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Review Article

Ultra Wideband (UWB) Multiple Input Multiple Output (MIMO) Antenna : A Review

Firdaus[1,2], Rahmadi Kurnia[1], Ikhwana Elfitri[1]

[1]*Electrical Engineering Department, Faculty of Engineering, Universitas Andalas, Padang, Indonesia 25163*
[2]*Electrical Department, Politeknik Negeri Padang, Indonesia 25164*

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E-mail: firdaus@pnp.ac.id

A B S T R A C T

Since the Federal Communication Commission (FCC) issued a license for the 3.1 – 10.6 GHz frequency spectrum for unlicensed radio applications, many papers have been published regarding ultrawideband (UWB) antenna design. The issue of UWB antenna design is determining how to create an antenna with a wide bandwidth, capable of rejecting communication systems that coexist with UWB bands, and capable of designing UWB antennas for multiple input multiple output (MIMO) communication system applications. This study examines the design of UWB antennas with monopole and slot types based on evaluations published over the last two decades. The discussion began with UWB and MIMO systems and then moved on to the configuration of monopole and slot UWB antennas. UWB antenna layout with notched bands and the several types of notched bands available. Finally, two port and quad-port MIMO antenna configuration is examined. To further understand UWB antenna design, numerous UWB antenna configurations are simulated. The outcomes of this review can be utilized as preliminary reading material for researchers looking into UWB antennas.

INTRODUCTION

The Ultra Wideband (UWB) system has been around since Hertz introduced radio communications nearly 100 years ago. Hertz developed a comprehensive radio system, which included a spark gap dipole antenna as a transmitter and a loop antenna as a receiver [1], [2]. The gap antenna loop might receive sparks from the transmitter. A spark is a short-duration pulse with a large bandwidth. Systems that use short pulses are referred to as ultra-wideband communication systems. Sending pulses of short duration with a very wide band was considered a disadvantage at the beginning of radio communication since it occupies a large frequency spectrum. Therefore, at that time the research switched to a narrow band system which was considered more efficient in the use of the frequency spectrum [1].

In the 1960s, the UWB system was revived for military applications, and subsequently for commercial applications in the 1970s [2]. The Federal Communication Commission (FCC) awarded a permit for UWB communications in the 3.1 - 10.6 GHz frequency band in 2002, with a maximum radiation power limit of - 41 dBm [3]. With this low power, the UWB system has many advantages, including high data transfer rates, the ability to work at low SNR, being difficult to detect by other systems, being resistant to jamming, having good performance in multipath conditions, and being a carrier less system, which simplifies transceiver design [2].

According to Shanon's theorem, the greater the bandwidth, the greater the data transfer rate. Therefore with the UWB system, the data transfer speed of the system will increase [4]. However, because of the power limitation on the UWB system, it will limit the data transfer speed. By combining a UWB system with a Multiple Output and Multiple Output (MIMO) system, the shortage due to this power limitation can be overcome [5]. The MIMO system uses Diversity Technology so that data can be sent effectively in a multipath fading environment and increase channel capacity. By combining UWB and MIMO technologies, a communication system with very high data transfer rates can be realized [5].

Along with the development of the UWB system, research on antennas and propagation for UWB systems is also developing [6]. Separately, antenna research and propagation for MIMO systems are becoming more advanced. MIMO antennas have numerous antennas on both the trasmitter and receiver sides. Similarly to UWB antennas, MIMO antenna was developed based on the dipole antenna and then developed into a monopole antenna on the substrate material to get a smaller size and better performance [7]. Due to the multipath environment, the design of MIMO antennas depends on the layout and design of the antenna

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elements and mutual coupling between the antenna elements. Numerous researches have been published on UWB MIMO antennas. In this paper, we make a review of UWB MIMO antennas design. Furthermore, some insights and basic knowledge are provided to help the reader understand the UWB MIMO antenna design.

UWB MIMO SYSTEM

UWB Basic

The UWB system, as previously stated, is a wireless communication system without a carrier. Data transfer employs very short pulses (picosecond - nanosecond or duty cycle less than 0.5%), resulting in a low average transmission power of approximate microwatts, thousands of times less than the power released by mobile phones. The instantaneous power of UWB pulses can be high, but since they are transmitted over such a short period, the average power is significantly lower. Since frequency is inversely related to time, a short duration pulse would disperse its energy over a large frequency range from near DC to a few GHz with a low power spectral density of -41 dBm/MHz, equal to 75 nanowatt/MHz. Because of this power restriction, UWB systems can operate below the noise level of a conventional narrow band receiver, allowing UWB signals to coexist with existing radio services with little or no interference.

Improved channel capacity is one of the key benefits of the huge bandwidth for UWB pulses. The greatest quantity of data that may be carried per second through a communications channel is defined as channel capacity or data rate. The large channel capacity of the UWB communication system can be proven from Hartley-Shannon for information capacity formula :

$$C = B\log_2(1 + SNR) \quad (1)$$

where C is the channel capacity, B is the bandwidth and SNR is the signal-to-noise ratio. As shown in equation (1), the channel capacity increases linearly with bandwidth. For pulses with a bandwidth of several GHz, it will produce a transfer rate of several Gigabits per second (Gbps).

The multipath fading phenomenon will result in the degradation of the narrow band signal if the direct path signal and the non-direct path signal are in different phases. This does not happen to UWB signals because the signal is transmitted in a short duration, so the possibility of a collision between the direct path signal and the reflected path will be very small. But that does not mean the UWB system is immune to distortion due to multipath. based on previous research, depending on the type of modulation used, the UWB signal will experience large distortions in a lot of scattering conditions.

Unlike the narrow band system, the UWB system can penetrate a variety of different materials because the UWB signal contains a large frequency band. Through-wall detection applications can also be performed by UWB signals. As mentioned earlier, the data information UWB system is not modulated to a continuous carrier signal with a certain carrier frequency like a narrow band system. As a result, the UWB system has fewer RF components. The UWB system's design and architecture will be significantly simpler and less costly. A power amplifier at the transmitter is not required for low-power transmission. Because the UWB system is carrierless, no oscillators or mixers are required. As with narrowband technology, carrier recovery is no longer required at the receiving end.

Besides the advantages, many challenges are faced in realizing the UWB system. UWB signals with low power will experience a very significant distortion during transmission. So the estimation of the channel in the communication system will be much more complicated. The narrow pulse duration causes time synchronization to be a major challenge and has been widely studied in UWB communication system studies. Multiple access interference is also a big challenge in UWB systems. Because of the low power, it makes separating the desired signal from multiple access interference very difficult.

MIMO System Principle

The MIMO system uses multiple antennas on the transmitting side and receiving side to get a higher data transfer rate. Information bits are sent independently by several transmitters and several receivers. Figure 1 shows a MIMO communication system. The input data will be fed in parallel as s_1 to s_{Nt} and respectively modulated by an identical modulator and transmitted in parallel by several N_T antennas that are spatially separated and received by the N_R receiving antennas which are also spatially separated.

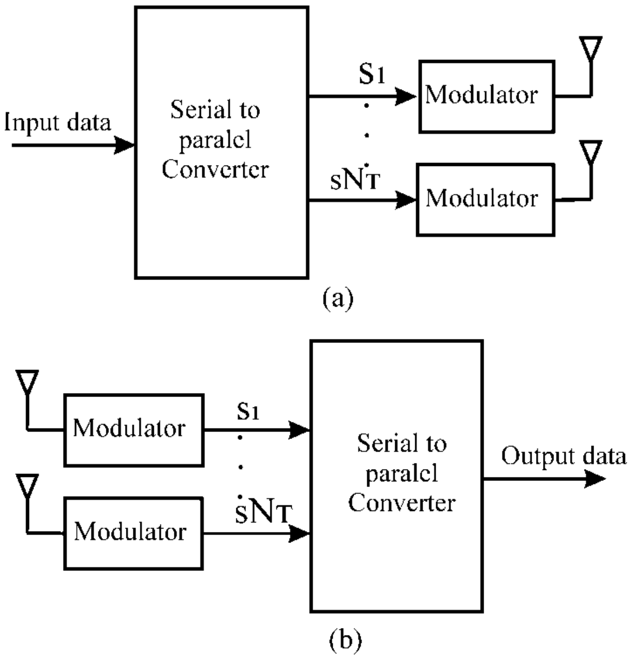

Figure 1. MIMO Communication System (a) Transmitter, (b) Receiver

The demodulator output can be written in matrix form as:

$$\boldsymbol{y} = \boldsymbol{Hs} + \boldsymbol{n} \quad (2)$$

where $\boldsymbol{y} = [y_2, y_2, y_3, \dots, y_{N_R}]^t$, $\boldsymbol{s} = [s_1, s_2, s_3, \dots, s_{N_T}]^t$, $\boldsymbol{n} = [n_1, n_2, n_3, \dots, n_{N_R}]^t$ while $\boldsymbol{H}$ is the channel matrix $N_R \times N_T$. In the discrete model, a MIMO system with multiple antennas at each interval is depicted in Figure 2.

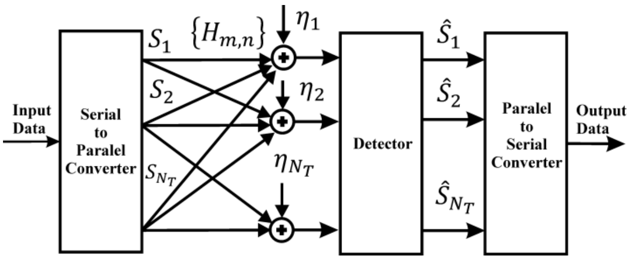

Figure 2. Discrete-time model MIMO Communication System with multiple Tx and Rx antennas

Using an Inverse Channel Detector (ICT) $\boldsymbol{s},$ it can be estimated by combining the received signals linearly. By setting $N_T = N_R$ and choosing the weight matrix $\boldsymbol{W}$ so that interchannel interference can be eliminated where $\boldsymbol{W}^H = \boldsymbol{H}^{-1}$thus:

$$\hat{\boldsymbol{s}} = \boldsymbol{H}^{-1}\boldsymbol{y} \tag{3}$$
$$\hat{\boldsymbol{s}} = \boldsymbol{s} + \boldsymbol{H}^{-1}\boldsymbol{n} \tag{4}$$

If $N_R > N_T$, the weight matrix $\boldsymbol{W}$ can be chosen as the pseudo inverse of the channel matrix, namely:

$$\boldsymbol{W}^{\boldsymbol{H}} = (\boldsymbol{H}^{\boldsymbol{H}}\boldsymbol{H})^{-1}\boldsymbol{H}^{\boldsymbol{H}} \tag{5}$$

UWB MIMO ANTENNA STRUCTURE

In the early days of UWB technology, the antennas used were biconical, horn, and bowtie antennas and their applications were limited to the military [6]. After the FCC released permission to use the unlicensed frequency 3.1 – 10.6 GHz. Antenna design becomes simpler with PCB materials and various applications such as radar, imaging, on body area networks.

There are several UWB antenna designs on PCB found in the literature including planar monopole [8]–[10] planar dipole[11], slot[12], diamond [13], bowtie[14], and cone [15]. In this paper, we will discuss Monopole and Slot UWB antennas.

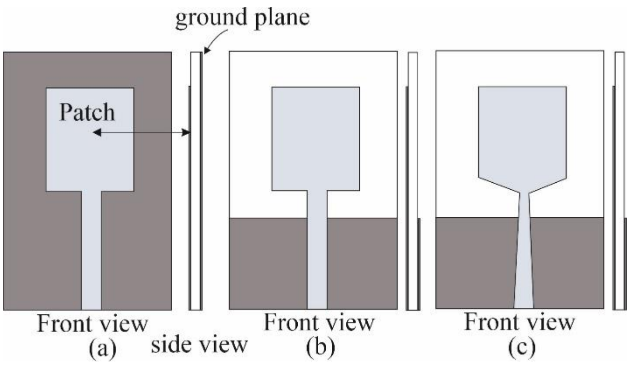

Figure 3. Antenna patch monopole (a) conventional (b) UWB (c) UWB with tapered side and tapered feed.

Monopole Uwb Antenna

The monopole UWB antenna structure consists of a monopole radiator and a partial ground plane. where the ground plane is an important part to get a wide bandwidth impedance [16]. The monopole UWB antenna is a modification of the conventional patch antenna which is designed on a substrate material with two layers of conductors. The conventional patch antenna is shown in figure 3(a). The antenna radiator is in the form of a rectangular patch and is fed with a 50-ohm microstrip line on one of the conductor layers. The patch can be square, circular, triangular, or other planar shapes. The other conductor layers function as a ground plane where the dimensions of the substrate are the same as the dimensions of the ground plane. This antenna produces a narrow band frequency response and unidirectional polarization. The standard patch antenna design formula can be found in [17]. The patch antenna simulation results using the formula in [17] for a frequency of 8 GHz are shown in Figure 4.

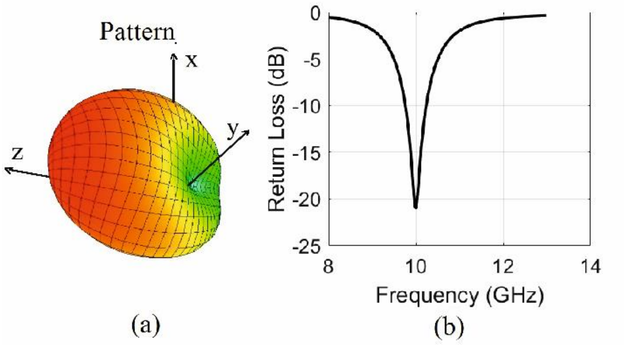

Figure 4 Patch antenna simulation results for the 8 GHz frequency. (a) Conventional patch antenna radiation pattern and (b) S11 [16]

By modifying the ground on the standard patch antenna to become a partial ground plane as shown in Figure 3(b), there will be a change in the frequency response and antenna polarization. By reducing the ground plane, you can see a gradual change in working frequency from narrowband to wideband. In figure 5 can be seen the shift in L_g to the S11 (return loss) curve.

Figure 5 shows the results of a patch antenna simulation using an FR4 substrate with dimensions of 8 × 30 × 1.6 mm and a dielectric constant of 4.4, patch length of 11 mm, a patch width of 8 mm, and a 50-ohm microstrip line. Changes in the length of the ground to the value of S11 were noted in the simulation. It can be shown that the antenna resonates at 7.9 GHz and has a narrow band response under the initial conditions with L_g = 30 mm. When L_g = 15 mm, the bandwidth widens and falls below – 4dB. Figure 7 depicts the change in the value of L_g. The change in the size of the L_g ground plane gradually makes the antenna radiation pattern slowly change from unidirectional to omnidirectional. This is because by gradually shifting L_g from 30 mm to L_g = 15 mm the patch area is increasingly open so that it is no longer covered by the ground plane and the patch can radiate electromagnetic waves in all directions.

For good impedance matching conditions, the S11 response should be below –10 dB, hence from the design in Figure 5, it is necessary to adjust the impedance matching betwen the patch and microstrip line. It can be done by adding a tapered side to the patch [8], a linear tapered impedance transformer on the feedline and a trident-shaped feeding strip [18]. By changing the design of Figure 5 to a patch with tapered sides and adding tapered transformers to the feedline, a better impedance matching is obtained, where the S11 curve is below -10 dB for frequencies 4.2 - 11.3 GHz as shown in Figure 6. Adding a tapered side to the patch provides the improved resonance and slightly increases the bandwidth at high frequencies, while the addition of a tapered side transformer enables the antenna to achieve UWB band impedance.

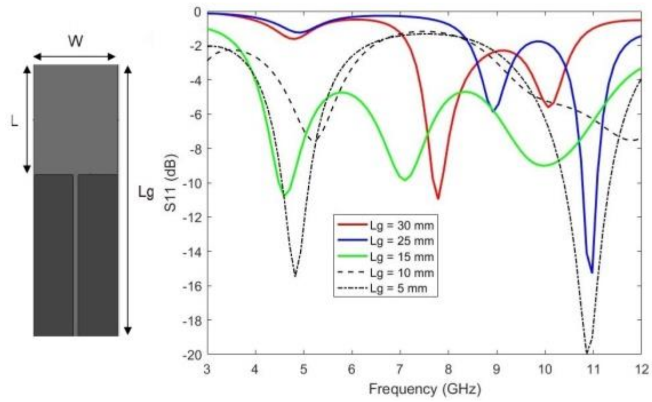

Figure 5. Change of ground length to patch antenna frequency response

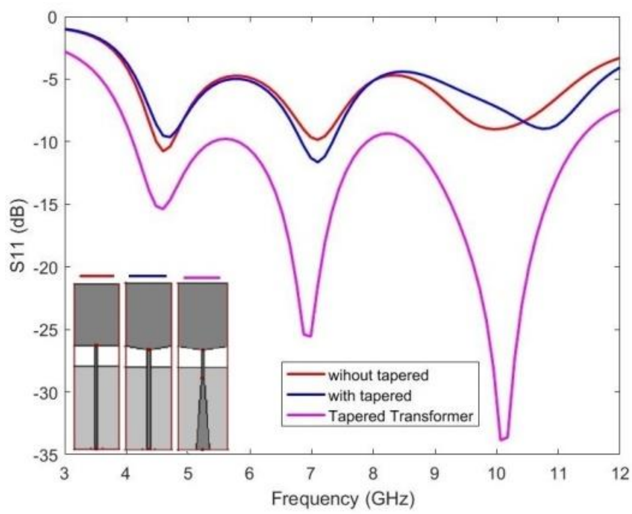

Figure 6 Effect of transformers on impedance matching in UWB antennas

Besides using tapered transformers to achieve impedance matching, several other methods that we find in the literature are Coplanar waveguide signal strips terminated with a semi-elliptic stub [19], a two-step microstrip feed line[20], by modified truncated ground plane[21], defected ground structure [22]–[26], ground plane width selection on Coplanar waveguide fed [27], modified ground plane in the form of an L-shaped stub, and a rectangular slit [28], modified patch shape modified bottom side of the patch [29].

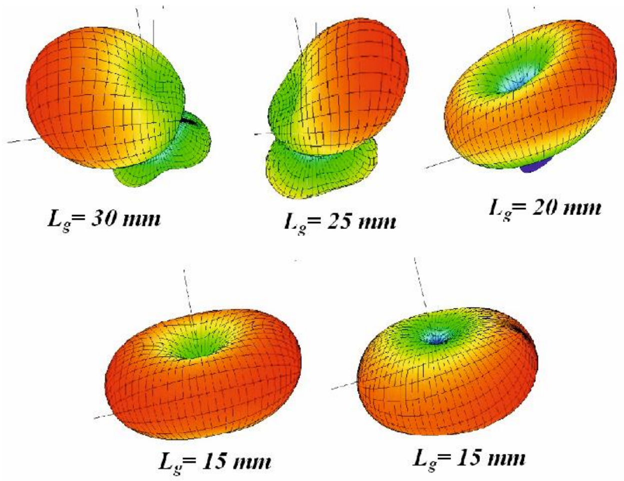

Figure 7. Changes in patch antenna polarization to changes in ground length on monopole patch antennas

Several narrow band applications overlapping with UWB frequencies include WiMAX (3.3 – 3.7 GHz), WLAN (5.15 – 5.875 GHz), and X-band (7.1 – 7.9 GHz). As previously explained, the UWB system will not interfere with narrowband systems in the UWB band. But the signal from the narrowband system can be very large and can interfere with the UWB system. For this reason, UWB antennas are expected to have band notched that can cancel the interference signal. For this purpose, several ways can be done in designing UWB antennas including adding stubs [29], [30], slot [31], [32] slit [33], Split Ring Resonator (SRR) [23], Open Loop Resonator [34] and electromagnetic band gap [35]. An illustration of the band-notched method is illustrated in Figure 8. The actual dimensions and performance of each method can be studied in the respective literature mentioned.

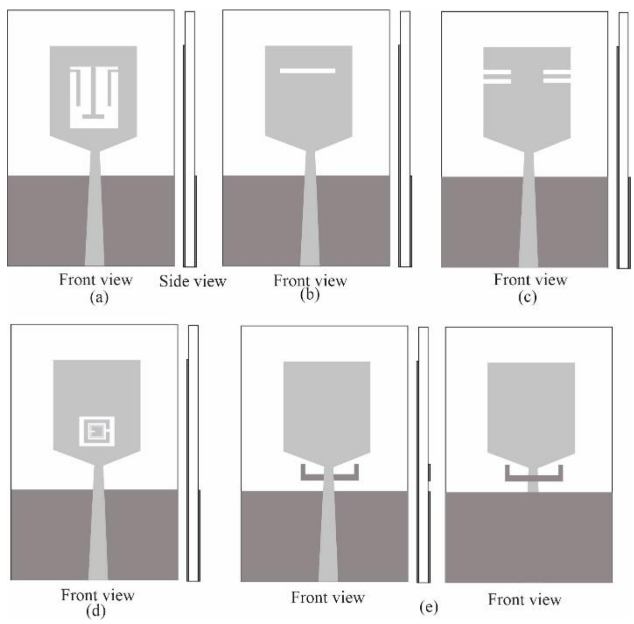

Figure 8 UWB antenna with band-notched, (a) stub, (b) slot, (c) slit, (d) SRR, (e) Open loop Resonator

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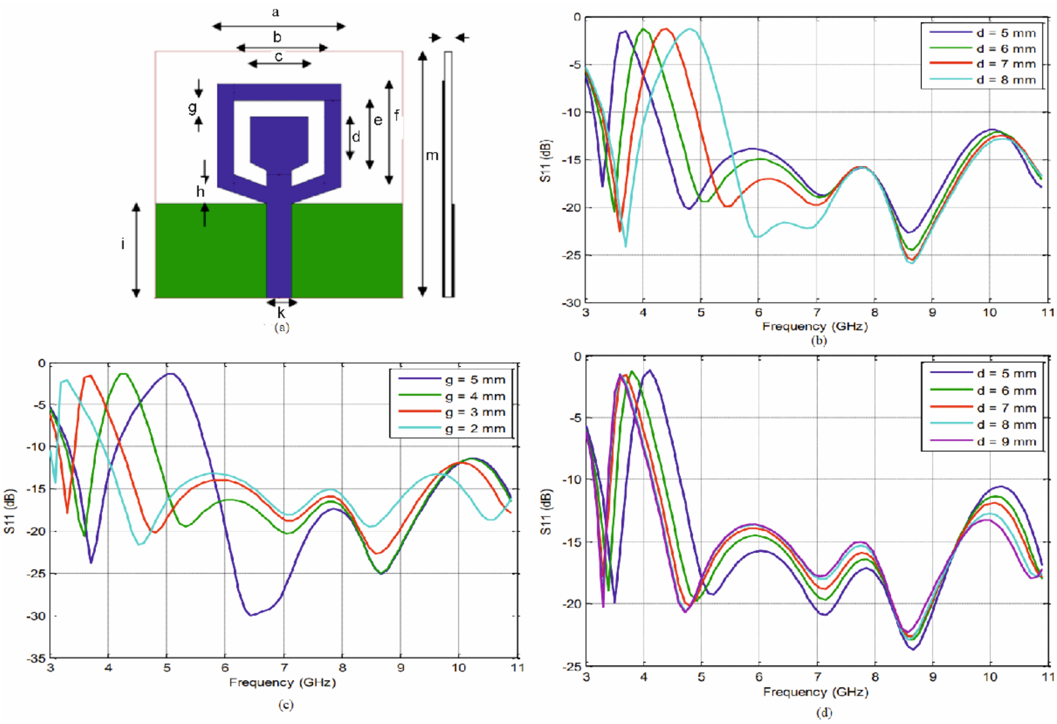

Figure 9. Simulation of slot dimensions as notched bands

One method that has been simulated and tested is the slot method as shown in Figure 9. A rectangular patch antenna with a C-slot and a partial ground plane with a size of 30×30 mm overall size. The substrate used is FR4 with a dielectric constant of 4.3 and a thickness of 1.6 mm. The antenna is fed with 50-ohm microstrip line. The antenna design is shown in figure 8(a) where a = 15 mm, b =11 mm, c = 7 mm, d =4.5 mm, e = 8.5 mm, f = 12.5 mm, g = 2 mm, h= 2 mm, i =11.5mm, k =3mm, l =1.6mm. m= 30mm. The simulation results and antenna measurements can be seen in Figure 10. The simulation results in the same notched band as the experimental findings. However, at high frequencies, the impedance matching results are not as excellent as the simulation findings. To achieve the precision of simulation and measurement, antenna printing and soldering require high accuracy. The notched band may be simply modified by adjusting the values of c, d, and e, as illustrated in Figures 9(b) – 9(d). To obtain the results of a soft notched band tuning, change the value of c; for coarser tunings, use e or d.

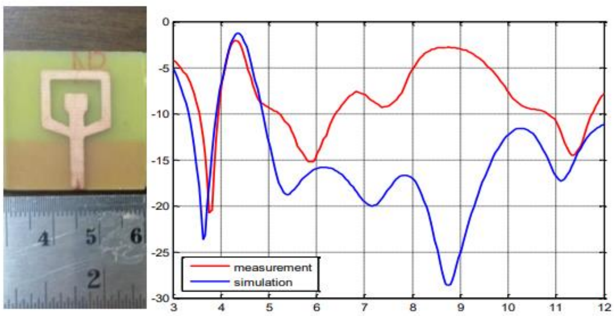

Figure 10. Comparison of measurement and simulation on UWB antenna with C-shape slot

Dual Port Monopole Uwb Mimo Antenna

The monopole UWB antenna design is popular for MIMO applications. Taking into account the needs of MIMO antennas including isolation between elements and impedance adjustment in wideband. UWB MIMO antennas can be built using multiple UWB antennas according to the multiple antennas used in the MIMO system. MIMO 2 × 2 can be implemented by using two monopole UWB antenna elements. The antenna design for mobile devices or hand-held devices is expected to be as small as possible so that they can be easily installed on the device. Therefore it requires that the antennas are in adjacent positions. So that in MIMO applications the mutual coupling between antennas must be as small as possible. For that, we need good isolation between antenna elements. To get good isolation between MIMO antenna elements there are several strategies that we find in the literature. To get good isolation, monopole antennas can be positioned perpendicular to each other [36] [37] [38]. The illustration is shown in figure 11(a). To increase the impedance bandwidth, protruding ground stubs are added to the ground plane [36] or by adding T-shape stubs to the patch [37], or by making the monopole patches complementary to one another. Grounds can be connected to form a common ground [36] or use a common ground [37] [38]in order to increase the isolation.

Some of the UWB MIMO antennas do not use perpendicular patch positions, but remain in the same position [39]–[45]**.** To obtain good isolation between elements, a stub is added as a decoupling structure on the ground [39]–[43], [46]. A decoupling structure is an additional structure on a UWB antenna to increase the isolation between antenna elements. The illustration is shown in Figure 11 (b). From the literature, we also get that monopole patch antennas can be formed opposite or complementary each other to increas the mutual coupling as shown in Figure 11 (c).

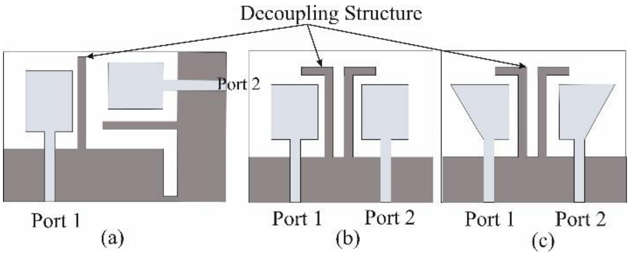

Figure 11. Two port MIMO with three enhanced isolation methods. (a) perpendicular monopole element, (b) same element position (c) complementary monopole element.

To get the band notched on the MIMO antenna, it use the same method that we found on the monopole UWB that was presented in the previous subsection, namely adding slots [38], slit [46][47], EBG [48], SRR [49]. Figure 12 is a simulation and measurement of a UWB MIMO antenna with the monopole antenna elements arranged parallel to the C-shaped slot. It can be seen that the slot can reject the 5 – 5.2 GHz frequency band. There is a slight difference between simulation and measurement. Isolation between elements is achieved by adding L-Shape stubs and defected ground structure. The simulation results show very good isolation, that is, all are below -20 dB. On the measurement, the isolation around low frequency is slightly decreased.

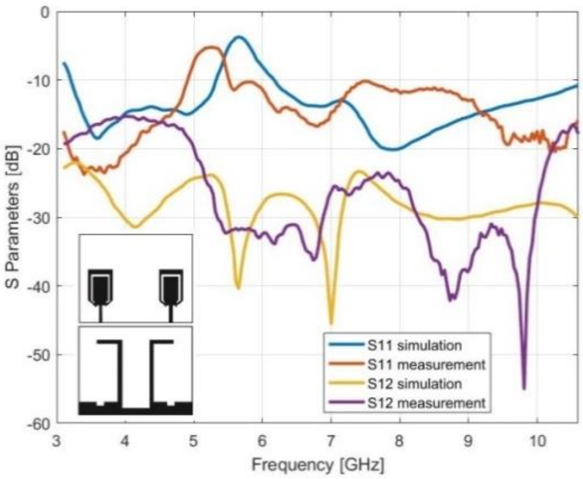

Figure 12. UWB MIMO Antenna with Band Notched

Dual Port Slot UWB MIMO Antenna

To reduce the dimensions of the antenna, a slot antenna is an option that can be considered. A slot λ/2, long, cut in an infinitely stretched-out conducting surface and fed in the centre of the sides, radiates a wave in the same way as an antenna. The radiating slot can be compared to a straight λ/2 dipole, because both radiators are geometrically complementary to each other as despicted on figure 13(a) and 13(b). Directional pattern of both antenna structures are the same, whereby the vectors of the electric and magnetic fields of the complementary antenna in the far-field region, are exchanged with each other Slot antennas have the same dimensions and are similar to dipole antennas. There will be electromagnetic wave radiation on both sides of the slot. The dipole antenna's radiaton pattern is donut-shaped, but the slot antenna radiation pattern is bidirectional, with maximum radiation occurring in the center of the slit and minimum radiation occurring at both ends of the slot. If the slot antenna is formed in the shape of an open slot on one side of the plate, as shown in Figure 13 (c), a unidirectional radiation-pattern antenna is created. To enhance antenna bandwidth can achieve by constructing a slot in stepped-slot or modifying it logarithmically as shown in Figure 13 (d).

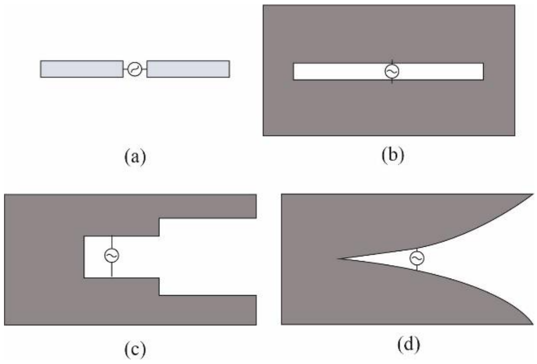

Figure 13. Antenna Slot (a) dipole (b) slot, (c) step slot, (d) vivaldi

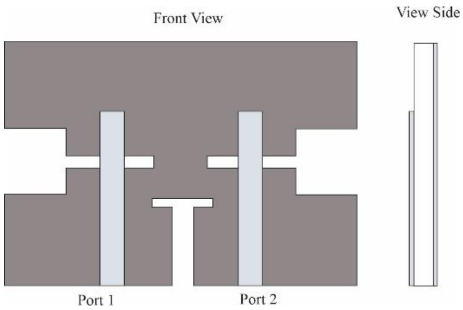

Figure 14 Antenna UWB MIMO Slot

Slot antennas can also be made using PCB substrate materials. By using a double layer PCB substrate, slots can be made on one layer and feedlines on another. To design a 2 x 2 MIMO slot antenna can be done by assembling two open-ended slot antennas on one of the metal conductor layers and feeding in proximity with microstrip lines on another metal conductor layer as shown in Figure 14 which is redrawing antenna design on [50]. Positioning the slots in opposite directions (self-complementary), will increase the isolation between the antenna elements. Several MIMO antennas were found to adopt the same structure as [50] such as [51], [52], and [53]. To increase the impedance matching characteristic at low frequencies and reduce mutual coupling at high frequencies, a T-shape slot is added to the ground plane. Impedance matching can also achived by adding transformers to the feed line as in[45], [46], [51], [53]. The band-notched techniques for UWB MIMO slot antennas are using z-shape slots on the ground plane [52], slit on ground plane [46], and split ring resonators placed adjacent to the feedline [53]. To reduce the dimensions of the antenna, a common slot is used as has been examined in [46] with isolation achieved by using two orthogonal microstrips feed-lines in [54].

To understand the performance of the following UWB MIMO slot antenna, we simulate the antenna design on [52] with the design shown in Figure 15. The simulation results are shown in Figure 16. The performance of the MIMO antenna is shown by the isolation between the antenna elements or mutual coupling which is observed through S11 and S12 parameters. Antenna isolation is expected to be greater than 15 dB. In Figure 16 the isolation is quite good at frequencies from 5 to 8 GHz and 9 to 11

GHz. However, it decreases at low frequencies ranging from 3 to 4.5 GHz. This is due to manufacturing tolerance, feeding cables utilized, and the use of SMA connections.

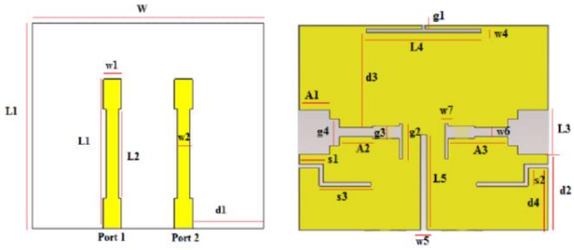

Figure 15 UWB MIMO slot antenna design [52]

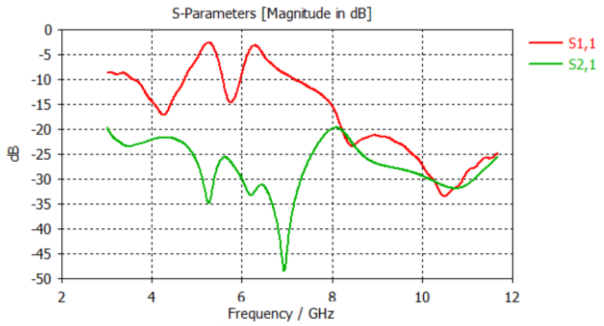

Figure 16 Simulation results

The researchs of shared slots on UWB antennas was studied in [46], [48], [54]**.** The purpose of implementing a common slot is to reduce the dimensions of the antenna to be more compact size. UWB MIMO and band-notched performance is achieved by the design of the microstrip line feed and the decoupling structure. To strengthen the isolation between elements in [54]**,** line feeds are placed in complementary places to each other. In [48] isolation between elements is achieved by positioning the radiators perpendicular to each other. The notched band is applied by adding slits on the radiator and decoupling the structure in the form of parasitic strips. In [46] isolation between elements is also achieved by placing the microstrip channels perpendicular to each other. The T-shape is added to improve isolation over just using a line feed, while the notched band is achieved by etching a slit in the ground plane.

Quad Port Monopole Uwb Mimo Antenna

For a quad-port or 4×4 UWB MIMO system, monopole antennas can also be built perpendicular to each other to obtain good isolation between adjacent elements. In the literature, various monopole shapes are found, including quasi-rectangular [55]–[58], circular with fractal-shaped circles [59] or the shape of the Covid-19 virus [60], and annular rings [61]. The illustration of quad port UWB MIMO antenna is shown in Figure 17. To increase isolation as in a dual port UWB antenna, a decoupling structure is added in the form of grounded stub among monopole [59], [61], in the form of planar [55] or strip line [58], [60], [62] between adjacent monopole elements. Notched band applications also use almost the same method as dual ports UWB MIMO antenna, such as adding slots on monopoles [55]–[57], [59], [60] slit on the ground [60], slit and split ring resonator on radiator [63].

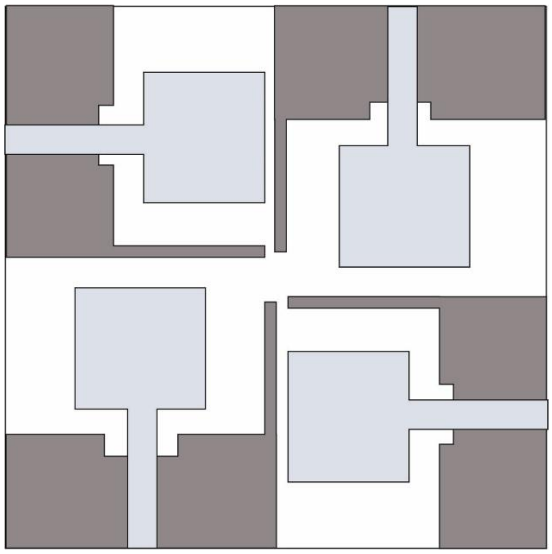

Figure 17. UWB MIMO antenna with monopole element

CONCLUSIONS

UWB antenna design has been discussed, beginning with the fundamental UWB and progressing to a UWB with notched band characteristics, as well as the several types of notched bands that have been published. It has also been considered for 2-port and 4-port systems for UWB MIMO applications. To evaluate the performance of the UWB antenna, several configurations were simulated and measurements were discussed.

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