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Design of MIMO Antennas for Ultra-Wideband Communications

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Résumé
La radio Ultra Large Bande (ULB) est un bon candidat pour les transmissions sans fil car elle nécessite de faibles puissances en transmission et utilise des dispositifs faibles coût. Cependant en raison du faible niveau des signaux transmis, les systèmes ULB sont limités à des applications sur courtes distances ou alors à débits modérés. Par conséquent pour envisager la faisabilité et le futur succès commercial de ces systèmes, il est crucial de déterminer une solution permettant la meilleure utilisation possible de la puissance rayonnée et reçue. Dans ce contexte, l'utilisation des techniques MIMO (Multiple Input Multiple Output) semble être une réponse très intéressante. Il a été montré que les techniques MIMO utilisées dans les systèmes UWB permettront d'améliorer la robustesse du lien de communication et le débit des données. Mais ceci impose quelques défis liés à la conception de ces systèmes d'antennes, comme la réduction du couplage mutuel et de la corrélation entre les éléments de ces systèmes. Dans cet article, nous présentons des systèmes d'antennes ULB de la littérature et ceux que nous avons proposés. Nous soulignons plus particulièrement l'ensemble des méthodes que nous avons adoptées pour résoudre les défis de conception liés à la bande de fréquences dédiées à la technologie ULB [3.1 – 10.6 GHz], en termes d'efficacité, de diversité, de rayonnement, de taille, etc.

Abstract
UWB radio has proved itself a suitable candidate for its low power and low cost design. However, very low transmitted power in UWB systems limits the applications to short range or to moderate data rate. Therefore, it is crucial to find some solution that will make the best possible use of radiated and received power, for the feasibility and future commercial success of UWB communication systems. In this context, research is carried out and MIMO has been found one of the best solutions. MIMO technique in UWB systems will improve link robustness of UWB or data rate. But some challenges arise in designing of the MIMO antenna systems for UWB applications. These challenges include the reduction of the mutual coupling and the correlation between the elements of the antenna systems. In this article, antenna systems proposed in the literature as well as by authors have been discussed. Some techniques have been presented to face these challenges. Finally, proposed UWB-MIMO antenna systems in the frequency band of 3.1 – 10.6 GHz are efficient in terms of diversity, radiations, size, etc.

Mots-clés : Antenne diversité, antenne planaires, couplage mutuel, MIMO, UWB

Keywords : Diversity antenna, mutual coupling, MIMO, planar antenna, UWB.

1 Introduction

1.1 UWB

Ultra Wideband (UWB) is a very promising technology for short-range wireless communications providing the opportunity of high data rate communications [1,2]. In 2002, the Federal

Communication Commission (FCC) regulated the UWB technology utilisation for commercial applications in the United States in the frequency range of 3.1–10.6 GHz [1]. 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 Radio (IR) [2]. The MB-OFDM divides the UWB spectrum in 14 sub-bands, the utilisation of the bands is managed for a code time-frequency exploiting the spatial-temporal diversity [3], while the IR transmits pulses of very short duration that occupy the entire allowable frequency band [4]. However, this article focuses on the UWB impulse radio aspects.

1.2 MIMO

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, multi-path, increasing interference and limited spectrum. MIMO technology exploits multi-path 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 diversity (spatial, polarization or pattern diversity) to increase the strength of the transmitted signals and therefore to improve the SNR. Spatial multiplexing in MIMO systems helps in increasing data rate. Beam-forming is used either to increase data rate or to strengthen the signal.

1.3 Objectives and Challenges

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 [1] 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 [7]. However, a number of challenges arise to shape this solution physically. In this paper, we will take the challenges into account related to antennas as their properties play a key role in determining MIMO system performance.

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.

2 State of the Art on UWB-MIMO Antennas

A lot of UWB antennas and MIMO antennas have already been presented in the literature. But very few publications have been presented on the design and characterization of MIMO antennas for UWB applications [8,9,10,11]. In [8], a vector antenna with large form factor, consisting of a loop antenna and two orthogonal bowtie antennas on a substrate of $\varepsilon_r = 2.6$, is presented operating in the frequency range of 3.6-8.5 GHz. The mutual coupling is always less than -15 dB because the bowtie and loop antennas have dominant radiating components in vertical and horizontal planes, respectively. In [9], two antenna systems fed by 50 ohm co-axial probes have been designed where each antenna system consists of two suspended UWB plate antenna elements operating at 3.0–6.0 GHz and installed on a finite size system ground plane related to the mobile phone. The correlation analysis is performed for both systems and a value of less than 0.5 is achieved. In [10], 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 mutual coupling is always less than -15 dB. Further, four-element MIMO antenna system with enhanced isolation, by introducing discontinuities between elements and the system ground plane, has been presented in [11]. The obtained results show very good isolation i.e. 20 dB. However, the system works over the frequency range of 2.0-6.0 GHz.

3 Authors' Contributions

3.1 Design and Structure of Antenna Systems

Different types of MIMO antenna systems have been proposed for UWB applications. The designed systems show good impedance characteristics in the frequency band of 3.1-10.6 GHz, thus fulfilling the FCC requirements for UWB communications. These systems also have very low mutual coupling and correlations, so they provide good diversity performance. These MIMO antennas are composed of either identical stepped patch or identical circular disc monopole elements. Both planar UWB antennas fed by 50 Ω microstrip line i.e. stepped patch and circular disc monopole have already presented in [12] and [13] 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 dimension as compared with those presented in [12] and [13]. First of all, in [14], a compact antenna system comprising two identical stepped patch elements has been proposed as shown in Fig. 1. The dimensions of the antenna system are: W = 68 mm, L = 30 mm and d = 8 mm. The stepped patch elements have been integrated on a single substrate (1.6 mm thick) orthogonally with respect to each other. This geometrical configuration is well justified by comparing with 0 degree and 180 degree positions of two antenna elements on the basis of S-parameters.

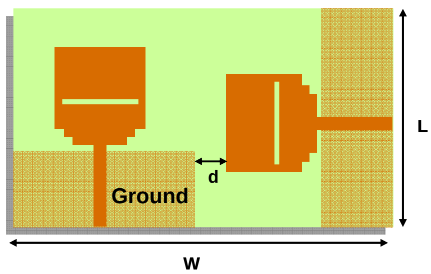

FIG. 1 - UWB-MIMO antenna system with two identical stepped patch elements

Another antenna system is presented in [15] that consists of two identical circular disc monopoles as shown in Fig. 2. The monopoles elements have been placed in the same position on a single substrate FR4 of 0.8 mm thickness and 0.0029 dielectric losses.

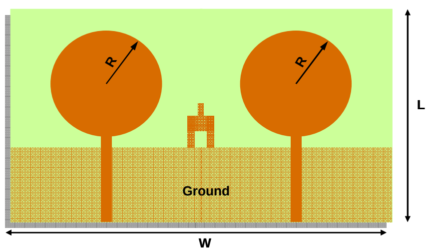

FIG. 2 - UWB-MIMO antenna system with two identical circular disc monopoles

From [14], it was being learnt that parallel placement of identical elements causes much coupling between the elements. Therefore, in this design, a stub is being used to reduce the mutual coupling. This results in a compact antenna system and easy to integrate as both elements can be fed on the same side. The dimensions referred to Fig. 2 are: R = 12 mm, W = 40 mm, L = 34 mm.

A four-element diversity antenna has been proposed in [16]. Four identical circular disc monopole elements have been integrated on FR4 substrate of 0.8 mm thickness as shown in Fig. 3. The radii of the discs and the dimensions of ground planes are optimized to ensure the required impedance bandwidth. The distance *d* between adjacent elements is optimized to attain as low mutual coupling as possible. In addition to this, the isolation is being improved by exciting the elements in orthogonal polarization. The dimensions of the proposed antenna system are: R = 10.7 mm, W = L = 80 mm and d = 37.8 mm.

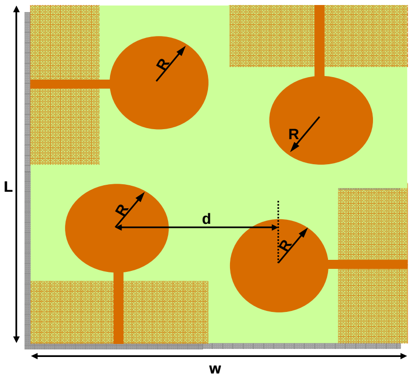

FIG. 3 – A 4-element UWB-MIMO antenna system with identical circular disc monopoles

Above-mentioned proposed systems are not pertinent to some specific application and are generally applicable to any type of UWB wireless communication systems using MIMO techniques. The commercially available CST Microwave Studio is used for the design, the optimization and the simulations.

3.2 Performance Evaluation of Antenna Systems

Under this heading, it has been discussed that what types of parameters can be used to evaluate the performance of MIMO antennas for UWB applications. The objective of this paper is to describe our research work and our contribution, therefore all the results of three proposed antenna systems have not been presented. However, some of them have been shown as an example.

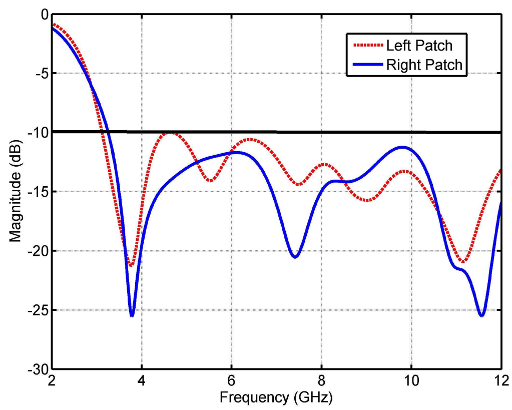

FIG. 4 – Reflection coefficients of left and right patch elements of antenna system of Fig. 1

3.2.1 Impedance Matching

Whenever antennas are being designed, impedance matching is the most demanding feature. It can be characterized by the reflection coefficient (S_{11}). Generally, it is well understood that S_{11} less than -10 dB gives good impedance matching. All three proposed antenna systems have good impedance matching in the range of frequency of interest i.e. 3.1 – 10.6 GHz. As an example, Fig. 4 shows the reflection coefficient curves for both elements in antenna system proposed in [14]. It can be noticed that S_{11} is not equal to the S_{22} i.e. symmetry does not exists due to orthogonal position of the elements.

3.2.2 Radiation Patterns & Gain

It is being considered good to have an omni-directional pattern of the antennas provided they are being employed in the wireless devices. For UWB antennas, it is not an easy task as the range of frequency is very wide. The radiation patterns of each element of the proposed UWB-MIMO antenna systems have been simulated in both planes i.e. E-plane and H-plane. Nearly, an omni-directional pattern is being achieved in H-plane. For example, Fig. 5a and Fig. 5b show the radiation patterns of left stepped patch element of antenna system [14] at frequencies 4, 6, 8 and 10 GHz in both H and E planes respectively.

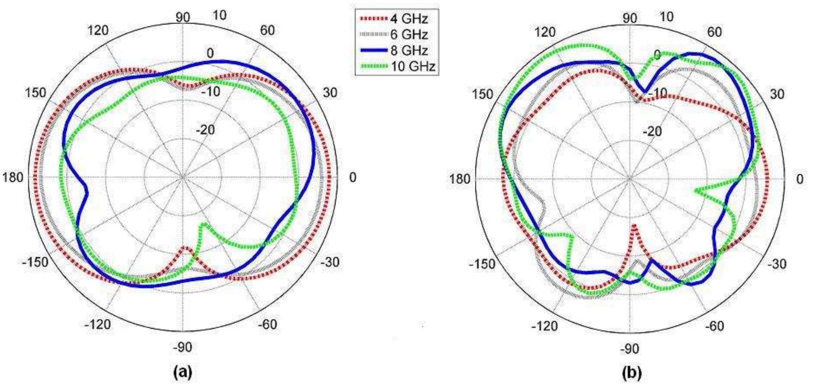

FIG. 5 – Radiation patterns of left stepped patch elements in (a) H-plane and (b) E-plane

Also, whenever radiation patterns are discussed, the gain and antenna efficiencies are being noticed. The gain variations should be low for antennas to avoid the distortions in the signals over wide range of frequency. The overall gain variation obtained for system, shown in Fig. 5, is not more than 3.6 dBi and the antenna efficiency is also 89%.

3.2.3 Impulse Response

This parameter to evaluate the performance of the antennas is typically related to UWB antennas design. The pulses are transmitted in UWB communication (UWB-IR), therefore this parameter becomes very significant. It measures the distortion of the transmitted pulse through the antennas. Fig. 6 shows the impulse response of the antenna element of the system [15]. A pulse of 0.18 ns width (measured at 50% of maximum amplitude) is being used to excite one element. It has been observed that signal received at probes has width of 0.22 ns.

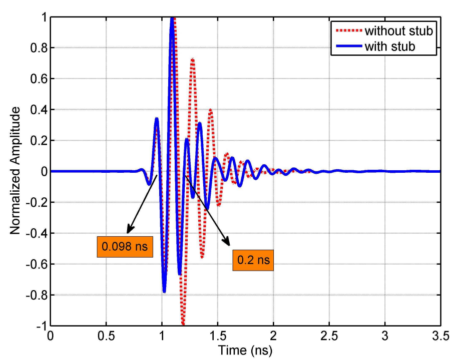

FIG. 6 – Impulse response of an element of antenna system of Fig. 2 with and without stub

3.2.4 Mutual Coupling

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. Now 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. The mutual coupling can be measured by S_{12} and S_{21} parameters when one of the two elements of the antenna system is excited while the other is terminated with matched impedance, i.e. 50 Ω. Also, in the literature, different techniques have been presented either to reduce the mutual coupling or to enhance the isolation. The matching and decoupling networks have been used to improve diversity performance of two-port antenna in [17]. A neutralization technique to enhance port-to-port isolation is presented in [18] where two PIFA structures (one with folded neutralizing link and other with inverted U-shaped neutralizing link) have been presented. The modification of ground plane is made to reduce the mutual coupling i.e. a slot is inserted in [19] and ground plane discontinuities have been introduced in [11]. The orthogonal placement of radiating elements with respect to each other is used in [20]. Three stubs have been inserted on the ground plane to enhance the isolation in [10].

In the same context, our proposed antenna systems also exploit the same ideas to reduce the mutual coupling. In [14], low mutual coupling has been obtained on the basis of geometrical configuration i.e. orthogonal placement of antenna elements as shown in Fig. 1. In [16], in addition to geometrical placement, antennas are placed enough apart to optimize the isolation between four elements as shown in Fig. 3. An inverted Y-shaped stub has been inserted on the ground plane of antenna system proposed in [15] as shown in Fig. 2. The advantage of the addition of the stub is that the mutual coupling is well reduced even though antennas are closely packed, thus giving a very compact design. For this design, Fig. 7 presents the mutual coupling. It can be clearly noticed that S_{21} is less than -15 dB throughout the frequency band of interest. Also, it is worthy to mention, the antenna system holds the reciprocity and symmetry, and therefore S_{21} and S_{12} are the same.

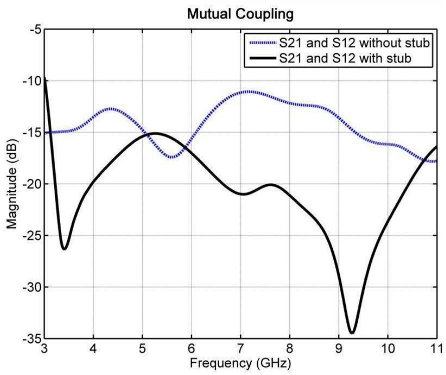

FIG. 6 – Mutual coupling between the elements of antenna system of Fig. 2

3.2.5 Correlation and Diversity Gain

It becomes important to measure the degree of correlation between two antenna elements where diversity is exploited in the systems, for instance in MIMO systems. The minimization of the correlation is required to evaluate the diversity performance of the systems because of the inverse relationship between the correlation and diversity gain. There exists an approximate relationship between diversity gain (G_{app}) and correlation (ρ) that can be written mathematically [21] as in Eq. (1),

$$G_{app} = 10 * \sqrt{1-|\rho|} \qquad (1)$$

The correlation coefficient can be calculated from radiation patterns or scattering parameters. For a simple two-port network, assuming uniform multipath environment, the envelope correlation (ρ), simply square of the correlation coefficient, can be calculated conveniently and quickly from S-parameters [22], using Eq. (1) given as in Eq. (2),

$$\rho = \left| \frac{S_{11}^* S_{12} + S_{21}^* S_{22}}{\left(\sqrt{1-|S_{11}|^2-|S_{21}|^2}\right)\cdot\left(\sqrt{1-|S_{22}|^2-|S_{12}|^2}\right)} \right|^2 \quad (2)$$

Fig. 8 shows the plot of envelope correlation in dB over the frequency range for the system proposed in [14]. Generally, it is considered that antennas with a level of envelope correlation less than -6 dB are capable of providing significant diversity performance [23]. From the results, it can be seen that the correlation for the proposed antenna system is less than -20dB that is quite good.

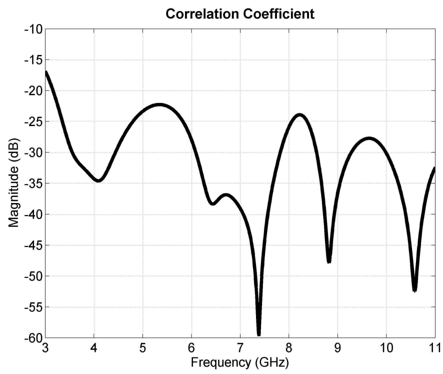

FIG. 8 – Calculated envelope correlation of antenna system of Fig. 1

4 Conclusions and Perspectives

The design of antenna systems on the basis of idea of using MIMO techniques combined with UWB systems has been discussed. The conventional characteristics of antennas like impedance matching, radiation patterns and gain to evaluate their performance as well as specific characteristics like impulse response, mutual coupling, correlation and diversity gain have been presented. The designed antenna systems work efficiently in the band of 3.1-10.6 GHz. Furthermore, these are compact, planar and low-cost. These antenna systems can be employed in handheld wireless devices. Further applications could be medical imaging and localization.

Future work includes the development of prototypes of these systems and to justify the simulations with measurements. Also, more detailed study is required on the characterization of antennas in terms of capacity evaluation. A study on how to feed these systems is also remaining.

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