null. Polarization mismatches can also cause fading of the transmitted power. It is therefore difficult to maintain the quality of service. Isotropic antenna is a hypothetical idealized device that does not exist in reality (Mathis, 1951). A close approximation can be a stack of two pairs of crossed dipole antennas driven in quadrature. When space has to be covered in all directions, smart antennas with pattern and polarization agility are required. However, for many applications, generalizations of adaptive smart antenna are still far away due to their high cost or power consumption or because of size and integration issues. Consequently, there is a need for small antennas with optimized radiation pattern and polarization to provide wide coverage. One method to obtain quasi-isotropy behavior is to associate several elementary antennas in complementary way in terms of fields and polarization. The concept of spatial coverage factor as well as its application to a quasi-isotropic antenna has been introduced (Huchard et al., 2005). 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 (Mitola, 1995; Mitola and Maguire, 1999). 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.

1.2 Ultra Wideband technology

Ultra Wideband (UWB) is an emerging technology for future short-range wireless communications with high data rates as well as radar and geolocation (Yang & Giannakis, 2004). Indeed, the use of large bandwidths offers multiple benefits including high date rates, robustness to propagation fading, accurate ranging and geolocation, superior obstacle penetration, resistance to jamming, interference rejection, and coexistence with narrow bandwidth systems. It should be noted that the first UWB signals were generated in experiments by Hertz who radiated sparks via wideband loaded dipoles. However, this type of communication was abandoned at that time due to non-availability of resources to recover the wideband energy effectively. Later during the 1960s and 1970s, impulse radio technologies were being used to develop radar, sensing, military communications and niche applications. A landmark patent in UWB communications was submitted by Ross in 1973. However, it was in 1989 that the term "Ultra Wideband" appeared in a publication of department of defense in the United States (U.S.) and the first patent with the exact phrase "UWB antenna" was filed on behalf of Hughes in 1993. Thus, interest in UWB was revived in the 1990s thanks to the improvements in digital signal processing and notably the investigation on Impulse Radio (IR) by Win and Scholtz (Win & Scholtz, 1998). Finally, it was in 2002 when the interest for UWB systems was greatly magnified by the decision of the United States frequency regulating body, the Federal Communications Commission (FCC), who released a report approving the use of UWB devices operating in several unlicensed frequency bands [0-960 MHz], [3.1-10.6 GHz], and [22-29 GHz]. Since then, regulations were defined through notably emission spectral masks around the world,. In Europe, the Electronic Communications Committee (ECC) has proposed its most recent proposal in April 2009. In contrast to the FCC's single emission mask level over the entire UWB band, this report proposed two sub-bands with the low band ranging from 3.1 GHz to 4.8 GHz (authorized until 2011 with mitigation techniques included to ensure coexistence) and the high band from 6 GHz to 8.5 GHz. The upper bound for Effective Isotropic Radiation Power (EIRP) is common and has been set out to be - 41.3 dBm/MHz. Even if the authorized frequency bands are different according to the world regions, the definition of UWB is universal. UWB describes wireless physical layer technology which uses a bandwidth of at least 500 MHz or a bandwidth which is at least 20% of the central frequency in use. Two approaches have been developed for UWB systems: pulsed operation and multiple narrow bands. Among these techniques, the original approach is based on IR concept. Impulse Radio refers to the use of a series of very short duration pulses, which are modulated in position or/and amplitude. As signals are carrier-less, i.e., only baseband signals exist; therefore no intermediate frequency processing is needed. Alternative schemes are Multi-Band Orthogonal Frequency Division Multiplexing (MB-OFDM) and Multi-Carrier Code Division Multiple Access (MC-CDMA).

To guarantee the coexistence of UWB with other communication standards, the authorized transmitted power is always very low which limits the development of UWB communication systems with very high data rates and/or the coverage of larger distances. The association of Multiple Input Multiple Output (MIMO) systems (which exploit rich scattering environments by the use of multiple antennas) with UWB technology is more and more studied. It seems to be a very potential approach for enhancing capacity, increasing range, raising link reliability and improving interference cancellation (Siriwongpairat et al., 2004; Yang & Giannakis, 2004; Kaiser et al., 2006). Recent works have also shown the

prospects of using the UWB technology into the next generation RFID (Radio Frequency Identification) systems. Indeed, promises have been highlighted in order to achieve larger operating range, accurate localization, robustness to interference and more security in multiple access systems (Zou et al., 2007; Hu et al., 2007; Dardari & D'Errico, 2008). Further, when the wireless systems that are potential candidates for cognitive radio are considered, UWB seems to be one of the tempting choices because it has an inherent potential to fulfill some of the key requirements of cognitive radio (Manteuffel et al.; 2009). These requirements include no spurious interference to licensed systems, adjustable pulse shape, bandwidth and transmitted power, support of various throughputs, provision of adaptive multiple access, and security of information. However, it is not claimed that a cognitive wireless system using only the UWB technology can handle all the requirements of an ideal cognitive radio. Advances in reconfigurability of RF front-ends, particularly reconfigurable (multiple) antennas, afford a new "hardware" dimension for optimizing the performance of wireless communication systems (Sayeed & Raghavan, 2007).

The prospects of UWB are always growing, however, the future wireless systems using UWB technology involve many new challenges, especially, related to the design and modeling of UWB antennas. Section 2 presents an overview of different categories of UWB (single and multiple) antennas emphasizing their main properties. Section 3 focuses on the approaches for the characterization and modeling of UWB antennas. Conclusions and perspectives are presented in the last section.

2. Design of Ultra Wideband Antennas

2.1 UWB antenna properties

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.

Particularly, a UWB antenna is defined as an antenna having a fractional bandwidth greater than 0.2 and a minimum bandwidth of 500 MHz.

$$BW = 2\frac{f_H - f_L}{f_H + f_L} \geq 0.2 \quad \text{and} \quad f_H - f_L \geq 500\,\text{MHz} \tag{1}$$

where f_L and f_H are the frequencies defining the antenna's operational band. For example, an IR-UWB system, which would comply with the emission mask and operate within the 3.1-10.6 GHz frequency range allocated in U.S, needs an antenna achieving almost a decade of impedance bandwidth spanning 7.5 GHz.

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, high radiation efficiency and linear phase response (for IR).

2.2 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 (Schantz, 2003): "*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 (Schantz, 2005; Wiesbeck & Adamiuk, 2007; Chang, 2008) and in some patents (Akdagli et al., 2008). The main challenge to design a UWB antenna comes from the coverage of large bandwidth because the matching and energy transmission require to be verified for the entire bandwidth. However, the traditional trade-offs such as size vs. efficiency and size vs. bandwidth (Chu-Harrington limit) still influence the characteristics and performance of antennas.
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.

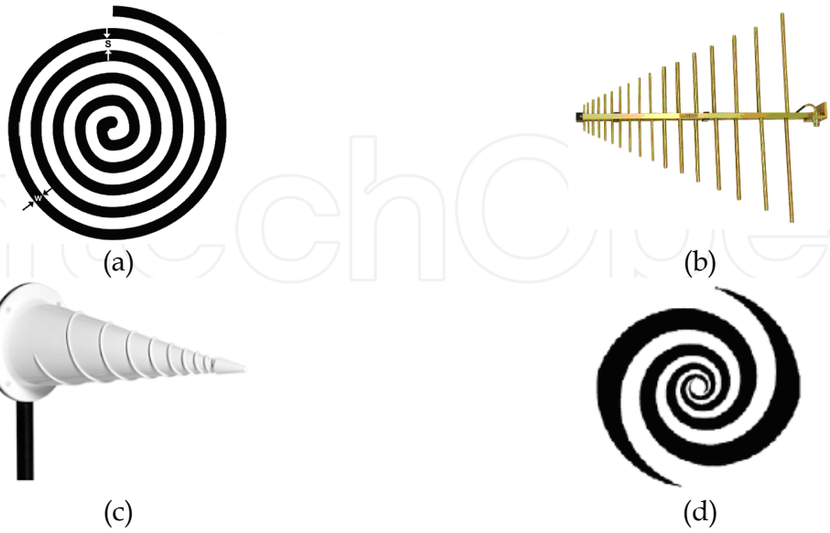
2.2.1 Frequency independent antennas

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 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 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 $\eta^2/4$, where η is the intrinsic impedance. Hence, if an antenna is its own complement, the frequency independent impedance behavior is obtained. In Fig. 1 (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 (d) shows the geometry of a logarithmic spiral antenna.

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.



(a) (b)

(c) (d)

Fig. 1. (a) Spiral antenna; (b) Log periodic antenna (SAS 510-7 from A.H. Systems Inc); (c) Conical spiral antenna; (d) Logarithmic spiral antenna.

2.2.2 Multi-resonant antennas

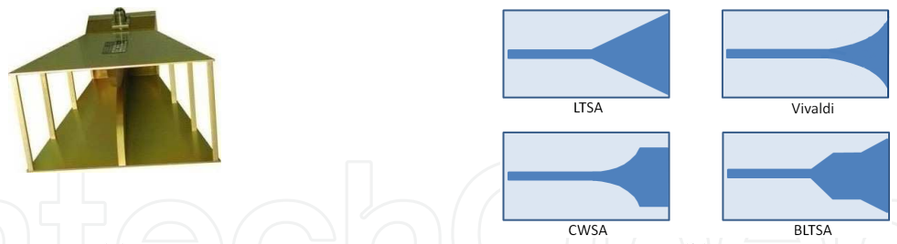
Multi-resonant antennas are composed of an arrangement of multiple narrowband radiating elements. This type of antenna includes log periodic antennas or Yagi antennas (Fig. 1(b)). Planar versions of these antennas also exist. Although these antennas are UWB, yet they are not convenient for IR-UWB systems because their phase centers are not fixed in frequency and therefore exhibit dispersion.

2.2.3 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. 2 (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. 2 (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.



(a) (b)

Fig. 2. (a) Horn Antenna – SA S571 A.H. Sys. Inc; (b) Tapered slot antennas.

2.2.4 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.

Fig. 3 (a) and Fig. 3 (b) show the evolution from a thin-wire dipole antenna towards a biconical antenna, which presents a frequency independent impedance response. Further evolution may be found in dipole and monopole antennas formed by spheres and ellipsoids (Schantz, 2005). The biconical antenna evolved towards a single cone (Fig. 3 (c)) which presents a limited well-matched impedance bandwidth but a stable phase center within the bandwidth. Thanks to these qualities, the discone antennas are applied for UWB channel measurements and UWB system testing. Fig. 3 (d) and Fig. 3 (e) show alternative possible asymmetrical structures. Another evolution of the biconical antenna is the bow-tie antenna, the flat version of the biconical antenna (Fig. 3 (f)). One of the poles can be transformed into a ground plane (i.e., an electrically large conducting plate) as shown in Fig. 3 (g).

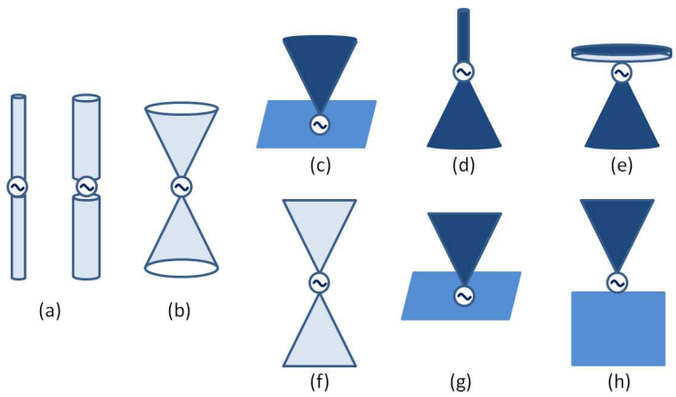


Fig. 3. Evolution of dipole, conical and planar antennas.

Fig. 3 (g) can be also considered as the evolution of the conventional monopole having a straight wire configuration against a ground plane. The monopole is one of the most widely used antennas for wireless communication systems due to its simple structure, low cost, omni-directional radiation patterns and ease for matching to 50 Ω (Balanis, 2005). Besides, it is unbalanced, thus it eliminates the need for a balun, which may have a limited bandwidth. The bandwidth of a straight wire monopole is typically around 10% - 20%, depending on the radius-to-length ratio of the monopole. When the monopole radius is too large related to the feeding line, the impedance mismatch between them becomes significant and the bandwidth cannot be further increased. Finally, a method to obtain bandwidth enhancement is to replace the wire element with a plate which is obviously much “fatter". This plate can take various configurations, such as triangle, circular, square, trapezoid, pentagonal, hexagonal, elliptical and so on (Fig. 4.). Circular and elliptical shapes present especially good broadband characteristics due to the smooth transition between the radiator and the feeding strip.

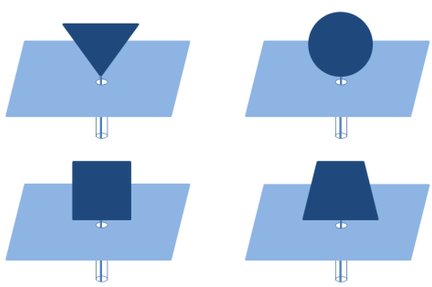


Fig. 4. Examples of triangle, circle, square and trapezoid monopoles.

These broadband monopoles feature wide operating bandwidths, satisfactory radiation properties, simple structures and ease of fabrication. Several techniques have also been proposed to improve the antenna bandwidth, for example, the use of a beveling plate (Ammann & Chen, 2003b), a double feed (Antonino-Daviu et al., 2003) or an asymmetrical feed arrangement (Ammann & Chen, 2003c), a trident-shaped feeding strip (Wong et al., 2005), etc. However, they are not planar structures because their ground planes are perpendicular to the radiators. This drawback limits their practical applications due to their large area.

Research focuses on antennas that can be easily integrated into other RF circuits as well as can be embedded in UWB devices. From 2004, works are intensified on planar and printed UWB antennas. The printed monopole antennas present wideband matching characteristic, omnidirectional radiation patterns, high radiation efficiency and compact size. Many microstrip UWB antenna designs were proposed. The planar radiators are etched onto the dielectric substrate of the printed circuit boards (PCBs). The ground plane may be either coplanar with the radiators or under the substrate. The radiators can be fed by a microstrip line and coaxial cable. Some examples of geometry of such antennas are given in Fig. 4. A printed planar circular disc monopole fed by a microstrip line is presented in Fig. 4 (a) (Liang et al., 2004). A printed planar elliptic patch presenting an impedance matching technique of creating a notch at the ground plane opposite to the microstrip line is illustrated in Fig. 4 (b) (Huang & Hsia, 2005). A rectangular patch with two steps and a slot to improve the impedance matching especially at high frequencies is shown in Fig. 4 (c) (Choi et al., 2004).

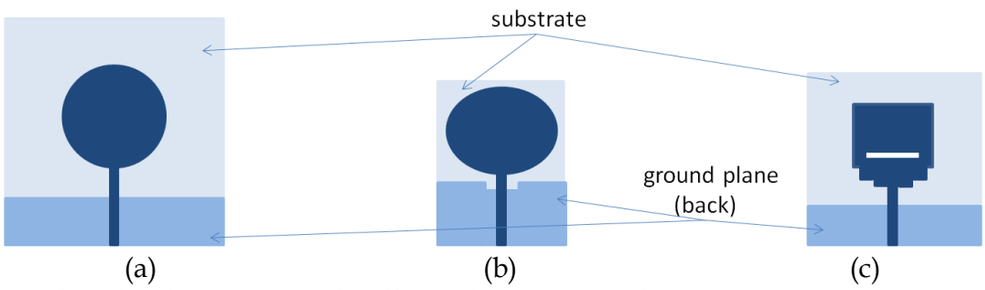


Fig. 4. (a) Circular disc antenna; (b) Elliptical antenna; (c) Square antenna.

2.3 Frequency notched UWB antennas

To prevent interference with existing wireless networks with standards, such as IEEE 802.11a wireless LAN in USA (5.15 GHz - 5.35 GHz, 5.725 GHz – 5.825 GHZ) and HIPERLAN/2 in Europe (5.15 GHz - 5.35 GHz, 5.47 GHz – 5.725 GHz), stopband characteristics of UWB systems are required. However, the use of an additional filter would increase the complexity of UWB systems. To tackle this problem, several novel UWB antennas with band-notched characteristic have been presented. The most popular and the easiest technique is to embed a narrow slot into the radiating patch in order to change the current flow on the metallic parts of the antenna. The slot may have different shapes, such as V-shaped (Kim & Kwon, 2004), U-shaped (Vuong at al., 2007), C-shaped (Lin & Hung, 2006), H-shapped (Bao & Amman, 2007), etc. Other possibilities in order to create a band-notched function are the insertion of strips in the patch (Lin & Hung, 2006), and the insertion of a function of filtering in or before the feed line of the antenna (Visser, 2007; Djaiz et al. 2009).

The compact band-rejected U-slotted planar antenna for IR-UWB presented below illustrates the concept of co-design approach, i.e., antenna and filter. This design is inspired from the planar UWB antenna proposed by Choi (Choi et al., 2004). Fig. 5 shows the geometry of the antenna. A U-Slot filter was added to reject the undesired frequency bandwidth. The antenna is fed by a 50 Ω microstrip line printed on a substrate with partial ground plane.

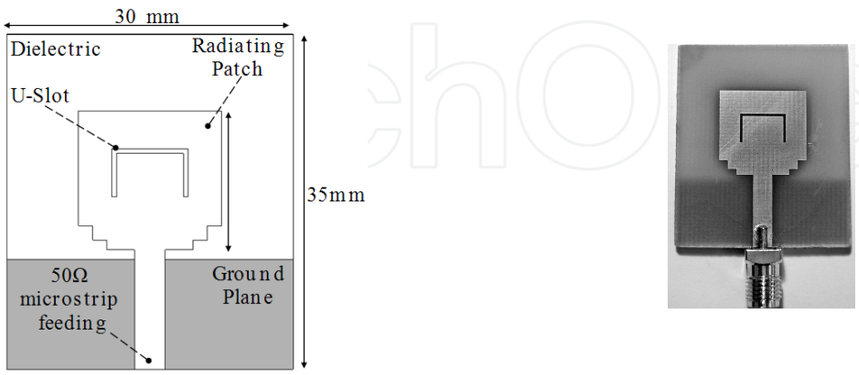


Fig. 5. UWB compact planar monopole antenna (Vuong et al., 2007).

Techniques applied to match the antenna over the UWB frequency band are: the use of two steps and a partial ground plane. The antenna was first studied without the U-Slot filter to operate in the overall UWB frequency band. Once the antenna was designed for operation within the overall UWB frequency band, the U-Slot filter is added to reject the undesirable 5.15 GHz to 5.825 GHz frequency band (Fig. 6).

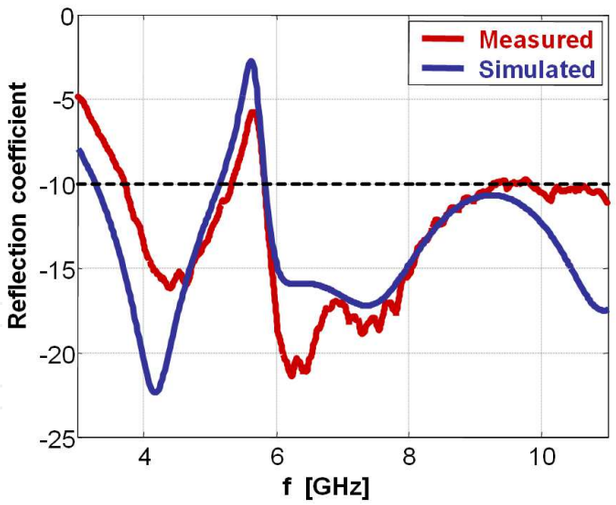


Fig. 6. Measured and simulated reflection coefficient.

Fig. 7 shows the surface current distribution at different frequencies. It can be observed on Fig. 7 (a) that the current concentrated on the edges of the interior and exterior of the U-Slot are opposed at 5.5 GHz. The rejected frequency occurs where the total U-slot length is equal to half the wavelength. Consequently, the antenna impedance changes at this frequency due to the resonant properties of the U-Slot. This leads to a high attenuation of the undesired frequencies. For other frequencies, the addition of the U-Slot filter has few effects.

(a) (b)

Fig. 7. Simulated current distributions. (a) 5.5GHz. (b) 7GHz.

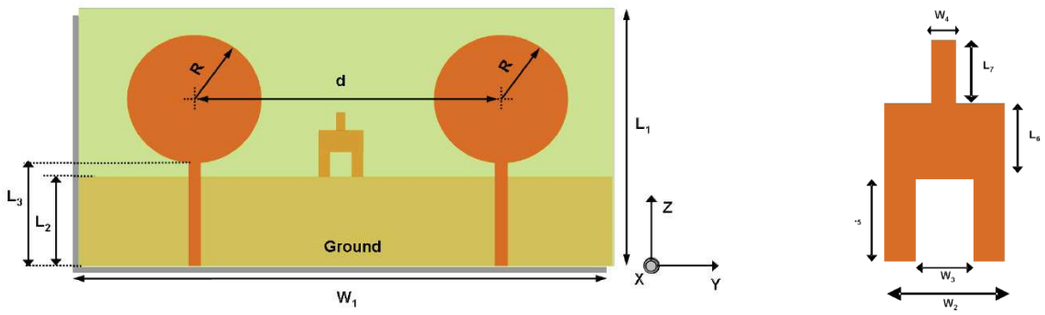
Finally, it should be noted that frequency-notched UWB antennas can also be used in multi-band systems, where the use of a single antenna that can function at potentially widely separated narrow bands of interest, is relevant for economic and cosmetic reasons (Schantz et al., 2003).

2.4 MIMO UWB antennas

Recent studies have demonstrated several advantages of using multiple antenna techniques in UWB wireless communications. Two main kinds of applications have been considered. First, instead of using one radiation element to cover the entire bandwidth, an approach is to use an antenna array in order to improve the global characteristics. The antenna array is made of several radiation elements, each covering a relatively narrow bandwidth, and the sum of their bandwidths fulfils the UWB requirements. The second application is the well-known MIMO technique for the narrowband systems: beamforming, spatial multiplexing and diversity coding techniques. Beamforming techniques use switched-beam smart antennas, adaptive beamformers (adaptive array smart antennas) or phased arrays in order to achieve beam-steering and to increase the signal gain by constructive interference, and finally to reduce the multipath fading effect. Spatial multiplexing exploits MIMO antenna configuration in order to increase the channel capacity; high data rates are achieved by transmitting parallel data streams in the same frequency spectrum. Diversity coding techniques emit a signal from each of the transmit antenna using a space-time coding. It provides signal diversity by exploiting the independent fading in the multiple antenna links. This section focuses on multi-antenna system composed of more than two UWB antennas operating over the same band to achieve the targets of high transmission speed and channel capacity by mitigating the effects of multipath, small-scale fading and co-channel interference. Like single antenna design, multiple-antenna systems are also ideally designed targeting planar geometry and compact size for the reason that it is easy to integrate with the radio devices. However, when the distance between antennas in the system decreases, mutual coupling between them increases causing a degradation of diversity performance. In this context, the main challenge in the design of MIMO antenna is to obtain the independence of each element from the others keeping their size as compact as possible. Research on MIMO antennas has always been carried out for the last several years and is still in progress. A number of MIMO antennas for portable devices have been presented in the literature. These antennas are of multimode, multi-polarized and/or array types exploiting pattern, polarization and/or spatial diversity respectively. The UWB-MIMO antennas have gained popularity very recently. Several strategies have been identified in

order to enhance the port isolations of the UWB multi-antenna systems: spatial and angular variations (Wong et al. 2008; Lin & Huang, 2008; Najam et al., 2009), diversity polarization (Mtumbuka et al., 2005; Adamiuk et al., 2009), vector antennas (Rajagopalan et al. 2007), use of stepped ground plane (Cheng et al., 2008), and insertion of stubs (Hong et al., 2008). Moreover, in these applications, it is generally desired to achieve quasi omni-directional radiating patterns and flat gain variations in the operating frequency bands.

From circular disc monopole antenna, the MIMO-UWB antenna, presented below (Fig. 8), has been designed and optimized to match the bandwidth defined by the FCC (i.e. 3.1–10.6 GHz), to achieve a reduced mutual coupling and enhanced isolation, and also to have a compact size. This antenna exploits the approach of using stubs on the ground plane in order to enhance isolation between the radiators.



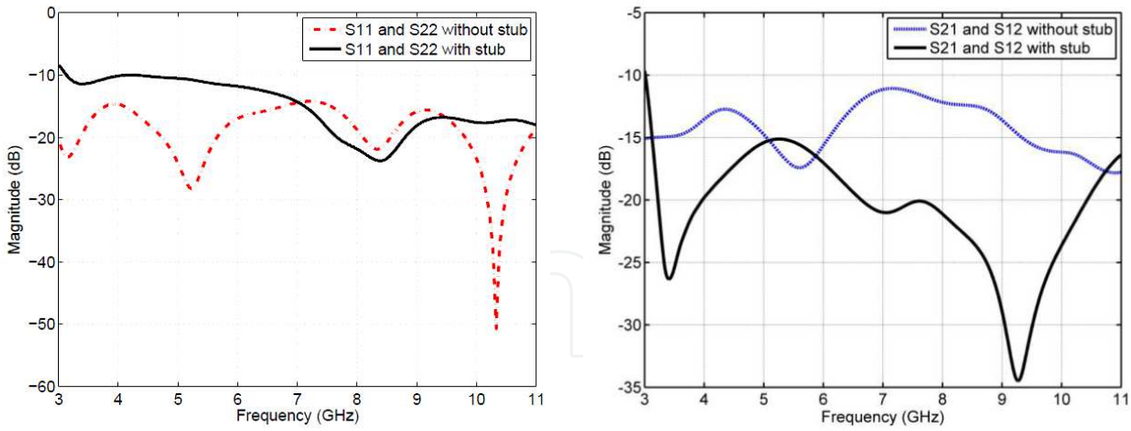
(a) (b)

Fig. 8. (a) Layout of UWB MIMO antenna: global view (L_1 = 40 mm; W_1 = 68 mm); (b) Layout of inverted-Y shaped stub.

The simulated reflection coefficients (S_{11} and S_{22}) for both radiating elements of antenna in decibels are shown in Fig. 9 (a). Due to the symmetry in the structure, S_{11} and S_{22} are the same. Fig. 9 (a) also presents the reflection coefficients of the antenna when there is no stub. It is noticed that the return loss is significantly changed at lower side of the operating band after adding the stub. Thus, it can be said that the return loss is sensitive to the insertion of stub on the ground, yet an impedance bandwidth of 3.2-10.6 GHz is available.

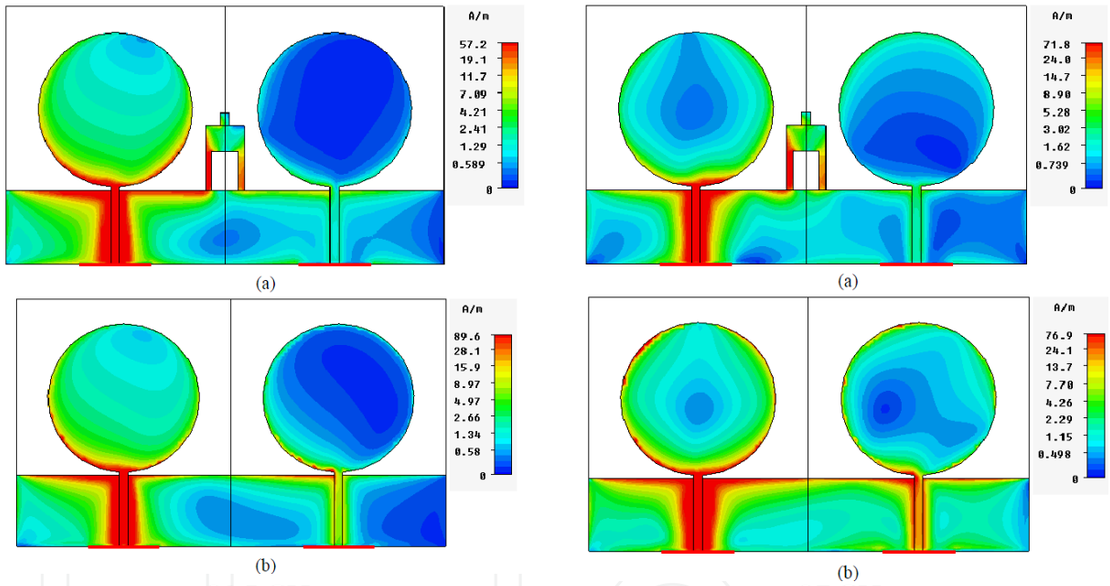
Fig. 9 (b) represents the simulated isolation between the antenna elements considering the case in which one antenna is excited and the other is terminated with matched impedance. Due to symmetry and reciprocity, S_{21} and S_{12} are the same. It is clear from the results that mutual coupling is always less than -11 dB in the frequency range of interest when there is no stub. The addition of the stub reduces mutual coupling significantly, i.e., less than -20 dB in the band of 3.2 - 4.0 GHz, less than -15 dB in the band of 4.0 - 6.8 GHz and less than -20 dB in the band of 6.8 - 10.6 GHz.

To elaborate further, the degree of isolation in the proposed antenna can also be determined by observing surface current distributions. Fig. 10 shows the current distributions with and without stubs at two frequencies 3.5 GHz and 7 GHz when port 1 (left radiating element) is excited and port 2 (right element) is terminated with a load impedance of 50 Ω. The effects of the stub can clearly be noticed by comparing with those without stub. The current is absorbed by stub and thus it reduces the mutual coupling between the two monopoles.



(a) (b)

Fig. 9. (a) Simulated reflection coefficient; (b) Simulated isolation.



@3.5 GHz @7 GHz

Fig. 10. Surface current distributions of antenna (a) with and (b) without stub.

2.5 Conclusions

UWB antennas make an old but developing subject. Many designs have been developed and new designs are emerging all the time. Future works will focus on the improvement of actual antenna structures and the integration of reconfiguring abilities. For example, concerning the coexistence of UWB systems with the wireless services at 5 GHz, recent studies have shown the interests to use composite right\left-handed (CRLH) metamaterials for designing a very small notch filter (Kahng et al., 2009), and to use either PIN diodes or microelectromechanical system (MEMS) switches for achieving reconfigurable UWB antennas with band-notched characteristics (Nikolaou et al., 2009). On the other hand, reconfigurable antennas based on the use of active components with low frequency tuning

and switchable UWB band have also been proposed recently (Loizeau & Sibille, 2009). These antennas offer the frequency agility of the RF stages as needed by multi-standard radios. Further in terms of reconfigurability, future antennas should enable to modify their radiation patterns, frequency, polarization, etc.

Another future axe of development resides in flexible, wearable and/or textile antennas. Thus, new applications have been imagined where people will carry a range of devices and sensors including medical or positioning sensors which will enable them to communicate with each other. In this context, UWB systems are the potential candidates. UWB antennas will then be fabricated on flexible organic substrates and integrated into clothing. In the same time, their performance must gain robustness against the deformations.

Finally, it should also be noticed that as analytical solutions to antenna problems (e.g., optimization of the geometry) are very difficult (near to impossible), therefore computer numerical simulation has become the major antenna design tool, especially after the publication of Harrington's book on method of moment in 1968. Significant improvements and advancements have been made in the antenna software industry over the past 15 years. Many fine software packages are now available in the market as an essential aid for antenna analysis and design.

3. Modeling of Ultra Wideband Antennas

3.1 Overview

Considering an antenna as an electromagnetic radiator, a Radio Frequency (RF) engineer will be interested in its radiation pattern, directivity, gain, aperture, efficiency and polarization. However, considering an antenna as a circuit element, an RF circuit designer will be more interested in its input impedance, reflection coefficient and voltage standing wave ratio. Taking account of narrowband systems, all of these characteristics can be considered as frequency independent, i.e., constant for the frequency band in use. Whilst in wideband systems, conventional properties become strongly frequency dependent. Consequently, one important feature of UWB antennas is that they introduce some pulse dispersion due to its frequency sensitive characteristics. Notably concerning impulse radio applications, antennas are critical components since the emitted and received pulse shapes are distorted.

New parameters have been introduced to take into consideration the transient radiations and to reveal phase variation effects. The antenna effective lengths can be considered to specify impulse radiation and reception characteristics of antennas (Shlivinski, 1997). More recently, with the emergence of UWB technology, the frequency domain transfer functions and the associated time domain impulse response derived from antenna effective lengths, have been preferred to describe these characteristics. The antenna is then modeled as a Linear Time Invariant (LTI) system for which the performance will affect the overall performance of the wireless communication system. Different definitions of the parameters involved in obtaining transmit and receive transfer functions have been proposed (Mohammadian et al., 2003; Qing et al., 2005; Duroc et al., 2007). In practice, the transfer functions are deduced from the simulated or measured complex scattering parameter, i.e., transmission coefficient, S_{21}. A Vector Network Analyzer (VNA) is generally used in the frequency domain and a post-treatment allows the assessment of time domain measures (Hines & Stinehelfer, 1974). It should be noticed that the time domain measurement is

possible but the corresponding calibration is not always well established, however the two approaches were demonstrated to be quasi-equivalent (Sörgel et al., 2003). In the literature, the papers which present new UWB antennas propose not only the design aspects and conventional characteristics but also, more and more, a time domain characterization in order to validate the antenna's ability to transmit short pulses and to receive these pulses with low distortion. Moreover, performance parameters (e.g., the fidelity factor and the full width at half maximum), issued to transfer function or impulse response, were introduced to quantify and analyze the pulse-preserving performance of UWB antennas (Sörgel & Wiesbeck, 2005; Kwon, 2006). One issue with many published propagation measurements was that the antenna effect is implicitly included in the measurement but not explicitly allowed for in the channel analysis, e.g., the IEEE 802.15.3a standard model. Thus, the consideration of the antenna effects in order to analyze or evaluate the performance of a UWB system also implied the introduction of antenna models based on transfer function or pulse response (Zhang & Brown, 2006; Timmerman et al., 2007). On the other hand, a lot of research is dedicated to the approaches for the modeling of UWB antennas directly in RF circuit simulators in order to simulate the performance of circuit with the antennas included. A transient model using cascaded ideal transmission lines has been proposed for UWB antennas (Su & Brazil, 2007). Demirkan and Spence have presented a general method for the modeling of arbitrary UWB antennas directly in RF circuit simulators. The antenna modeling approach is also based on the measurements of S-parameters (Demirkan & Spencer, 2007). Finally, recent studies have shown that a parametric modeling could improve the modeling (Licul & Davis, 2005; Duroc et al., 2006; Roblin, 2006). Analytical and compact expressions of transfer functions and impulse responses can be computed from simulations or measurements. The parametric methods are based on the Singularity Expansion Method (SEM) which provides a set of poles and residues.

About MIMO antennas, in the case of narrowband, different parameters can be used to characterize physical effects: the scattering parameters, the envelope correlation, and the total active reflection coefficient. However, these descriptions are not fully adequate when UWB systems are studied. Several works have proposed additional measures dedicated to MIMO-UWB antenna systems in order to improve the effect of the mutual coupling. The effects of UWB array coupling have been investigated using the general expressions for the time domain active array factor and active element factor. The interaction between radiators in a UWB biconical array has been analyzed (D'Errico & Sibille, 2008). Scattering and coupling are discriminated, and a scattering coefficient is introduced neglecting the incident wave curvature and near field effects but allowing the prediction of the multiple antennas performance. A method to compare dual-antenna systems by introducing a referenced diversity gain has been presented (Dreina et al. 2009). A model of coupled antennas, in order to integrate the effects of the coupling between antennas in a model of the propagation channel obtained from ray-tracing or asymptotic methods, has been studied (Pereira et al., 2009). From scattering parameters, a coupling matrix is being introduced, and this approach is validated for the case of canonical antennas and UWB antennas.

In the following part, the prospects of the use of parametric models are shown through several examples.

3.2 Prospects of the use of parametric models

The following applications of the use of parametric models are presented using the small U-slotted planar antenna discussed earlier (§2.3).

3.2.1 Preamble: brief summary of the Singularity Expansion Method

Two of the most popular linear methods are: the polynomial method (first developed by Prony in 1795), and the Matrix Pencil Method which is more recent and computationally more efficient because the determination of the poles is a one-step process (Sarkar & Pereira, 1995). These methods use the same projection in a base of exponential functions. The model is given by:

$$x(t) = \sum_{i=1}^{N} R_i \exp(s_i t) \tag{2}$$

where $\{R_i\}$ are the residues (complex amplitudes), $\{s_i\}$ are the poles and N is the order of the model. Then after sampling, and with the poles defined in the z-plane as $z_i = \exp(s_i T_e)$, the sequence can be written as

$$x(k) = \sum_{i=1}^{N} R_i z_i^k \tag{3}$$

The knowledge of the poles and the residues allows the direct determination of the impulse response and the transfer function. The frequency representation is also a direct function of the poles and residues and can be written in the Fourier plane and z-plane in the equations as follows

$$X(f) = FT[x(t)] = \sum_{i=1}^{N} \frac{R_i}{2\pi j f - s_i} \tag{4}$$

$$X(z) = zT\{x(k)\} = \sum_{i=1}^{N} \frac{R_i}{1 - z_i z^{-1}} = \sum_{i=1}^{N} \frac{R_i z}{z - z_i} \tag{5}$$

where the operator "FT" corresponds to the Fourier transform and the operator "zT" corresponds to the z-transform. Using an inverse Fourier transform, the impulse response x(t) of the antenna is determined from the transfer function X(f).

From time domain responses (i.e., impulse responses) characterizing the antennas, the parametric modeling allows the calculation of poles and residues. Hence, a compact and analytical time-frequency model can be deduced.

The quality of the modeling is a compromise between accuracy and complexity, i.e., the order of the model N. Generally, this parameter is not known and it is necessary to estimate it, but there is no straightforward method. It is possible to choose the most significant residues. However, in the presence of noise or considering an on-dimensioned system, the use of singular value decomposition is more relevant. The accuracy of the fit model can then be achieved by calculating the "mean square error" of the difference between the model and

the measured or simulated impulse responses or transfer functions (Duroc et al. 2007). In the following analysis, the Signal to Noise Ratio (SNR) is deduced from the power of the obtained error.

3.2.2 Directional time-frequency parametric model of the antenna response

In UWB, as explained previously, additional characteristics of antenna must be introduced to take into account the transient radiation and to reveal phase variation effects. Thus, UWB antennas are considered as linear time invariant systems defined in the frequency domain and the time domain by a complex transfer function and the associated impulse response respectively. The antenna characteristics also depend on the signal propagation direction. As a result, transfer functions and impulse responses characterizing UWB antennas are spatial vectors. Such a characterization provides especially the radiated and received transient waveforms of any arbitrary waveform excitation and antenna orientation. In this context, the presented method provides a compact and analytical time-frequency model of the directional antenna response from a parametric modeling.

A common approach for determining the transfer function and the associated impulse response of a UWB antenna is to exploit the simulated or measured two-port S-parameters of a two-element antenna system. Supposing that the impulse response of a reference antenna is known, then the parametric model of the antenna under consideration can easily be deduced using the previously presented methods. The modeling can be applied for several orientations of the antenna to obtain a directional model. However, whatever is the considered directional impulse response, the dominant poles are the same and only residues need to be adapted (Licul & Davis, 2005). Thus, the complete model can be reduced even further.

For example, the antenna radiation characteristics in the time domain can be represented by the impulse response vs. azimuth angle. For the antenna under test, the model contains only 30 complex pole pairs and 30 associated complex residue sets for any orientation. Moreover, due to the symmetry of the antenna geometry, the models for the considered symmetric orientations ($\theta = -45°$ and $45°$) are the same. In consequence, the antenna model complexity is divided by two. Fig. 11 presents the antenna radiation characteristics in the time domain for four orientations of the azimuth plane. The measured and modeled curves match with a very good accuracy (SNR = 54 dB).

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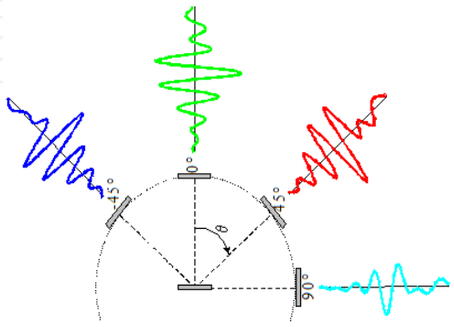

Fig. 11. Antenna radiation characterization in the time domain.

3.2.3 Equivalent circuit of UWB antenna input impedance

In circuit design, antennas are considered as loaded impedances. In narrowband systems, an antenna is simply represented by a 50 Ω resistor or an RLC parallel circuit to consider mismatching. However, when UWB antennas are considered, the circuit modeling becomes more complex as several adjacent resonances have to be taken into account. An efficient method, also based on a parametric approach, can obtain an equivalent circuit of antenna input impedances. Indeed, the parametric approach can also be applied to the antenna input impedance and associated to the Foster's passive filter synthesis method allowing the determination of an equivalent circuit of this impedance.

Firstly the antenna input impedance Z_a is deduced from the reflection coefficient Γ by the equation written as

$$Z_a = Z_0(1+\Gamma)/(1-\Gamma) \tag{6}$$

where Z_0 is the reference impedance (generally Z0=50Ω). As previously mentioned, a parametric model of Z_a can be determined. The achieved model can then be identified as the impedance of the Foster's filter given by

$$Z(p) = \sum_j \frac{A_j p + B_j}{p^2 + 2\alpha_j p + \omega_j^2} \tag{7}$$

Finally, the parametric model of the studied antenna input impedance possesses 12 complex and conjugate couples of poles and residues. The equivalent circuit model is represented in Fig. 12. It should be noted that some resistors have negative values and hence are unphysical electrical components. However, the electric circuit behaves as the antenna input impedance.

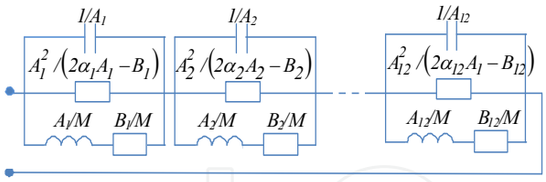

Fig. 12. Equivalent electric circuit of antenna input impedance.

Fig. 13 shows the measured real and imaginary parts of the antenna input impedance compared to the results from the parametric model and the circuit equivalent model simulated with the software SPICE. The model could be improved by increasing the order of the parametric model and the precision of the values allotted to components.

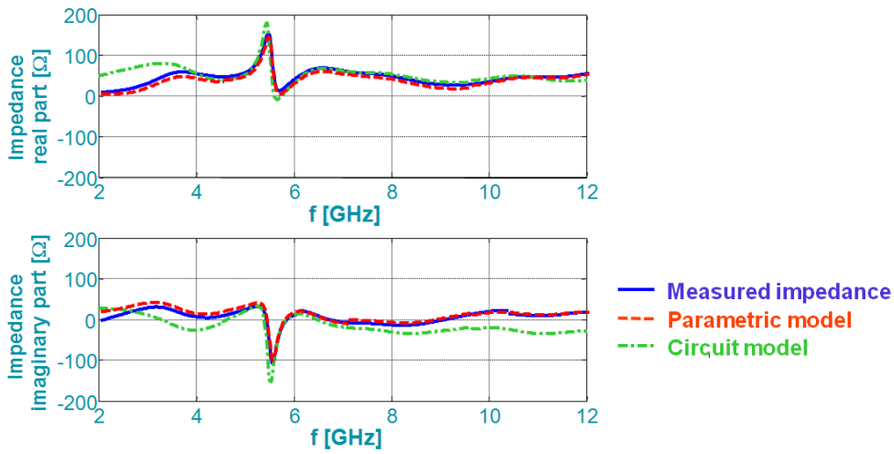

Fig. 13. Real and imaginary parts of antenna input impedance.

3.2.4 VHDL-AMS modeling of an UWB radio link including antennas

A new interesting way to model UWB antennas is to consider them as a part of the radio link in order to design or to optimize a complete UWB transceiver. Such transceivers are generally complex RF, analog and mixed-signal systems. They need an analog and mixed simulation environment for RF, analog and digital simulations. For high level system simulation, Matlab is the traditionally used tool but its use is generally limited to functional exploration. When the circuit design level is needed, every "design community" has its own simulation tools: digital designers work with event-driven simulators, analog designers use SPICE-like simulators, and Radio Frequency Integrated Circuits (RFIC) designers need specific frequency/time domain analysis tools. This large number of simulators makes the design time expensive and generates many compatibility problems. Recently, two major environments have made possible the combination of the three mentioned simulation families in order to suit hybrid system designers needs; the newly released Advance MS RF (ADMS RF) from Mentor Graphics, the RFDE design flow from Cadence/Agilent permit multi-abstraction and mixed-signal simulation and multilingual modeling (VHDL-AMS and SPICE). Some works have shown the usefulness of such an approach for complex mixed-signal system design. None of these works has included the antennas within their models. However, the UWB radio link model including antennas can be written in VHDL-AMS (Very high speed integrated circuit Hardware Description Language – Analog and Mixed Signal) from the parametric model of the transmission parameter S_{21} (Khouri at al., 2007). In order to illustrate the approach, the complete UWB communication chain based on a simple architecture with a non-coherent reception technique is simulated and illustrated in Fig. 14. In the transmission chain, a Rayleigh pulse generator controlled by a clock is used. Consequently, digital data is modulated using OOK (On-Off Keying) which is the classical modulation technique used for UWB energy detection receivers. The reception chain consists of a square-law device used for energy detection of the received signal, a comparator and a monostable circuit.

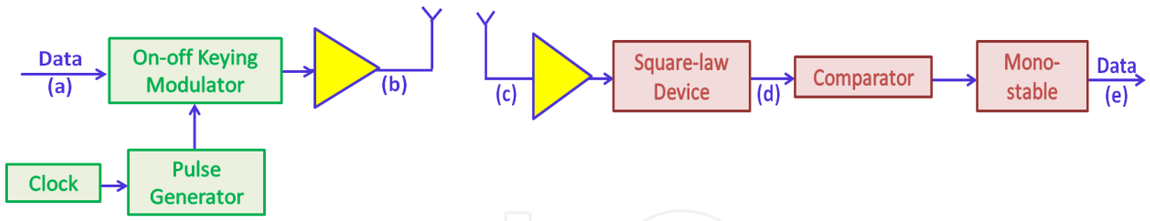

Fig. 14. Simulated UWB communication chain.

Fig. 15 is a UWB transmission chronogram and illustrates the obtained signals. Fig. 15 (a) is a random digital data flow representing the information to be sent. Fig. 15 (b) is the impulse radio OOK signal where pulses are easily modeled in VHDL-AMS by the Rayleigh monocycle. After propagation, the received signal shown in Fig. 15 (c) indicates the attenuation, propagation delay, and antenna's filtering effects. These effects can be better observed by taking the zoom as given in Fig. 16. Then, Fig. 15 (d) represents the extracted energy from which the digital signal in Fig. 15 (e) is recovered.

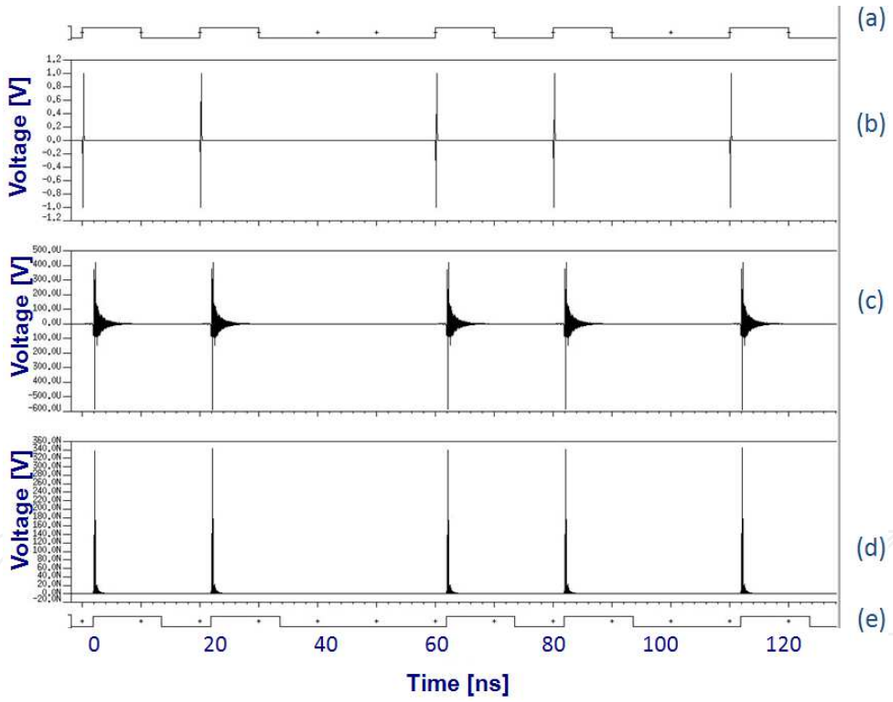

Fig. 15. (a) Random digital flow representing the information to be sent; (b) Impulse radio OOK signal (Ralyleigh monocycle); (c) Received signal (delayed, attenuated and distorted); (d) Extracted energy; (e) Recovered digital signal.

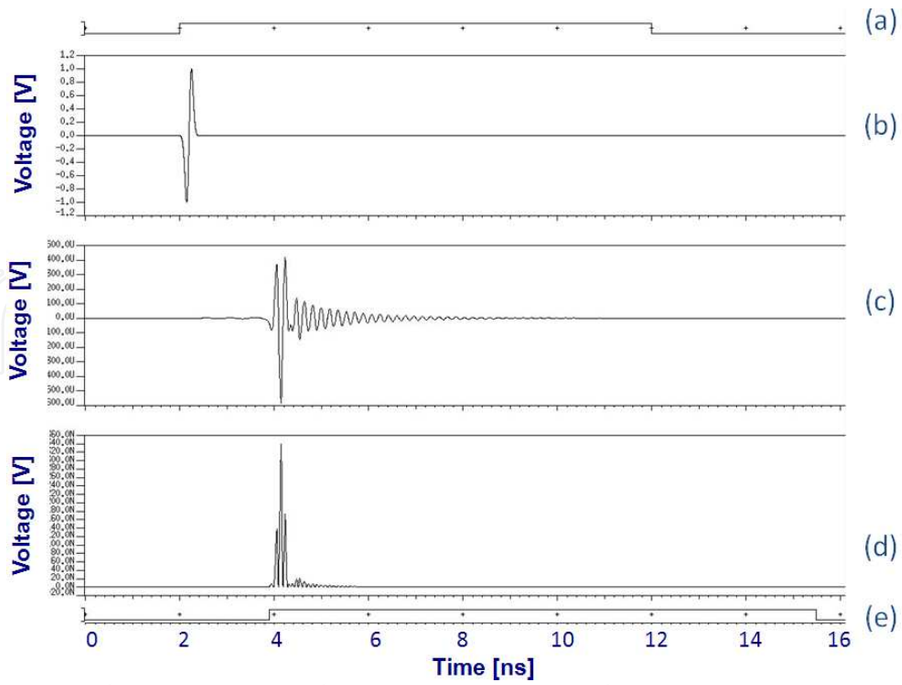

Fig. 16. Zoom on the transmission chronogram represented in Fig. 15.

4. Conclusions and Perspectives

The wide bandwidths of UWB systems present new challenges for the design and modeling of antennas. Familiar antenna architectures like patches and slots have been modified to meet the extension of the bandwidths; the familiar techniques like arrays have been expanded to UWB applications as well as more recent concepts like antenna spectral filtering. The antennas are no more considered as simple loads of 50 Ω or simple energy detectors but as fundamental parts of RF systems providing filtering properties.

UWB systems also appear as very promising solutions for future RF systems. Their next development will imply the need of UWB antennas integrated with new functionalities. The functions of antenna, more particularly the multi-antenna, will evolve and accommodate new technology aspects, such as diversity, reconfigurability and cognition. Obviously, the multi-antenna is not only an association of two or several radiating elements but it will also be integrated with sensors and electronic circuits. Under this evolution, embedded signal processing will be an obligatory stage. The future UWB antennas will be able to scan the environment, to harvest ambient energy, and to reconfigure spatially and spectrally themselves while maintaining the basic communication functions in transmission and reception. Moreover, in a long term perspective, integration of the whole antenna function into a chip would be a significant and strategic added value. In addition, the physical implementation of the "intelligence" with the antenna is also a real challenge. It is a fundamental reason behind the existence of few real physical smart antennas. Furthermore, when wideband systems are envisaged, the design considerations and guidelines for antennas are of the utmost importance. Some works have already presented promising original solutions in order to physically realize analog and digital processing, thanks to

microwave analogue FIR (Finite Impulse Response) filters and FPGA (Field Programmable Gate Array) architectures, respectively.
New UWB antennas models must be developed being radically different from those currently available, and this implies the development of original and innovative approaches. New models should allow the intrinsic characterization of antennas and also the evaluation of their performance in given situations. These models will be able to take into account different functions, such as microwave, signal processing and radiated elements. They must be scalable, generic and adaptive. Taking into account the long term vision of silicon integration of smart antennas, these models must be compliant with classical silicon integrated circuit design tools. Several levels of abstraction must be envisaged, notably with a co-design orientation. Further, the suggested models must give new ways to improve the current structures of antennas and to associate them with new control laws.

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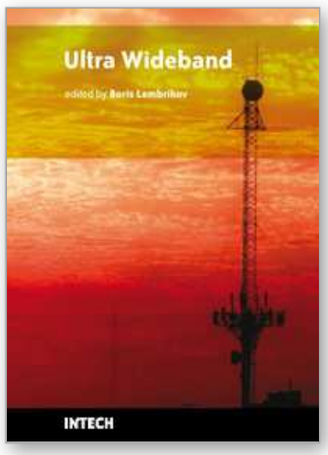

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Ultra wideband technology is one of the most promising directions in the rapidly developing modern communications. Ultra wideband communication system applications include radars, wireless personal area networks, sensor networks, imaging systems and high precision positioning systems. Ultra wideband transmission is characterized by high data rate, availability of low-cost transceivers, low transmit power and low interference. The proposed book consisting of 19 chapters presents both the state-of-the-art and the latest achievements in ultra wideband communication system performance, design and components. The book is addressed to engineers and researchers who are interested in the wide range of topics related to ultra wideband communications.

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