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Multiple-Input Multiple-Output Antennas for Ultra Wideband Communications

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1. Introduction

UWB is a very promising technology for short-range wireless communications providing the opportunity of high data rate communications. In 2002, the Federal Communication Commission (FCC) regulated the UWB technology utilization for commercial applications in the United States in the frequency range of 3.1–10.6 GHz [1]. Other than the United States, UWB regulations have been issued in Europe, Japan, Korea and Singapore. These regulations did not stipulate the technology type to be used. Later, two distinct techniques were envisaged: the Multi-band Orthogonal Frequency Division Multiplexing (MB-OFDM) and the Impulse-UWB (I-UWB) [2]. The MB-OFDM divides the UWB spectrum in 14 sub-bands, the utilization of the bands is managed for a code time-frequency exploiting the spatial-temporal diversity [3], while the I-UWB transmits pulses of very short duration that occupy the entire allowable frequency band [4]. UWB has vast array of applications in wireless world. The dominant applications include WBAN, WPAN, RFIDs, sensor networks, radars, etc. The relevant IEEE standards for UWB are: 802.15.3a for high data rate and 802.15.4a for low data rate. Digital communication using Multi-Input Multi-Output (MIMO) processing has emerged as a breakthrough for wireless systems of revolutionary importance. All wireless technologies face the challenges of signal fading, multipath, increasing interference and limited spectrum. MIMO technology exploits multipath to provide higher data throughput, and simultaneous increase in range and reliability all without consuming extra radio frequency. Early studies conducted by Foschini and Gans [5] indicated that capacity increases were possible by using MIMO systems. In a rich scattering environment, Telatar showed that the capacity of system consisting of M transmitter and N receiver antennas is $min(M, N)$ times that of a single transmitter receiver system [6]. MIMO systems exploit the antenna diversity (spatial, polarization or pattern diversity) to increase the strength of the transmitted signals and therefore to improve the Signal Noise Ration

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(SNR). Spatial multiplexing in MIMO systems helps in increasing data rate. Beamforming is used either to increase data rate or to strengthen the signal. The applications of MIMO include digital television (DTV), wireless local area networks (WLANs), metropolitan area networks (MANs), and mobile communications. IEEE standard related to MIMO technology is 802.11n.

Where one says that UWB is a classical solution to the demand of high data rate communications, there arise the questions while thinking of UWB and MIMO together in the wireless systems. Obviously, it can be answered in terms of the reasons rather motivations behind this combination of two technologies. In effect, it is well known that the main applications of UWB technology are found for WPAN and WBAN (Wireless body area network) in indoor environments where the dense multipath propagation leads to generally detrimental Inter Symbol Interference (ISI). Therefore, to turn this drawback into an advantage, multiple antennas or MIMO techniques can be employed to exploit such rich scattering environments. The more important is that the applications of UWB are limited to the short distance communication due to very low transmission power allowed by the FCC. Hence, using MIMO together with UWB helps in extending the communication range as well as offers higher link reliability. The benefits of UWB-MIMO can be summarized as following [7]-[8]: interference mitigation/suppression, higher data rates, improved link quality, extended coverage, reduced analog hardware requirements, and concurrent localization. Apart from these benefits, there are also challenges for the joint implementation of UWB and MIMO. These challenges include: UWB-MIMO signaling trade-offs, UWB-MIMO channel modeling, the optimization of UWB-MIMO modulation schemes, design of compact and suitable UWB antenna arrays, efficient and cost-effective UWB-MIMO RF circuit design, etc. Among these challenges, the design of compact and suitable UWB diversity antennas has appealed many researchers to work on this topic. The significance of antenna in a wireless communication system cannot be avoided. It also becomes a critical element to be miniaturized along with the other circuit elements. The design of antenna faces a lot of challenges itself in this race. As devices are going to be more compact, therefore the antennas must be positioned within the available space. Moreover, MIMO can be implemented by three ways: beamforming, spatial multiplexing and diversity techniques. Diversity techniques, more specifically antenna diversity techniques (i.e., spatial, polarization and pattern), are adopted for MIMO antenna designs. Hence, the implementation of multi-antenna structures becomes more challenging in the very limited space provided by the small terminals. The limitations to exploit the diversity arise when the antennas are placed in close vicinity. So, it is required to decorrelate their patterns, or in other words, mutual coupling should be minimized. Another challenge is the enhancement of isolation between the access ports of MIMO antennas. In the literature, a relative few MIMO antenna designs have been presented for UWB systems. In this context, this chapter presents an overview of MIMO UWB antennas with the main following objectives: to highlight the additional parameters required to characterize the performance of UWB antennas as well as MIMO antennas, to bring a state of the art in MIMO antennas for UWB

systems, and to present a state of art in techniques to be used to reduce mutual coupling and enhance the isolation. This chapter also describes some of our proposed designs and structures of the different types of MIMO antennas for UWB applications exploiting spatial, polarization and pattern diversities, and a solution to enhance the isolation with reduced size of antenna.

2. Antenna theory

The antennas are an essential part of any wireless system. According to the IEEE Standard Definition of terms for Antennas, an antenna is defined as "a means for radiating and receiving radio waves" [9]. In an advanced wireless system, an antenna is usually required to optimize or accentuate the radiation energy in some directions and suppress it in others at certain frequencies. A good design of the antenna can relax system requirements and improve overall system performance. To describe the performance of an antenna, there are several commonly used antenna parameters, including impedance bandwidth, radiation pattern, directivity, gain, efficiency, and polarization [10].

2.1. Specific parameters for UWB antennas

In UWB systems, the previous fundamental and classical parameters must be considered in designing antennas but there are more challenges to monitor them and some additional parameters.

Bandwidth - First of all, what distinguishes a UWB antenna from other antennas is its ultra wide frequency bandwidth. According to the FCC's definition, a suitable UWB antenna should be able to yield an absolute bandwidth of not less than 500 MHz or a fractional bandwidth of at least 0.2. Moreover, UWB antenna must be operable and must have stable impedance matching over the entire 3.1-10.6 GHz frequency range in the case of I-UWB following the FCC defined spectral mask. Sometimes, it is also demanded (e.g., in Europe) that the UWB antennas should provide the band-rejected characteristic to coexist with other narrowband devices and services occupying the same operational band [11].

Radiation Pattern - Directional or omni-directional radiation properties are needed depending on the practical application. Omni-directional patterns are normally desirable in mobile and hand-held systems. For radar systems and other directional systems where high gain is desired, directional radiation characteristics are preferred. High radiation efficiency is usually required for antennas but it is imperative and essential for an ultra wideband antenna because the transmit power spectral density is excessively low. Therefore, any excessive losses incurred by the antenna could potentially compromise the functionality of the system.

Size and Cost - A suitable antenna needs to be small and of light weight enough to be compatible to the application. As we are projecting UWB for the applications that include

especially mobile and portable devices, therefore it is highly desirable that the antenna should feature low profile and compatibility for integration with printed circuit board (PCB).

Specific parameters to be required to characterize UWB antennas are now described.

Compliance with Spectral Masks - A good design of UWB antenna should be optimal for the performance of overall system. To avoid the possible inband/outband interference between the UWB systems and existing electronic systems, the antenna should be designed such that the overall device (antenna and RF front end) complies with the mandatory power emission mask given by the FCC or other regulatory bodies. The emission limits will be determined by both the selection of source pulse and design of antennas in UWB systems.

Impulse Response - As the origin of UWB technology stems from time-domain electromagnetics, therefore UWB antenna is required to achieve good time domain characteristics (i.e., good impulse response). The idea is simply to characterize the LTI (Linear Time Invariant) system by its response to an impulsive excitation instead of amplitude and phase and measurements versus frequency (i.e., swept frequency response). For the narrowband case, it is approximated that an antenna has same performance over the entire bandwidth and the basic parameters, such as gain and return loss, have little variation across the operational band. In contrast, I-UWB systems often employ extremely short pulses for data transmission. In other words, enormous bandwidth has been occupied, thus the antenna can't be treated as a "spot filter" any more but a "band-pass filter". In this case, the antenna imposes more significant impacts on the input signal. As a result, a good time domain performance (i.e., minimum pulse distortion in the received waveform) is a primary concern of a suitable UWB antenna because the signal is the carrier of useful information [12]. Therefore, it is indispensable and important to study the antenna's characteristics in time domain.

Group Delay - It is an important parameter that represents the degree of distortion of UWB signal. Group delay is a measure of the slope of the transmission phase response. The linear portion of the phase response is converted to a constant value and deviation from linear phase are transformed into deviations from constant group delay. The variations in group delay cause signal distortion, just as deviations from linear phase cause distortion. It can be given as

$$group\ delay = -\frac{\Delta\varphi}{\Delta\omega} \tag{1}$$

where φ is the total phase shift in radians, and ω is the angular frequency in radians per unit time, equal to $2\pi f$, where f is the frequency. The group delay variations induced by the radiation pattern of the antenna will affect the overall receiver system performance, since it can bring relatively large timing errors. An antenna gain versus frequency without nulls, means a linear phase response, hence a constant group delay.

In summary for the applications of portable devices, general specifications required to design UWB antennas under the FCC regulations can be summarized in Table 1.

Parameter	Value
VSWR bandwidth	3.1-10.6 GHz
Radiation pattern	Omnidirectional
Radiation efficiency	High (> 70%)
Gain	Smooth in the band of interest
Phase	Linear ; nearly constant group delay
Physical profile	Small, compact, planar

Table 1. Characteristics of UWB antenna for portable devices.

2.2. Specific parameters for MIMO antennas

Like the case of UWB, there are also some additional parameters other than the fundamental parameters to be taken into account while designing MIMO antennas.

Mutual Coupling and Isolation - In MIMO applications, the signals transmitted by multiple antenna elements are generally supposed to be independent or uncorrelated. But in reality, the current induced on one antenna produces a voltage at the terminals of nearby elements, termed as mutual coupling [13]. It means there is always mutual coupling present between nearby antenna elements. However, for MIMO applications, the mutual coupling should be minimized to as low value as possible. In a contradictory way, it should be noted that it is also studied that mutual coupling can help to reduce the correlation between the different channel coefficients in nearby placed antenna elements scenario, thus escalating the capacity [14]. This is an important issue for the antenna community. In a general way the coupling has an adverse effect and mutual coupling has to minimize [15].

The port-to-port isolation is defined as the transmission of power between two of the input ports of the multiport antenna under test. It is characterized by $|S_{21}|$ parameter. It must be noted that isolation is a positive quantity and is given as

$$Isolation = -10 log_{10} |S_{21}|^2 \qquad (2)$$

In MIMO systems, to maximize the energy radiated by an antenna, it should be ensured that negligible amount of transmitted energy is lost into the ports of other antennas terminated by the matched impedances. In other words, MIMO systems require the $|S_{21}|$ to be minimized to as low value as possible as isolation is directly related to the antenna efficiency. A lot of research has been done on the reduction of mutual coupling and the enhancement of the isolation. It is worth mentioning that the mutual coupling is characterized most of the times by the isolation in the literature. However, in [16], it is stated that isolation is not the exact representation of mutual coupling, as it is possible that there is very good isolation but it is not necessary for mutual coupling to be low in this case. Hence, to evaluate the mutual coupling, it is better to observe the surface current distributions on the non-excited radiating element, when nearby radiating element, is excited. Although the

ports may be isolated, there is a possibility of having large induced currents in the neighboring antenna, which, in turn, affects the radiation pattern of the antenna considered. It is good to mention that we will take both mutual coupling and isolation into account differently unlike majority of the authors (Table 2) who have given S_{21} parameter as mutual coupling. However, we will always present surface current distributions as well. Further, the techniques to reduce mutual coupling and to enhance the isolation are discussed in detail in section 3.

Mean Effective Gain - The performance of MIMO systems is also characterized by the mean effective gain (MEG) of the antennas. The MEG is a statistical measure of the antenna gain that can be defined as the ratio of the mean received power of the antenna and the total mean incident power. It can be expressed by the following equation as in [17]

$$MEG = \int_0^{2\pi} \int_0^{\pi} \left(\frac{XPR}{1+XPR} G_\theta(\theta,\varphi) P_\theta(\theta,\varphi) + \frac{1}{1+XPR} G_\varphi(\theta,\varphi) P_\varphi(\theta,\varphi) \right) sin\theta d\theta d\varphi \qquad (3)$$

where P_θ and P_φ are the angular diversity functions of the incident power with respect to θ and φ directions respectively, G_θ and G_φ are the gains with respect to θ and φ directions respectively, and XPR represents the cross-polarization power gain which is defined as

$$XPR = \frac{\int_0^{2\pi} \int_0^{\pi} P_\theta(\theta,\varphi) sin\theta d\theta d\varphi}{\int_0^{2\pi} \int_0^{\pi} P_\varphi(\theta,\varphi) sin\theta d\theta d\varphi} \qquad (4)$$

The MEG is a normalized measure of the received power, where the powers (either P_θ or P_φ) are normalized as [18]

$$\int_0^{2\pi} \int_0^{\pi} P_\theta(\theta,\varphi) sin\theta d\theta d\varphi = 1 \qquad (5)$$

and the gains are normalized in such a way that

$$\int_0^{2\pi} \int_0^{\pi} \left(G_\theta(\theta,\varphi) + G_\varphi(\theta,\varphi) \right) sin\theta d\theta d\varphi = 4\pi \qquad (6)$$

In the case where the antenna is located in a totally random channel environment, the value of XPR is 1 and $P_\theta = P_\varphi = 1/4\pi$. Then, MEG can be calculated using (3) as follows:

$$MEG = \int_0^{2\pi} \int_0^{\pi} \left(\frac{1}{1+1} \frac{1}{4\pi} G_\theta(\theta,\varphi) + \frac{1}{1+1} \frac{1}{4\pi} G_\varphi(\theta,\varphi) \right) sin\theta d\theta d\varphi = \frac{1}{2} \qquad (7)$$

The MEG is then equal to the total antenna efficiency divided by two or -3 dB [19] and it is independent of the radiation patterns. In order to achieve good diversity gain, the ratio of the MEG between the two antennas should close to unity in order to ensure that average received power by each antenna is nearly equal [20].

Correlation Coefficient - The correlation coefficient is a parameter of great importance for the systems providing diversity. The signals received in the diversity systems can be correlated to some extent. The correlation coefficient is a mathematical and statistical tool that measures the degree of similarity among the received signals. Its modulus varies from 0 to 1. Ideally, diversity systems require a correlation coefficient of zero or low by default.

This parameter can be viewed by three ways: complex, envelope and power correlation coefficients. Complex correlation coefficient gives the complex measure of correlation between received signals at the antennas. It can be given as [18]

$$\rho_c = \frac{\int_0^{2\pi} \int_0^{\pi} \left(XPRE_{\theta k}(\theta,\varphi)E_{\theta l}^*(\theta,\varphi)P_\theta(\theta,\varphi) + E_{\varphi k}(\theta,\varphi)E_{\varphi l}^*(\theta,\varphi)P_\varphi(\theta,\varphi) \right) sin\theta d\theta d\varphi}{\sqrt{\sigma_k^2 \sigma_l^2}} \tag{8}$$

where σ_k^2 and σ_l^2 represent the variances of kth and l^{th} branches and can be written mathematically as

$$\rho_c = \int_0^{2\pi} \int_0^{\pi} \left(XPRG_{\theta k}(\theta,\varphi)P_\theta(\theta,\varphi) + G_{\varphi k}(\theta,\varphi)P_\varphi(\theta,\varphi) \right) \tag{9}$$

also

$$G_{\theta k}(\theta,\varphi) = E_{\theta k}(\theta,\varphi)E_{\theta l}^*(\theta,\varphi) \tag{10}$$

$$G_{\varphi k}(\theta,\varphi) = E_{\varphi k}(\theta,\varphi)E_{\varphi l}^*(\theta,\varphi) \tag{11}$$

where $E_{\theta k}$ and $E_{\varphi k}$ are complex electric fields in the directions θ and φ respectively for the kth antenna. Similar expressions are valid for l^{th} antenna.

Usually, the envelope correlation is presented to evaluate the diversity capabilities of MIMO systems [21]. This parameter is always real and by definition gives the correlation among the amplitudes of the signals at antennas. For Rayleigh fading channel, the envelope correlation can be given as follows:

$$\rho_e = |\rho_c|^2 \tag{12}$$

It is clear that correlation should be preferably computed from 3D radiation patterns but it becomes tedious. However, assuming that the diversity system will operate in a uniform multipath environment, the correlation coefficient can be calculated from S-parameters using the following equation in [22]

$$\rho_e = \left| \frac{S_{11}^* S_{12} + S_{21}^* S_{22}}{\sqrt{1 - |S_{11}|^2 - |S_{21}|^2} \cdot \sqrt{1 - |S_{22}|^2 - |S_{12}|^2}} \right|^2 \tag{13}$$

It offers a simple procedure compared to the radiation pattern approach, but it should be emphasized that this equation is strictly valid when the following assumptions are fulfilled:

- Antennas should have high efficiency and no mutual losses.
- Antenna system is positioned in a uniform multipath environment which is not strictly the case in real environments; however, the evaluation of some prototypes in different real environments has already shown that there are no major differences in these cases.
- Load termination of the non-measured antenna is 50 Ω. In reality, the radio front-end module does not always achieve this situation, but the 50 Ω evaluation procedure is commonly accepted.

All these limitations are clearly showing that in real systems the envelope correlation calculated based on of the help of the S_{ij} parameters is not the exact value, but nevertheless

is a good approximation. In addition, it should be noted that antennas with an envelope correlation coefficient less than 0.5 are recognized to provide significant diversity performance.

Diversity Gain - The diversity gain (DG) is a figure of merit used to quantify the performance level of diversity techniques. The DG is the slope of the error probability curve in terms of the received SNR in a log-log scale. However, the DG can also be defined as the increment of the SNR at a given probability, normally 1% or 10% [23]. Such DG can easily be calculated by looking at the cumulative distribution function (CDF) curves of the SNR, and comparing the combined SNR using some specific diversity technique with the SNR of an un-coded SISO communication system. Mathematically, it can be expressed as

$$DG = \frac{(SNR)_c}{(SNR)_r} \qquad (14)$$

where indices "c" and "r" are used for the combined and the reference. In this context, DG can be defined as the difference between a combined CDF as compared to a reference CDF at a certain level of CDF [24]. Depending on the reference CDF, it is possible to write three definitions for the diversity gain:

- Apparent diversity gain - Difference between power levels in dB (at certain CDF level), between CDF of combined signal, and CDF of signal at the port with the strongest average signal levels.
- Effective diversity gain - Difference between power levels in dB (at certain CDF level), between CDF of combined signal, and CDF of signal at the port of an ideal single antenna (corresponding to radiation efficiency of 100%), measured in the same environment.
- Actual diversity gain - Difference between power levels in dB (at certain CDF level), between CDF combined signal, and CDF of signal at the port of an existing practical single antenna that is to be replaced by the diversity antenna under test, measured at the same location (for example, relative to a head phantom).

The DG is also related to the correlation coefficient. The relation between DG and correlation coefficient can be given approximately by

$$DG = 10\sqrt{1 - |\rho|^2} \qquad (15)$$

This relationship clearly shows that the lower the correlation coefficient the higher will be the diversity gain. Therefore, high isolation is required between the antennas otherwise the DG will be low. Further, whatever the combining method is being used, the maximum diversity gain is obtained when the correlation coefficient is zero. The measurements in different types of environments (urban, suburban, rural and motorways) have made possible to write empirical relationships [25] for each type of combination scheme. These formulae of diversity gain have been given as follows:

For Selecting Combining scheme,

$$DG(dB) = 5{,}71\ exp\left(-0.87\sqrt{\rho_e} - 0.16\Delta\right) \tag{16}$$

For Equal Gain Combining method,

$$DG(dB) = -8.98 + 15.22\ exp\left(-0.20\sqrt{\rho_e} - 0.04\Delta\right) \tag{17}$$

And for Maximal Ratio Combining method,

$$DG(dB) = 7.14\ exp\left(-0.59\sqrt{\rho_e} - 0.11\Delta\right) \tag{18}$$

Thus, in ideal conditions ($\rho_e = 0$; $\Delta = 0$), MRC (Maximum Ratio Combining) scheme gives the best diversity gain, i.e., 7.41 dB.

Total Active Reflection Coefficient - The reflection coefficient does not accurately characterize the radiation efficiency and bandwidth of a MIMO antenna. Instead of simple reflection coefficient, the array's total active reflection coefficient (TARC) can be used so that it accounts for both coupling and random signal combination. Thus, TARC provides a more meaningful measure of MIMO efficiency. For a desired port excitation, summation of the available power at all excitation ports is assumed as incident power, radiated power as transferred power, and the difference between these two as reflected power. The square root of the ratio of reflected power and incident power is defined as the TARC [26], mathematically given by

$$\Gamma_a^t = \frac{available\ power - radiated\ power}{available\ power} \tag{19}$$

For instance, TARC for a lossless N-port antenna can be described as

$$\Gamma_a^t = \sqrt{\sum_{i=1}^{N}|b_i|^2} \Big/ \sqrt{\sum_{i=1}^{N}|a_i|^2} \tag{20}$$

where $[b] = [S] \cdot [a]$, a_i is the incident signal vector with randomly phased elements and b_i is the reflected signal vector.

Furthermore, for 2×2 network, the scattering matrix can be written as

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \tag{21}$$

It can be assumed that the reflected signal will be randomly phased with independent and identical distributed Gaussian random variables because MIMO channels are assumed as Gaussian and multipath spread in the propagation channel. Since sum or difference of independent Gaussian random variables is Gaussian, reflected signals are characterized as

$$b_1 = s_{11}a_1 + s_{12}a_2 = s_{11}a_0e^{i\theta_1} + s_{12}a_0e^{i\theta_2} = a_1\left(s_{11} + + s_{12}e^{i\theta}\right) \tag{22}$$

$$b_2 = s_{21}a_1 + s_{22}a_2 = s_{21}a_0e^{i\theta_1} + s_{22}a_0e^{i\theta_2} = a_1\left(s_{21} + + s_{22}e^{i\theta}\right) \tag{23}$$

Therefore, TARC for two-port antenna can be described as follows [27]:

$$\Gamma_a^t = \sqrt{\frac{\left|S_{11}+S_{12}e^{i\theta}\right|^2 + \left|S_{21}+S_{22}e^{i\theta}\right|^2}{2}} \tag{24}$$

The TARC of MIMO antenna is calculated by applying different combinations of excitation signals to each port. There is no need to define the TARC as a complex number since the phase reference plane does not have any physical meaning for a multiport antenna. The TARC is a real number between zero and one. When the value of the TARC is equal to zero, all the delivered power is radiated and when it is equal to one, all the power is either reflected back or goes to the other ports.

2.3. Summary on UWB MIMO antenna characteristics

In context of UWB where the whole band approved by FCC is required to be covered in one shot, the design of antenna becomes challenging enough. The characteristics of the antennas are required to be stable for the wide frequency band. Moreover, time domain measurements like dispersion and group delay become significant in addition to conventional frequency domain characteristics. Furthermore, the development of future UWB-MIMO communication systems brings more challenges for the antenna design. MIMO antennas are required to be characterized for mutual coupling, correlation and diversity gain. However, a detailed study on characterization of MIMO antennas for UWB is among the current hot topics of research. Also, the design of UWB-MIMO antenna system is always confronted with the same constraints like cost, size, ease of fabrication and integration with other circuits as in the case of single antenna design. Having the specific parameters used essentially for the analysis of UWB and MIMO antennas, the current research orientations with a state of the art are now detailed.

3. Techniques to reduce mutual coupling and to enhance isolation

Theoretical work has proved that mutual coupling has a significant effect on MIMO channel capacity in rich scattering environments. The degree to which coupling induced correlation degrades MIMO channel capacity depends on the multipath's angular power spectral density. Another problem resulting from an increase in mutual coupling is the subsequent decrease of the array's radiation efficiency due to impedance mismatch. Hence, the reduction of mutual coupling becomes very important. Similarly, poor isolation also degrades the array's radiation efficiency due to the leakage of transmitted power from the excited antenna to the port of non-excited antenna. Therefore, the need of good isolation is imperative. The different techniques for this purpose are presented in the literature. Most of these techniques are vital only for narrowband MIMO systems however some of them are presented for UWB-MIMO systems. These techniques are discussed in the sub-sections as follows, and some examples illustrate them. A summarized state of art corresponding to the presented MIMO-UWB antennas is presented in Table 2 detailing the used method, the reference, the antenna layout and the analyzed parameters.

3.1. Using Decoupling and Matching Networks (DMN)

Narrowband MIMO systems - The achievement of low mutual coupling and good isolation using decoupling and matching networks is well explained by S. Dossche et al. in [28]. As earlier described in previous section, the envelope correlation can be calculated from the far-field radiation patterns as well as from the scattering parameters of the antenna system, assuming uniform propagation channel. The envelope correlation can be written as in (13) for a reciprocal and symmetrical antenna system:

$$\rho_e = \frac{|2Re\{S_{11}^* S_{12}\}|^2}{(1-|S_{11}|^2-|S_{12}|^2)^2} \tag{25}$$

From above equation, it is clear that by changing the magnitude and phase of either S_{11} or S_{12}, the correlation between the two antennas can be decreased. In practice, this can be achieved by using a matching network for connecting the antennas. From the system point of view, it is also important to consider the value of $1-|S_{11}|^2-|S_{12}|^2$ that takes into account the effective radiated power by the antenna system, and it is maximized by minimizing $|S_{11}|$ and $|S_{12}|$. Thus, two matching networks can be used at both sides to minimize S_{11} and S_{22} while a decoupling network can be used to make S_{11} in quadrature with S_{12} i.e., S_{12} is pure imaginary and thus the real part of mutual impedance Z_{12} is equal to zero. This can be achieved by using a lossless decoupling network.

Also, Weber et al. have used passive DMNs and studied them in detail [29]. In this context, the method for derivation of the admittance matrices of the DMN is explained. An important feature of this method is the formation of predefined orthogonal system port patterns. The admittance matrix can be converted to an actual circuit layout of the DMN in terms of capacitors and inductors. Recently, in [30], hybrid circuit is used as decorrelation circuit. This circuit provides a straightforward, frequency-independent, and feasible solution if the elements are symmetrically placed. This hybrid circuit introduces a 180° phase shift between the signals from the two antenna branches. A little variant of this technique can be observed in [31] where several parasitic elements have been employed between the radiating elements to reduce the isolation. The reduction is dependent on the length and number of the parasitic elements. At least 10 dB improvement, in isolation is noticed.

UWB-MIMO Systems - It can be noticed that lot of work has been presented to get better isolation using DMNs. However, this technique is not tractable for UWB-MIMO systems. The matching networks to design and to realize for multiband, wideband and ultra wideband MIMO systems are enough difficult. Thus, this technique is not employed yet for UWB-MIMO systems in the literature to the best of our knowledge.

3.2. Using Electromagnetic Band Gap (EBG) structures

As noted by Sievenpiper [32], an electromagnetic band gap (EBG) structure behaves as a high impedance surface. This structure consists of an array of metal protrusions on a flat metal sheet. They can be visualized as mushrooms or thumbtacks protruding from the

surface. If the protrusions are small compared to the wavelength, their electromagnetic properties can be described using lumped circuit elements – capacitors and inductors. The proximity of the neighboring metal elements provides the capacitance, and the long conducting path linking them together provides the inductance. They behave as parallel resonant LC circuits, which act as electric filters to block the flow of currents along the sheet. This is the origin of the high electromagnetic surface impedance. Because of its unusual impedance, the surface wave modes on this structure are very different from those on a smooth metal sheet. In this way, EBG structures have the ability of suppressing surface waves propagation in a frequency band which makes them very useful to improve the ports isolation in printed antennas.

Narrowband MIMO Systems - In [33], such structures are used to increase isolation in patch antennas by using very simple EBG structures with the help of a multilayer substrate containing a high and a low permittivity layers. A planar EBG consisting of a double squared ring is printed on high permittivity layer while antenna is printed on low permittivity layer. The isolation is enhanced by approximately 10 dB. Further, a simple line fed microstrip patch array designed on a relatively thick substrate gives very good port isolation by using three periods of mushroom EBG elements in addition to variable offset superstrates in [34]. The isolation was improved by 10 dB. However, bandwidth was increased by 50 MHz by using additional superstrates. Recently, in [35], a mushroom-type EBG structure is designed to minimize the loading effects between the two slot antennas without significantly modifying the radiation pattern and input impedance profile. When the EBG reflector is utilized, the insertion loss between the antennas is increased due to the suppression of the parallel-plate modes in the band-gap. The reduction in antenna coupling at some specific frequency is observed by more than 30 dB in comparison to the prototype without the EBG reflector.

UWB-MIMO Systems - Though this technique is widely used for narrowband MIMO systems, yet it has some constraints. The method is not viable for wideband systems because a large number of mushroom-like EBG structures will be required to cover the wide range of frequency. As a result, antennas will require large area to embed these structures for UWB-MIMO systems. Further, an intricate process is required to fabricate such structures. They involve an intricate fabrication process with cells shorted to the ground through vias.

3.3. Using neutralizing line

Narrowband MIMO Systems - The technique of using neutralizing line is based on the concept to neutralize two antennas operating in the same frequency band to enhance the isolation. Originally, this technique is proposed by C. Luxey et al. in [16]. They have used a suspended neutralization strip line physically connected to the antenna elements. This line samples a certain amount of the signal on one antenna element and delivers to the other antenna element in order to cancel out the existing mutual coupling, thus increasing total efficiency. In other words, an additional coupling path is created to compensate for the electrical currents owing on the PCB from one antenna to another. Initially for UMTS PIFAs,

this technique worked in both cases, i.e., the line is inserted either between shorting pins of PIFAs or between feeding pins of PIFAs. Later, the same technique has been tested for two square patch antennas in [35]. Recently, the same research group is presented a novel implementation of neutralizing line in [36] based on the same concept. In this new form, space between antennas is not occupied rather folded lines are used between the ground plane and the side of each PIFA without disturbing their initial resonant frequency. This idea is also employed to enhancing isolation by many other researchers of mobile companies due to its simplicity, e.g., Nokia [37], LG Electronics [38], and Samsung Electronics [39].

UWB-MIMO Systems - Although this technique is very attractive and has provided good results, yet it is not employed to UWB MIMO antennas so far. It could be very difficult to couple the elements operating over the wide range of bandwidth in such a way that they cancel out mutual coupling.

3.4. Using Defected Ground Structure (DGS)

The researchers have found that the defected ground structure (DGS) is also able to provide a bandstop effect due to the combination of inductance and capacitance [40]. The defects on the ground plane store a fraction of propagating energy and that can be modeled in terms of a simple equivalent reactive circuit as was explained in detail in [41]. DGS has been applied to antenna designs to suppress harmonics, cross polarization of a patch antenna, and to increase the isolation between antennas.

Narrowband MIMO Systems - In [42], a defected ground structure (DGS) consisting of concentric circular rings in different configurations is presented and its stop band characteristics are examined. Later, this DGS is being employed to reduce mutual coupling between two cylindrical dielectric resonator antennas. About 5 dB suppression has been obtained near the operating frequency around 3.3 GHz. Other variants of this technique could be embedding of slits [43] or meander lines [44] in the ground plane. In [43], the ground plane structure consisting of five pairs of slits etched into the middle of a ground plane of two closely packed planar inverted-F antennas is proposed. These slits are interleaved with metal strips and these strips could be thought of as capacitors. At the same time, some inductance is introduced along the central small connecting strip. Therefore, the structure behaves as a bandstop filter based on a parallel resonator. As a result, such a pattern etched onto the ground plane effectively suppresses mutual coupling. A significant improvement up to 20 dB in isolation is observed in the case of monopole antennas. In [44], it has been demonstrated that meander line embedded ground plane provides better isolation as compared with slitted ground plane. Recently, a combination of two techniques, i.e., DGS and EBG, is presented in [45]. A slitted pattern is etched on the ground plane and three mushroom photonic band gap (PBG) are etched on each wall. Using two techniques together, isolation between the ports of closely-packed antenna elements is increased by 30 dB.

UWB-MIMO Systems - In [46], a diversity antenna operating at a frequency range of 3.1-5.8 GHz is designed consisting of two orthogonal half circles with the radiators placed symmetrically with respect to a protruded T-shaped ground plane, which has a slot at the upper center portion of the ground plane. This slot helps in enhancing the isolation and matching the impedance. In [47], this technique is used in real sense where circular slot antenna with a stepped ground plane is proposed. A stepped ground plane generates non-planar connections and discontinuous interfaces between the elements and the system ground planes. This strategy has effectively decreased the mutual coupling and provided 10 dB enhancements in isolation characteristics. The antenna consists of four radiating elements and operates over the range of 2-6 GHz.

3.5. Using spatial and angular variations

Narrowband MIMO Systems - The technique of using spatial and angular variations relative to the antenna elements of array is very commonly used to reduce mutual coupling. It is well demonstrated that by increasing the space between the radiating elements decorrelates them and even the spacing greater than or equal to $\lambda/2$ gives mutual coupling less than -20 dB, where λ is free space wavelength at the center frequency [48]. However, the spacing becomes less than $\lambda/2$ in the case of compact MIMO antennas for portable devices, thus it requires considering the mutual coupling effects to be compensated [49]. Therefore, in addition to separating the radiating elements by some distance, positioning of the radiating elements at different angles with respect to each other helps to reduce mutual coupling by exploiting the diversity in polarization. Chae et al. [27] has presented the detailed study using this technique. Further, the same technique is described and employed in [50].

UWB-MIMO Systems - Being very simple technique, it has not some specific constraints relating to the bandwidth but with size of the antenna. First of all, this technique is used for UWB diversity antenna by Wong et al. in [51] where the antenna consists of two truncated square monopoles orthogonally and symmetrically printed on the two sides of a T-shaped protruded ground plane as shown in Table 2. This antenna operates over 2.3-7.7 GHz giving isolation more than 20 dB. Using T-shaped ground plane also indicates that the modification of ground plane is an additional technique used together with polarization diversity to enhance the isolation. Recently, Chen et al. have used the similar technique [52]. It presents very compact UWB diversity antenna exploiting polarization diversity. The antenna elements are fed orthogonally and are designed for the lower band of UWB, i.e., 3.1-4.8 GHz. The isolation between two antennas is greater than 20 dB across the bandwidth. Also, the same research group has presented a detailed analysis of two suspended UWB plate antennas operating over 3.0-6.0 GHz in [53] for UWB-MIMO systems. They tested two configurations; (i) when shorting walls are vertically positioned (ii) when shorting walls are horizontally positioned. The effects of the variation of distance between antennas on mutual coupling, isolation and impedance matching are presented.

3.6. Inserting stubs

Narrowband MIMO Systems - The technique of using stubs to get better isolation also deals with the ground plane instead of the radiating elements. One or more stubs are inserted to enhance the isolation. To the best of our knowledge, there is no scientific publication presenting the use of this technique for narrowband MIMO systems.

UWB-MIMO Systems - The method of inserting stubs is mainly found in the literature for UWB-MIMO antennas. For instance, in [54], two elements diversity planar antenna, with three stubs on the ground plane to improve the isolation, has been proposed particularly for PDA phone. The 10 dB return loss bandwidth is achieved from 2.27 GHz to 10.2 GHz and isolation is always more than 15 dB. Similarly, another printed UWB diversity antenna consisting of two square radiators and a cross stub placed between them on the ground is presented in [55]. The 10 dB return loss bandwidth of the antenna ranges from 3.1 GHz to 10.6 GHz and the isolation between the two ports is higher than 18 dB within 3.3 GHz to 10.5 GHz.

3.7. Using heterogeneous elements

Narrowband MIMO Systems - The method of using heterogeneous elements is sometimes used for multi-band antennas in narrowband systems. The objective is then relatively different than to realize a MIMO channel.

UWB-MIMO Systems - In [56], a vector antenna system has been presented. This vector antenna system comprises a center-fed loop antenna and two orthogonal bow-tie antennas in the plane of the loop. This antenna system has large form factor and operates in the frequency range of 3.6-8.5 GHz. The isolation between the antennas is more than 15 dB and reduced mutual coupling is obtained exploiting the advantage of orthogonal components of electric field. The capability of antenna system for UWB operations is authenticated by time domain measurements. It is shown that the vector antenna can provide nearly the same capacity as a traditional spatial array.

4. Some contributions towards UWB-MIMO antennas

4.1. Introduction

A lot of UWB antennas and MIMO antennas have already been presented in the literature. But few publications have been presented on the design and characterization of MIMO antennas for UWB applications as presented in the previous section. This section deals solely with our contributions towards UWB-MIMO antennas. It presents the defined objectives and consequently the followed approaches to achieve these goals. The designs and structures of the proposed different types of MIMO antennas for UWB applications exploiting spatial, polarization and pattern diversities are described. The analysis and evaluation of performance of these proposed designs are provides taking the special parameters into account which are necessary to characterize UWB-MIMO antennas. Finally, a solution to enhance isolation with reduced size antenna is presented.

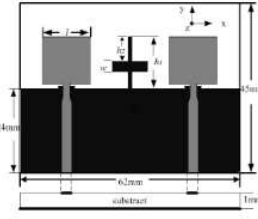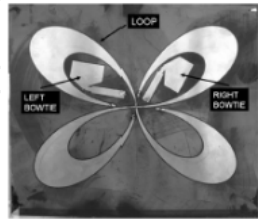| Technique	Reference	Antenna layout	Analyzed parameters
Using Defected Ground Structure (DGS)	Two cone-shaped radiating elements [46]		-substrate RO4003, 60×62 mm² -BW: 3.1-5.8 GHz -radiation patterns -gain variation: 2 dBi -efficiency: 75-93% -S_{21} < - 20 dB
Using Defected Ground Structure (DGS)	Four elements arranged as 2×2 array [47]		-substrate FR4, G×G mm² -BW: 2-6 GHz -radiation patterns -gain variation: 2.7 dBi -current distributions -S_{21} < - 25 dB
Using Spatial and Angular Variations	Two truncated square monopoles [51]		-substrate FR4, 80×48 mm² -BW: 2.3-7.7 GHz -radiation patterns -gain variation: 1.1 dBi -S_{21} < - 20 dB
Using Spatial and Angular Variations	Two notched triangular radiator [52]		-substrate: R04003, 45×37 mm² -BW: 3.1-5.0 GHz -radiation patterns -gain variation: 3.0 dBi -efficiency: 70-93% -current distributions -S_{21} < - 20 dB -correlation < - 25dB -time-domain performance
Using Spatial and Angular Variations	Two suspended UWB plate antennas with horizontal and vertical configurations [53]		-substrate 45×100 mm² -BW: 3-6 GHz -correlation < - 8dB
Inserting stubs	Two Y-shaped radiators with three stubs [54]		-substrate FR4, 64×60 mm² -BW: 2.27-10.2 GHz -radiation patterns -gain variation: 1.5 dBi -current distributions -S_{21} < - 20 dB

Technique	Reference	Antenna layout	Analyzed parameters
Inserting stubs	Two square patches with cross-shaped stub [55]		-substrate: $\varepsilon_r = 2.65$, $45{\times}62$ mm^2 -BW: 3.3-10.5 GHz -radiation patterns -gain variation: 3.2 dBi -current distributions -$S_{21} < - 18$ dB
Using heterogeneous elements	Vector antenna with one loop and two bow-ties [56]		-substrate: $\varepsilon_r = 2.6$ -BW: 3.6-8.5 GHz -radiation patterns -$S_{21} < - 15$ dB -impulse response / -phase response

Table 2. Summarized state of the art in UWB-MIMO antennas.

The objective is to design a UWB-MIMO antenna that covers the entire range of frequency approved by the FCC for UWB systems (i.e., 3.1-10.6 GHz) with minimum mutual coupling between the constituent antenna elements, thus attaining good diversity performance. The detailed specifications for the desired MIMO antenna for UWB applications are given in Table 3. To achieve the goal, two types of MIMO antennas are envisaged, i.e., homogeneous and heterogeneous MIMO antennas and are being designed. In wireless communications, the antennas are expected to be embeddable or easy to be integrated into wireless devices in system design; therefore the antennas directly printed onto a PCB/substrate are the most promising designs. Such antennas are usually constructed by etching the radiators onto the dielectric substrate of PCB slabs and a ground plane around the radiators. Taking this major argument into account, printed and planar monopoles have been selected as the constituent radiating elements for UWB-MIMO antennas.

Parameter	Value
Operating BW	3.1-10.6 GHz ($\pm$ 100 MHz acceptable)
Gain variation	Not more than 4 dBi
Radiation efficiency	High (> 70%) and variation not more than 25%
Group delay	Not more than 2 ns
Isolation	Not less than 14 dB
Correlation coefficient	Not more than – 15 dB
TARC	Not more than – 10 dB
Design profile	Compact, printed and easy to fabricate

Table 3. Design specifications for UWB-MIMO antenna.

4.2. Presentation of proposed designs

Different types of MIMO antenna systems have been proposed for UWB applications. These antennas are categorized in two groups: homogeneous UWB-MIMO antennas and

heterogeneous UWB-MIMO antennas. The term "homogeneous" refers to the fact that the identical radiating elements constitute MIMO antenna and the term "heterogeneous" is used to indicate that the constituent elements are not identical. A lot of UWB antennas have been presented in the literature. Among these antennas, printed and planar monopoles are very attractive for their efficient UWB attributes. Therefore, we have also selected printed monopoles to develop UWB-MIMO antennas.

Among the proposed and studied antennas, three homogeneous 2-elements UWB-MIMO antennas are designed using identical circular disc monopoles (system-1 and system-2) and identical stepped rectangular monopoles (system-3) and one heterogeneous 2-element UWB-MIMO antenna (system-4) is designed using stepped rectangular and circular ring monopole. The geometries of these antennas are shown in Figure 1.
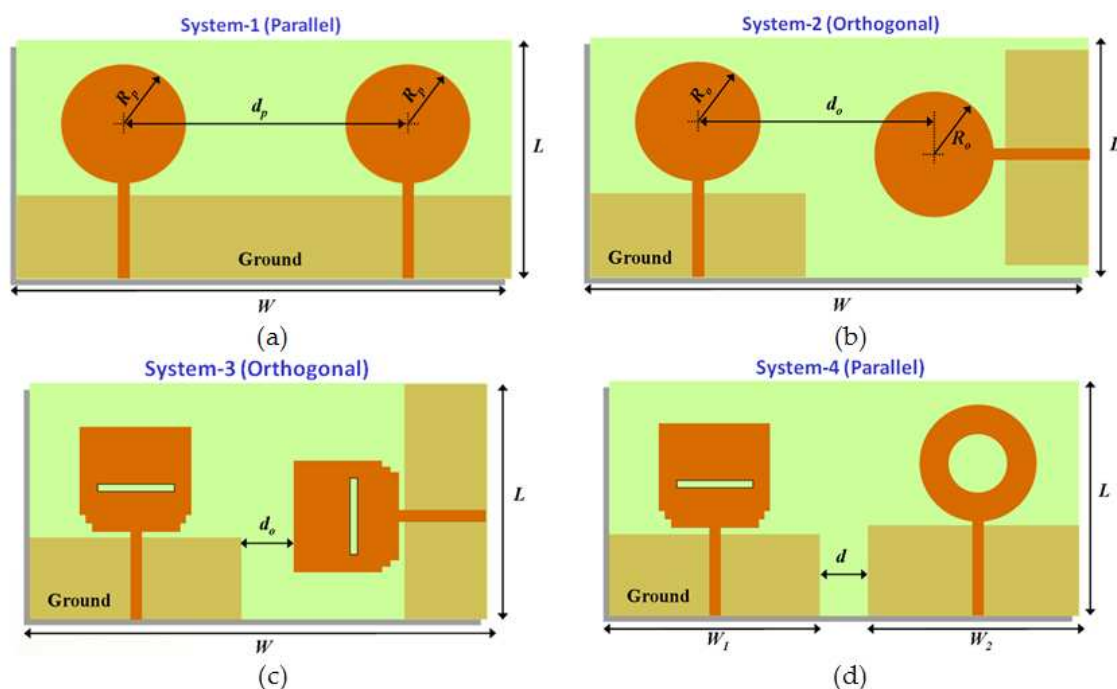
Figure 1. Geometries of designed UWB-MIMO antenna.

All the antennas are fabricated on the FR4 substrate of dielectric permittivity of 4.4, dielectric loss tangent of 0.02 and thickness of $0.8 \, mm$. The constituent printed UWB antennas i.e. stepped rectangular, circular disc and circular ring monopoles have already been presented in [57], [58] and [59] respectively. The selection of these antennas to design MIMO antennas can be justified by their good performance, size and ease of integration. However, these antennas have been redesigned to adapt the changes in substrate and thereafter optimized to reduce their dimensions as compared with those presented. It is found that partial ground plane and feed gap play vital role in matching the impedance thus increase the BW if optimally sized. The radiating elements are fed by $50 \, \Omega$ microstrip lines.

First of all, system-1 comprising two identical circular disc monopoles is designed as shown in Fig. 1a. The radiating elements have common ground plane of length of $12 \, mm$ and width of $80 \, mm$. The dimensions of the system-1 are: $= 80 \, mm \ (0.83 \, \lambda_0)$, $L = 43 \, mm \ (0.44 \, \lambda_0)$,

$R = 13.7\ mm\ (0.14\ \lambda_0)$, and $d = 43.5\ mm\ (0.45\ \lambda_0)$; where λ_0 is the free space wavelength corresponding to the lower edge frequency. System-1 is designed on the basis of using spatial diversity. The radiating elements are separated by such a value of distance that mutual coupling becomes less than $-10\ dB$. On the other hand, system-2 and system-3 exploit spatial and polarization diversities by placing the radiating elements orthogonally separated by some distance as shown in Fig. 1b and Fig. 1c respectively. The optimized dimensions of system-2 are: $L = 40\ mm$, $W = 80\ mm$, $R = 10.7\ mm$ and $d = 37.8\ mm$. Similarly, the optimized dimensions of system-3 are: $L = 30\ mm$, $W = 68\ mm$ and $d = 11\ mm$. System-4 is developed to exploit the spatial and pattern diversity therefore it consists of different radiating elements. The dimensions of system-4 after optimization are: $L = 35\ mm$, $W = 85\ mm$, $d = 20\ mm$. Both radiating elements have their own ground planes unlike system-1. It is worth mentioning that CST Microwave Studio is being used for designing and simulating the antennas. Figure 3 illustrates the UWB-MIMO performance of system-1. Figure 3a shows the simulated reflection coefficients of the left (S_{11}) and the right (S_{22}) monopoles of system-1. As illustrated in figure, the $-10\ dB$ bandwidth ranges less than 3.1 GHz to more than 10.6 GHz that confirms the UWB characteristics. Through simulations as well as from geometrical point of view, it is clear that symmetry exists for the antenna elements, i.e. S_{22} is the same as S_{11}. The radiation patterns (Figure 3c) are nearly omnidirectional at lower frequencies in H-plane. The pattern also follows donut shape at lower frequencies in E-plane, but it becomes more directional at higher frequencies. The transition of the radiation patterns from a simple donut pattern at the first resonance to the complicated patterns at higher resonances indicates that this antenna must have gone through some major changes in its behavior. The maximum absolute gain values and the total efficiency of the left and right monopoles are presented in Figure 3d and Figure 3e respectively. It can be recalled that the total efficiency of an antenna takes into account all the losses in the antenna such as reflections due to mismatch between transmission lines and the antenna, conduction and dielectric losses. From the plots, it can be noticed that gains as well as efficiencies of both elements are the same and it again confirms that the symmetry holds in system-1. The variation of the gain values along the wide range of frequencies is found to be less than 3.5 dBi for both radiating elements. The total efficiency is always more than 75% and the variation is less than 15% throughout the bandwidth of interest. The radiating elements are also characterized for their time domain performance to confirm their capability for UWB operations. The fifth derivative of Gaussian pulse is used to excite the antenna elements as this covers the FCC's defined UWB spectrum efficiently. The width of the pulse to excite the radiating elements is $0.13\ ns$ where the pulse width is measured at 50% of the maximum amplitude.

The time domain impulse response is determined by placing the probes in the far-field zone. Figure 3f shows the impulse response for both elements. It can be seen that the pulse of 0.32 ns wide is received. Figure 3g shows the group delay for both monopoles. A face-to-face arrangement with 500 mm distance between them is made to determine the group delay. The group delay is nearly within 2.2 ns throughout the whole of the required pass band. To attain better diversity performance it is important to keep mutual coupling between radiating elements as minimum as possible. The distance of 43.5 mm for system-1 is being selected on the basis of an optimization. Figure 3b shows the curves of S_{21} and S_{12}. There exists the reciprocity, so S_{21} and S_{12} are equal. Isolation is less than -10 dB. Figure 3h presents the

surface current distributions when the left monopole of system-1 is excited while the right monopole is terminated with the matched impedance. It can be observed that very low amount of current is coupled to the right monopole at first resonance and second resonance, and it is justified by the value S_{21} of at these frequencies. However, other two resonances have not also good isolations and current is coupled to some extent. Because of the symmetry of system-1, it is not required to show the current distributions when the right monopole is excited. To evaluate diversity performance into detail, the correlation coefficient is calculated from S-parameters as well as from 3D pattern (figure 3i). Finally TARC is calculated and shown in Figure 3j. It meets the requirement giving the values less than – 10 dB.
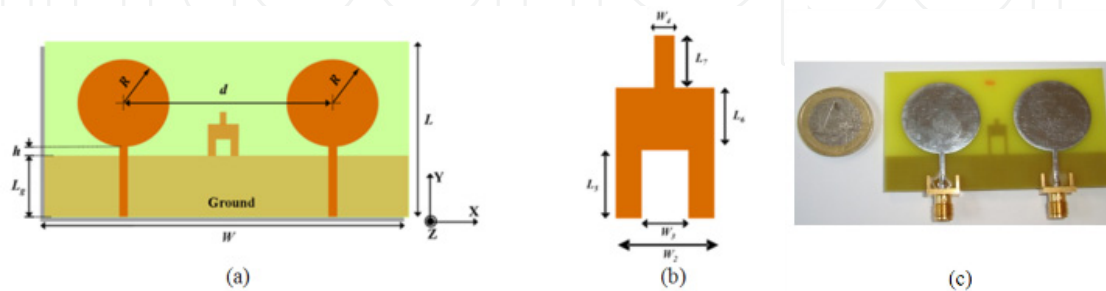
Figure 2. (a) Layout of UWB MIMO antenna (b) Detailed layout of inverted-Y shaped stub (c) photography of the prototype.

It can be noticed that the system-1 is not capable of meeting the specifications defined in Table 3 for group delay as well as isolation. The other solutions, presented previously, have been envisaged both this reason but also in order to improve the compactness. System-2 exploits spatial diversity as well as polarization diversity. The orthogonal configuration results in decorrelating the radiating elements: radiation pattern and isolation are improved while dispersion is mitigated. System-2 using orthogonal topology shows better results as it exploits the polarization diversity, however physical constraint lies regarding the antenna feeding. With comparable characteristics, system-3 constituted by two identical stepped patch monopoles presents a more compact size. System-4 is designed by integrating two non-similar radiating elements, i.e., stepped patch and circular ring monopole. The exploitation of pattern diversity eliminates the need to print the radiating elements orthogonally. Circular ring monopole nearly behaves the same as circular disc because the current distribution in the center of disc is negligible. The performance of these three solutions is presented with more details in [60], [61] and [62]. So far, the combinations of diversities to reduce the mutual coupling or to improve the isolation have been exploited. The antennas can be reduced in size if some special technique is used to overcome the problems of coupling and isolation between the radiating elements. From system-1, a novel UWB-MIMO antenna (called system-5) has been designed with enough compact dimensions taking advantage of a stub which is inserted on the ground plane. The design of stub, a sort of inverted-Y shape, is initiated from the idea of microstrip LC filters. The introduced stub behaves like a stopband LC filter; therefore it suppresses efficiently the currents from the excited port to the inactive port. The best position of the stub is found to be the middle of the ground plane. The performance has been evaluated numerically and experimentally [63]. Figure 4 displays the measured and simulated reflection coeffcients for the antennas with stub and without stub. It is noticed that the measured results
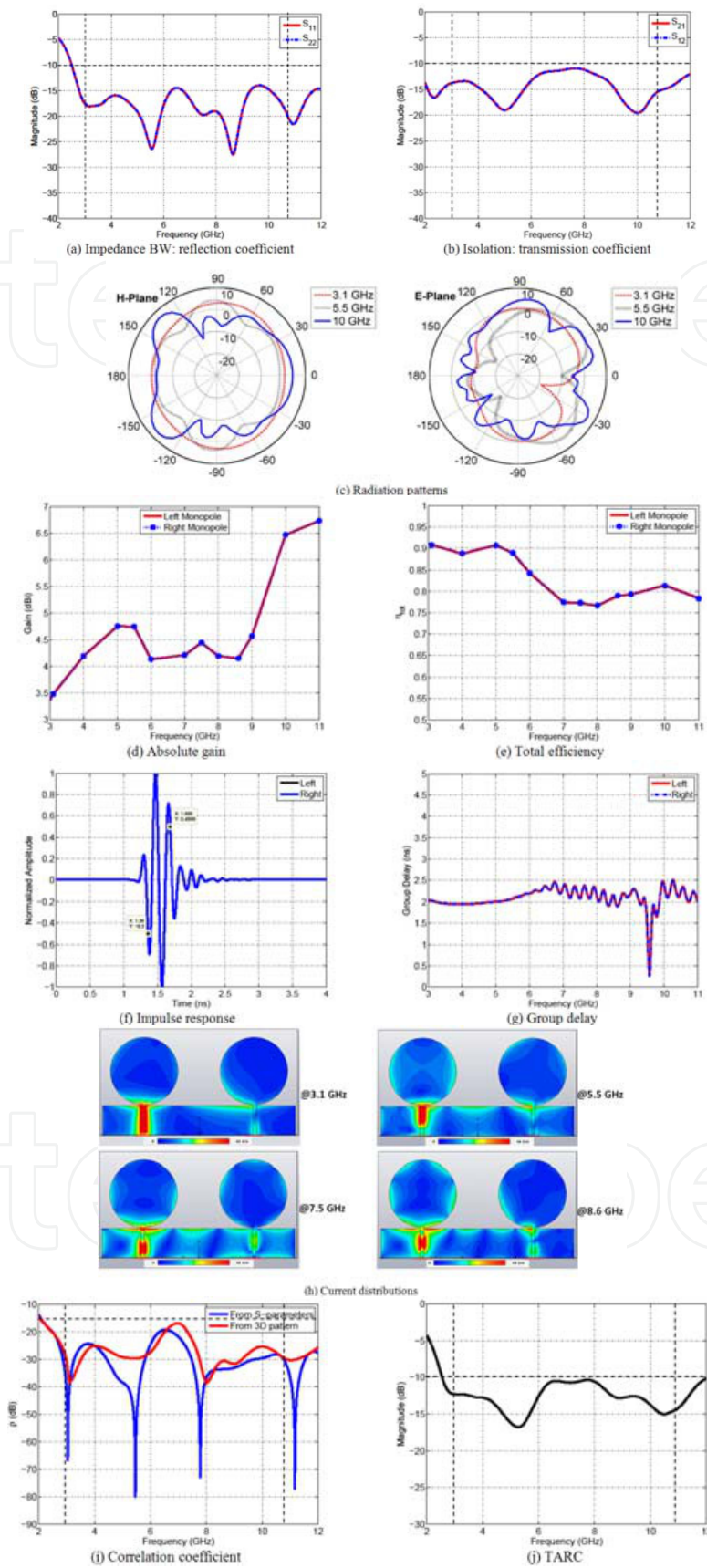
Figure 3. UWB-MIMO antenna performance of system-1.

agree with the simulated ones. The important point to be noticed is that the impedance BW remains the same, i.e., 3.2-10.6 GHz. Further, figure 5a gives the measured and the simulated port isolations for the case when there is stub and figure 5b depicts the results when there is no stub. It is clear from the measurements that the insertion of stub has played a vital role in enhancing the port isolation. System-5 is more compact and efficient as compared to system-1, and verifies the constraints given by table 3.

(a) S_{11} (with stub)   (b) S_{11} (without stub)
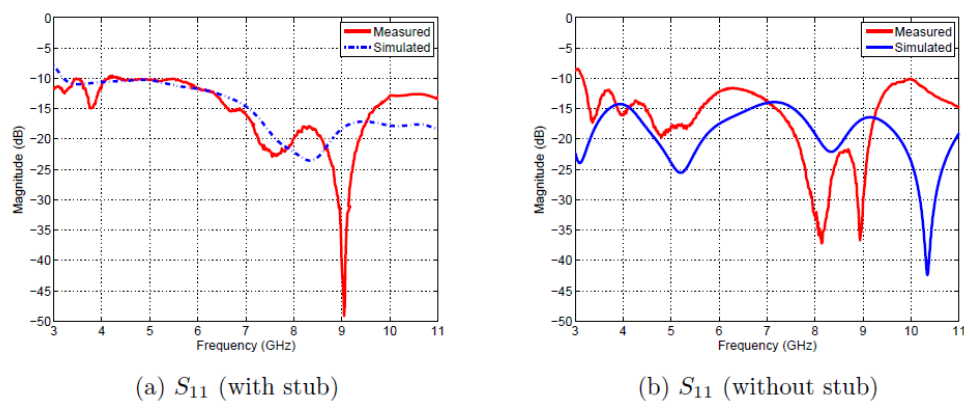
Figure 4. Measured impedance characteristics.

(a) S_{21} (with stub)   (b) S_{21} (without stub)
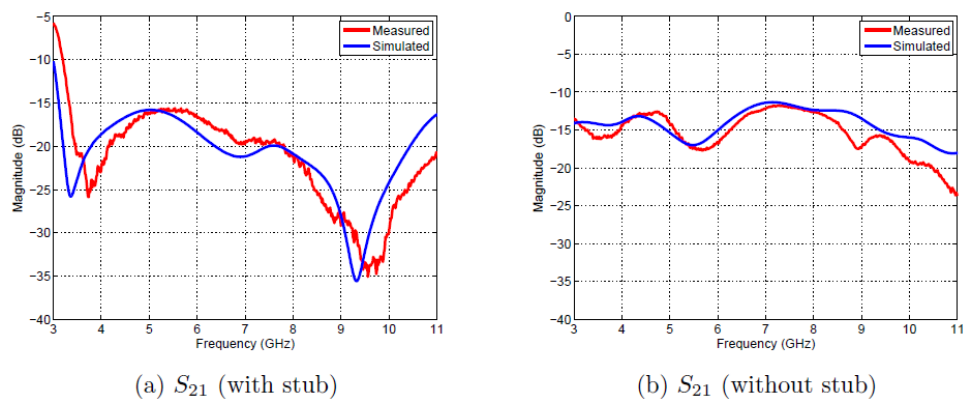
Figure 5. Measured diversity performance of UWB-MIMO antenna.

5. Conclusion

Taking a little overview of UWB and MIMO, it makes easier to understand the idea of implementing MIMO technique in UWB communications systems. As per FCC rules, extremely low power is being allowed to be transmitted, i.e. – 41.3 dBm/MHz, and it impedes the development of UWB communication systems with higher data rates or covering longer distances. To overcome this bottleneck, MIMO technique has been considered to be one of the solutions that will improve the reliability and the capacity of UWB systems. However, a number of challenges arise to shape this solution physically. In this chapter, we took the challenges into account related to antennas as their properties play a key role in determining MIMO system performance. Table 4 summarizes the presented UWB-MIMO antennas and compares the performance.
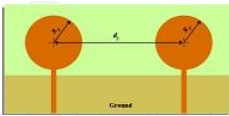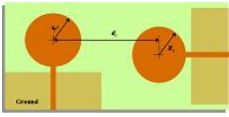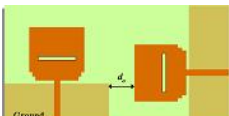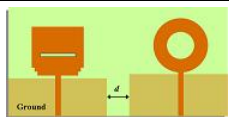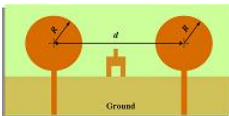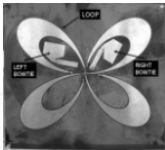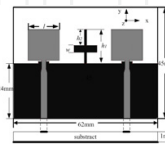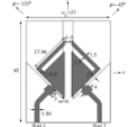
Topology	Size (mm²)	Impedance BW (GHz)	Radiation pattern	Variations in gain (dBi)	Efficiency (%)	Group delay (ns)	Isolation (dB)	Correlation (dB)	TARC (dB)
system-1 [60]	43×80	3.1-10.6	Distorted	3.5	75	2.2	11	- 17	- 10
system-2 [60]	40×80	3.1-10.6	Nearly original	3.5	80	1.7	15	- 28	- 10
system-3 [61]	30×68	3.2-10.6	Nearly original	2.5	74	0.8	15	- 20	- 10
system-4 [62]	35×85	3.1-10.6	Nearly original	2.5	73	1.2	14	- 20	- 10
system-5 [63]	40×68	3.2-10.6	Nearly original	2.2	78	1	15	- 20	- 9.5
[56]	125×125	3.6-8.5	Nearly original	--	--	--	15	--	--
[55]	45×62	3.3-10.5	Nearly original	3.2	--	--	18	--	--
[52]	45×37	3.1-5.0	Nearly original	3.0	--	--	20	--	--

Table 4. Summary: performance comparisons of presented UWB-MIMO antennas.

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