

Miniaturized Antenna Array with Low Correlation for Telemedicine and Body Area Networks Applications

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Abstract: The gain from Multiple-Input Multiple-Output (MIMO) techniques in wireless sensor networks equipped with miniaturized sensor nodes cannot be fully exploited due to the difficulty encountered when placing traditional multiple antennas with sub-wavelength physical separation. This paper presents a novel antenna array design using μ -negative metamaterial (MNG) structures that lead to low correlation between antennas when placed closely on a user's body utilizing a telemedicine or a Body Area Network based system. The obtained correlation coefficient of 0.04 is low enough for realizing full diversity gain from using such antenna array on sensor nodes in a telemedicine WLAN environment. Furthermore, Bit Error Rate (BER) simulation result for a 2×2 Alamouti diversity scheme in an IEEE 802.11a system is also presented. Design and simulations are conducted using CST Microwave Studio which is based on the Finite Integration Technique. Results suggest that the proposed design would be a suitable candidate for telemedicine and BAN applications that are constrained by limited space.

1 INTRODUCTION

Telemedicine has evolved rapidly over the past decade due to the increasing demand for remote health monitoring of post-surgery patients, recovery tracking, seniors, athletes, fire fighters and astronauts (Fong et al., 2012). In telemedicine systems, important health parameters such as body temperature, blood pressure, and heart rate are transmitted wirelessly to remote monitoring stations (clinics, hospitals, etc...) (Algaet et al., 2013).

Obviously, a reliable wireless scheme which is enabled by a use of antenna(s) is required for optimal performance of such systems. In this specific case, antennas are required to be small in size, lightweight, robust with desired radiation characteristics. They also need to be comfortable and conformal to the shape of the body. Microstrip antennas offer a favorable advantage in terms of a close to hemi-spherical radiation pattern, i.e. radiates away from the user's body, thus, minimizes the exposure to electromagnetic radiation. Furthermore, they offer a low profile solution, low cost, and ease of fabrication (Khaleel et al., 2010). However, this class of antennas suffers from a very narrow bandwidth, hence, a low profile antenna with a

directional radiation pattern and a wide bandwidth is essential in telemedicine applications. Several techniques have been proposed to achieve directional radiation pattern by adding a cavity or a shielding plane underneath the antenna, or using absorbers (Haga et al., 2009). However these techniques lead to either an unacceptable increase in the antenna's height, or a more complicated manufacturing process. In (Rowe et al., 2003), a PEC reflector was inserted between a human head and a folded loop antenna. This approach increases the return loss and decreases the antenna's efficiency. In (Islam et al., 2009), a Single Negative Metamaterial (SNG) is utilized to reduce the electromagnetic exposure, though efficient, it leads to a high profile system. Flexible Artificial Magnetic Conductor (AMC) based antenna is proposed in (Raad et al., 2013) for telemedicine application. A polyimide based printed antenna is integrated with an AMC ground plane which is utilized to minimize the specific Absorption Rate (SAR) and the impedance mismatch caused by the human tissues proximity. Although the proposed design offers a low profile solution, it is relatively large in some applications.

On the other hand, MIMO techniques employing

multiple antennas at one or both ends of a wireless communication link have shown the potential to reach higher spectral efficiencies (Chou et al., 2008), (Abouda et al., 2006). By combining signals at transmit antennas and receive antennas, MIMO substantially improves either data rate using Spatial Multiplexing (SM) or reliability using diversity techniques. Space-Time Block Code (STBC), known as Alamouti scheme (Alamouti, 1998) for two transmit antennas, is the simplest technique with linear receiver complexity to improve the reliability of a wireless communication system. The capacity and reliability of MIMO systems depend on the Signal-to-Noise Ratio (SNR) and the correlation properties among the channel transfer functions of different pairs of transmit and receive antennas (Shiu et al., 2000). One of the basic requirements to realize the gains from MIMO systems is low correlation in the effective channel. The correlation comes from three sources, namely, the correlated fading channel, correlation among the transmit antennas, and correlation among the receive antennas. The correlation between two antennas depends on the coupling and isolation between them (Kyritsi et al., 2003). The coupling in turn is dependent on the physical separation between antennas and the matching network.

Several papers including (Caban et al., 2007) have previously presented analysis and simulation of the effect of correlation between antennas on the performance of Alamouti STBC scheme. The Alamouti scheme starts losing performance as the separation between the two antennas reaches somewhere between 0.1λ to 0.3λ . The size of traditional antenna is a major concern in placing multiple antennas on a miniaturized sensor node. The free space wavelength for the frequency band at 5.2 GHz, used in WLAN, is 5.77 cm. To obtain low correlation for WLAN applications with physical separation between antennas to be $\geq \lambda/2 = 2.88\text{cm}$ is not difficult. However, application of MIMO in wireless sensor networks, especially in medical applications, requires multiple antennas to be placed on tiny sensor nodes. To place multiple antennas with physical separation of $\geq \lambda/2$ on a sensor node is very challenging using traditional antenna technologies.

This paper presents a unique antenna design and antenna array based on metamaterial that leads to correlation coefficient of 0.42 without isolation structure and 0.04 with proper isolation between antennas. We present the design, radiation pattern of antennas and BER performance of using them in a WLAN system.

The design of the model of the proposed system along with antenna correlation is introduced in Section 2. The antenna design is presented in Section 3 where both geometries and characteristics of the antenna and the metamaterial structures are provided. The error performance results of the proposed antenna system are introduced in Section 4. Finally, we conclude the paper in Section 5.

2 SYSTEM MODEL WITH ANTENNA CORRELATION

We considered a MIMO system with 2 transmit and 2 receive antennas having Alamouti STBC (Chou et al., 2008) encoder that maps the two consecutive symbols x_1 and x_2 to two antennas over two symbol periods at the transmitter. The correlation coefficient between the two transmit antennas Tx1 and Tx2 is α . The transmitted signals pass through a Rayleigh flat-fading wireless channel with a (2×2) channel matrix H with element $h_{ij} = \alpha_{ij} \exp(j\theta_{ij})$ representing the gain between transmit antenna j and receive antenna i and additive white Gaussian noise (AWGN). The correlation coefficient between the two receive antennas Rx1 and Rx2 is β . The decoding is based on linear combining of signals received at the two antennas over two symbol periods. This scheme performs maximum likelihood detection of x_1 and x_2 using simple linear combining. The discrete channel model for a (2×2) MIMO system is given below in (1)-(3).

$$Y = C_R H C_T X + N; X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, Y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \quad (1)$$

$$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}, N = \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \quad (2)$$

$$C_T = \begin{bmatrix} 1 & \alpha \\ \alpha & 1 \end{bmatrix}, C_R = \begin{bmatrix} 1 & \beta \\ \beta & 1 \end{bmatrix} \quad (3)$$

The correlation matrices between antennas at the transmitter and receiver are given by C_T and C_R , respectively in (3). The simple implementation of linear combiner at the receiver would lead to a minimal increase in the complexity of receiver at a sensor node. The performance gain from using Alamouti scheme has a direct relationship with the coupling between the two antennas. The coupling depends on the physical separation between the antennas. When we consider a two transmit antennas scenario, the correlation coefficient for a uniform distribution of sources is given by (4). The assumption of uniform distribution holds quite well in an indoor environment. In (4), S_{11} , S_{12} , S_{21} , S_{22} , are

scattering S-parameters for the antenna system. The S-parameters takes into account the relationship between voltage and current at the input and output terminals of the antenna, the loading, and matching network employed. The analytical derivation of S-parameters is quite involved and requires several approximations. The terms S_{12} , and S_{21} contain the effect of mutual coupling between antennas. The correlation coefficient can be computed either using (4) after obtaining the S-parameters from full-wave 3-D electromagnetic simulation of antennas or through measurement of antenna prototypes or using (5) from the three-dimensional far-field radiation pattern.

$$\rho_{12} = \frac{|s_{11}^* s_{12} + s_{21}^* s_{22}|^2}{(1 - (|s_{11}|^2 + |s_{21}|^2))(1 - (|s_{12}|^2 + |s_{22}|^2))} \quad (4)$$

$$\rho_{12} = \frac{\iint_{4\pi} \bar{G}_1 \bar{G}_2^* d\Omega}{\sqrt{\iint_{4\pi} \bar{G}_1 \bar{G}_1^* d\Omega \iint_{4\pi} \bar{G}_2 \bar{G}_2^* d\Omega}} \quad (5)$$

3 ANTENNA DESIGN

As mentioned previously, the reduction of mutual coupling between closely-spaced antenna elements is essential to the performance of MIMO systems due to the fact that the mutual coupling affects the phase and distribution of the current, input impedance and radiation pattern in each antenna element which significantly reduces the capacity of the MIMO systems. Several techniques have been reported to reduce the mutual coupling between radiating elements in MIMO systems. Some of these techniques are based on the use of Electromagnetic Band Gap (EBG) structures (Ikeuchi et al., 2011), defected ground plane (Caloz et al., 2004), and the use of μ -Negative (MNG) structures. In (Bait-Suwailam et al., 2010), MNG structures have been used to reduce the mutual coupling between two high profile monopoles, where the achieved reduction in mutual coupling was 20 dB. In this paper, we utilize MNG to reduce the mutual coupling between two conformal micro strip radiating elements sharing a common substrate intended for applications that require compact space, i.e, wearable medical devices and miniaturized sensor nodes. When MNG structures are excited with a specific polarization, an electric current is induced through the loops of split ring resonators, as a consequence, the structures act as magnetic dipoles and an effective medium with a negative permeability over a certain frequency range is

generated. As a result, the existence of real propagating modes is prevented within this medium (Pendry et al., 1999). This behaviour is utilized to block the mutual coupling between the radiating elements of the proposed antenna. The proposed design consists of two elliptical shaped patch elements with a major axis of 14 mm and a minor axis of 4 mm placed on a 19 mm \times 14.5 mm \times 0.85mm RO3006 substrate with a dielectric constant of 6.15 backed by a ground plane. Two identical elliptical radiating elements were designed to resonate at 5.2 GHz. The inter-element separation distance is 10.6 mm (0.18λ), where λ is the free space wavelength. Parametric study was performed for the two coaxial feed locations to achieve optimal impedance matching. The optimized locations are 8 mm along the major axis and 3 mm along the minor axis for the first element, and 6 mm and 2.5 mm for the second element. The return loss is -20 dB with a -10 dB bandwidth of 50 MHz. A unit cell of a square ring resonator is designed to provide an effective negative permeability of -8 at 5.2 GHz, which provides a reasonable isolation between the two elements. Next, a set of 8 unit cells is arranged horizontally between the radiating elements, separated by 1.5 mm from each other. The unit cell consists of two square metal strip inclusions with opposite orientation printed on both sides of a 4.4 mm \times 4.4 mm \times 0.8mm RO3006 substrate. The gap in each ring is 0.3mm. The height of the antenna along with the metamaterial structures does not exceed 6 mm which categorizes the design under low profile antennas. The front view and side view of the proposed antenna design along with corresponding dimensions are depicted in Fig.1 and Table 1, respectively.

Table 1: Dimensions of the proposed antenna system.

L	14.5	W_m	4.4
W	19	L_m	4.4
L_r	14	T	0.85
W_r	4	L_p	3.5
S	1.5	W_p	0.6
T_m	0.45	G	0.3

The antenna and MNG unit cell were designed and simulated using both time-domain and frequency-domain solvers of CST Microwave Studio which is based on the Finite Integration Technique (FIT). The simulated S-parameters for the proposed antenna are shown in Fig. 2.

From the transmission coefficient S_{12} , we observe a large reduction in mutual coupling (-26 dB) at 5.2 GHz for the design with MNG structures

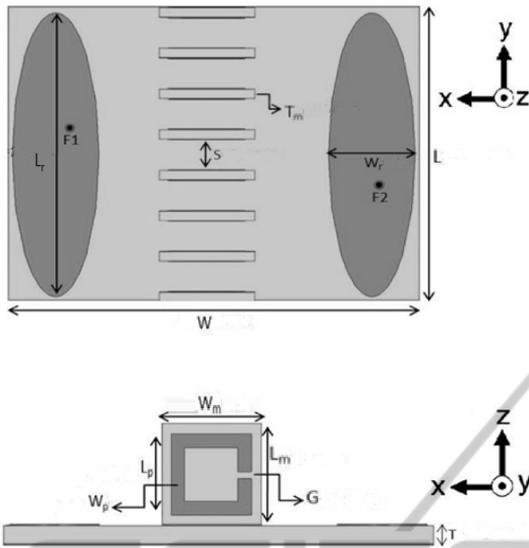


Figure 1: Two-element antenna array based on elliptical patch radiating elements with MNG. Top view (top) and side view (bottom).

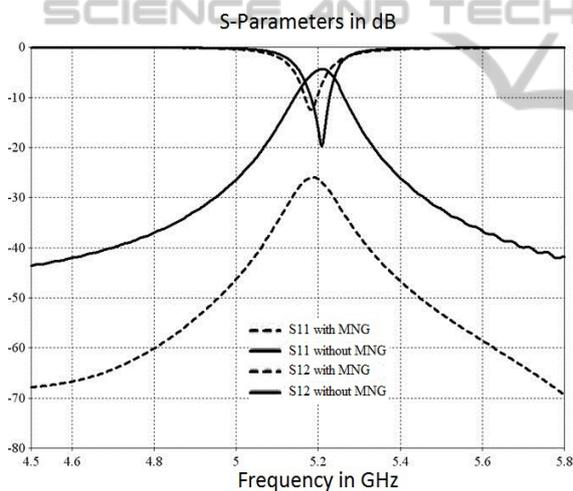


Figure 2: Simulated S-Parameter for both cases (with and without MNG).

compared to -4 dB for the design without MNG. We also notice a slight shift in the resonance frequency for the MNG case (around 20 MHz), which can be compensated for by slightly adjusting the patch length in order to keep the patch resonance frequency identical in both cases. Moreover, we simulated the correlation coefficient for both cases (with and without MNG structures). The correlation coefficient for the MNG case is 0.04 versus 0.42 for the case without MNG. It is also worth mentioning that the simulated correlation coefficient has been extracted from the far-field analysis which is more accurate than the S-parameter method (Blanch et al.,

2003). According to the S-parameters and correlation coefficient analysis, the design with MNG provides significant isolation between the radiating elements compared to the design without MNG with the same element spacing. The simulated E-plane and H-plane combined far-field radiation patterns at 5.2 GHz for the MNG case is presented in Fig.3.

4 ERROR PERFORMANCE SIMULATION

The setup for testing the performance of 2×2 Alamouti STBC scheme using the antenna array proposed in Section 3 is based on WLAN IEEE 802.11a system with 5.2 GHz carrier frequency, QPSK modulation scheme and simulation is performed under flat-fading channel with Rayleigh Fading coefficients. We used two transmit antennas on one substrate at the transmitter and two receive antennas on another substrate at the receiver. The BER which is an essential parameter in telecommunication systems, is the percentage of transmitted bits that have errors relative to the total number of bits received in a specific transmission process.

The BER performance for a) uncorrelated antennas at the transmitter (TX) as well as at the receiver (RX), b) antenna array designed using MNG structure (correlation coefficient at both TX and RX is 0.04), and c) antenna array designed without MNG structure (correlation coefficient at both TX and RX is 0.42), proposed in Section 3, is shown in Fig. 4.

We notice negligible performance loss for antenna array from MNG structure as compared to the performance for uncorrelated antennas.

5 CONCLUSIONS

In this paper, we presented a novel antenna array designed with MNG structure for exploiting diversity gain in a system where miniaturized sensor devices are equipped with multiple antennas. The negligible performance loss achieved by using the proposed MNG based antenna array compared to uncorrelated antennas renders the design suitable for integration on medical sensor nodes used in telemedicine systems that require miniaturization. We presented design, radiation pattern of such antennas and BER performance for such systems

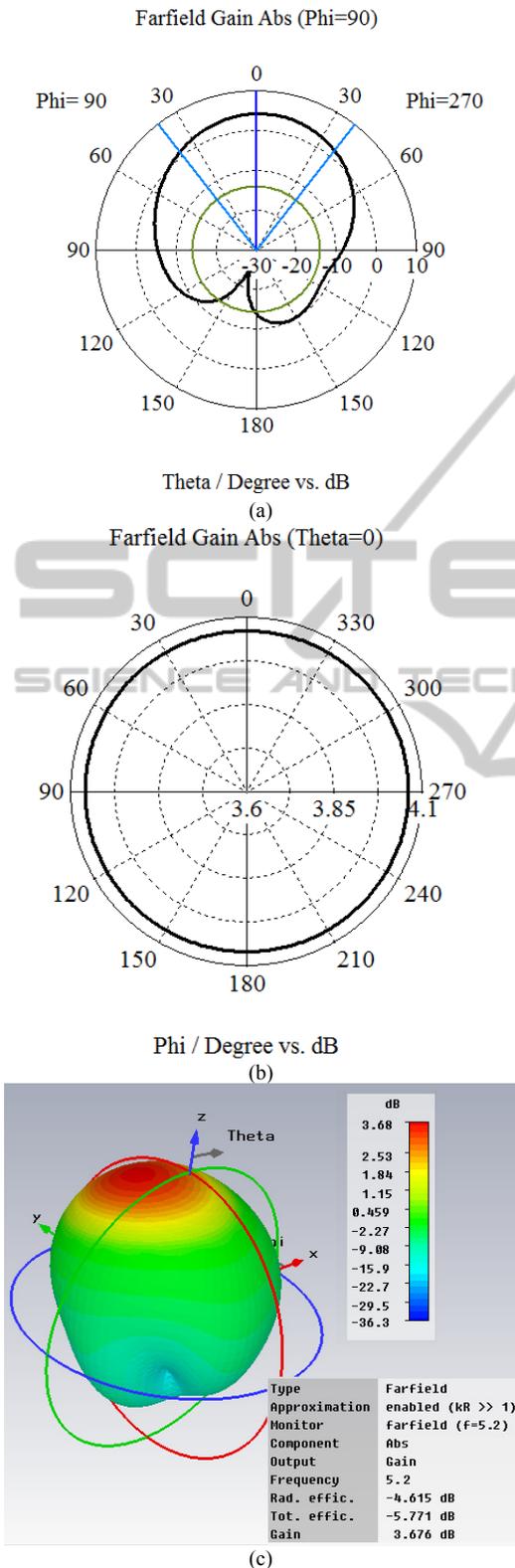


Figure 3: simulated (a) E-plane (YZ), (b) H-plane (XZ) and (c) 3D radiation patterns for the proposed antenna design at 5.2 GHz.

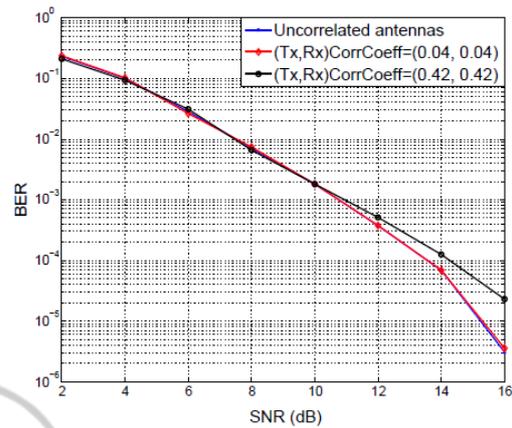


Figure 4: BER performance of (2 x 2) MIMO with correlated transmit and correlated receive antennas.

operating in a WLAN environment. Results suggest that the proposed design would be a reasonable candidate for telemedicine and BAN applications that are constrained by limited physical space.

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