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Smart antenna design alimented by a 4x4 butler matrix

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ABSTRACT

In the last decades, the development of efficient antennas for wireless power transfer applications has gained great attention from researchers worldwide and has become a vital research topic. In this paper, we propose the optimum design and implementation in microstrip technology of a switched beam smart antenna alimented by a 4x4 butler matrix (BM) for a microwave wireless power transmission system (MPT) at 5.8 GHz. The proposed smart antenna consists of a four linear microstrip patch antenna array and a 4x4 butler matrix beamforming network. It was able to form and steer four orthogonal beams in the four directions (±39°, and ±15°). Furthermore, it exhibited a high gain of 17.98 dB and good simulated and measured return losses. The design, optimization and simulation of the smart antenna components were performed using advanced design system (ADS).

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1. INTRODUCTION

Owing to the advancement in electronics in recent years, the emergence of electronic systems and wireless portable devices such as RFID systems, sensors, sensor networks and micro-drones has contributed to the prosperity of many key areas and especially the internet of things. These systems are massively used in places that are dangerous and unreachable [1], [2]. Nevertheless, they are limited in autonomy because of the rapidly unloading of their batteries.

With a view to improving the wireless systems autonomy, the researchers are increasingly turning to wireless power transfer technology [2]. In fact, wireless power transfer using microwaves (MPT) is an alternative and promising technology that can provide a source of energy able to improve the batteries life or to remote power to the electronic devices. In particular, a typical MPT system consists of two main parts: the transmission and the reception. The general block diagram of this system is depicted in Figure 1. In the transmission, a microwave generator converts the direct current (DC) power to the microwaves power. Then, the transmitting antenna radiates this power uniformly through the free space to receiver. In the reception, a rectenna captures and converts the microwaves back to useful direct power DC. In this study, we will focus on the development of the transmitting antenna (T_X).

In fact, in most recent research works, the directional antennas (or directional antennas arrays) are used as transmitting antennas in a MPT system [3]-[5]. However, these antennas are not reconfigurable, and they are not promising for wireless power transfer applications which have targets that can be mobile. Thereby, we propose to use smart antennas because they are reconfigurable and seem to be a promising technology to form, control and direct the microwave beam towards the target. Furthermore, they concentrate the energy only in the desired direction and can improve significantly the efficiency of a MPT system.

The smart antenna systems are basically divided into two categories [6]: adaptive array system based on the adaptive digital beamforming techniques (signal processing), and switched beam system based on the fixed beamforming techniques (analog circuits). The second system is widely recommended because it less expensive and easy to implement in comparison with the first system that requires many signals processing and complicated algorithms [6]. Butler matrix (BM) is one of the most popular beamforming networks used in a switched beam smart antenna system due to many advantages [7], [8]: Fist, it is able to generate orthogonal beams with high directivity. Second, it has a simple architecture with a reduced number of components compared to other beamforming networks (nolen matrix, blass matrix). Third, it can be easily implemented as well as the antenna array on the same substrate using mircostrip technology. This paper presents the study, design, simulation, and implementation of a switched beam smart antenna based on a planar 4X4 butler matrix at 5.8 GHz. It is proposed as the transmitting antenna for a MPT system.

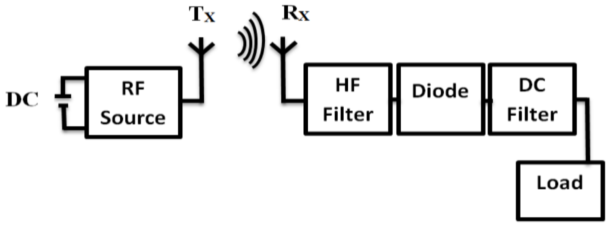

Figure 1. General block diagram of a MPT system

2. SWITCHED BEAM SMART ANTENNA

The switched beam system mainly consists of an antenna array and a beamforming network. It can form several fixed beams with enhanced sensitivity in a specific direction [9]. Moreover, it detects signal strength, selects one of the several predetermined fixed beams, and switches from one beam to another as the target moves [10]. Figure 2 illustrates the basic structure of a switched beam system that we will use in our study.

In transmission mode, when a RF signal is applied to the input of the switched beam smart antenna, it is switched to one of the beamforming networks ports (4x4 butler matrix in our study) [11], [12]. The port is selected according to the position of the desired target. The butler matrix divides the input signal into four signals of the same amplitude and with the required phase shift [11]-[23]. Finally, the antenna array generates the corresponding radiation pattern (Four orthogonal beams are generated and pointed in certain direction (angle θ_i)) [10]-[20]. Figure 3 illustrates an example of a 4x4 butler matrix [9], [18]-[24].

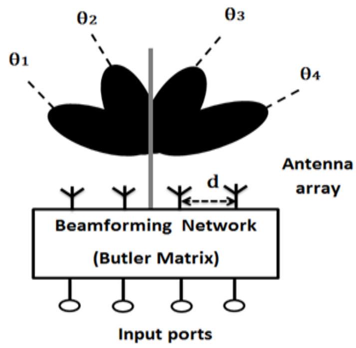

Figure 2. Basic structure of a switched beam system

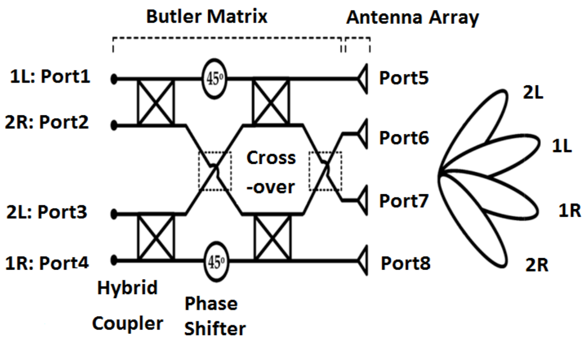

Figure 3. 4x4 Matrix Butler topology

The phase difference at the output ports is given by (1) [14]:

$$\Delta\varphi = \mp \frac{2n-1}{N} * 180° \tag{1}$$

with n represents the input port number with respected to the normal (1 or 2, in the case of a 4x4 matrix). The beam direction θ can be determined as follows (2) [15]:

$$\theta = \sin - 1\,(\pm\,(2n - 1)\,/N \tag{2}$$

3. PROPOSED SMART ANTENNA

The designs and simulations of all circuits at 5.8 GHz were performed using Momentum simulator of advanced design system (ADS) software [22]. All transmission lines (characteristic impedance of 50Ω) widths and lengths are calculated using the LineCalc tool. We have used the FR-4 substrate (dielectric constant of 4.4, thickness of 1.6 mm and loss tangent of 0.025) due to its low cost and easy fabrication [25].

3.1. Design

We have combined a 4x4 butler matrix to a linear antenna array (four patch antennas) on the same substrate FR4 to implement our smart antenna. We note that the design and simulations of our proposed butler matrix and patch antenna element are detailed in [19]. The distance between the butler matrix output ports represents the distance d between the antennas. It is about 0.5 λ in order to obtain orthogonal beams, maximum gain and minimum mutual coupling between antennas. Figure 4 represents the final geometry (90.61×96.54 mm^2) of the proposed switched beam smart antenna at 5.8 GHz. Table 1 presents the principal parameters of our proposed smart antenna.

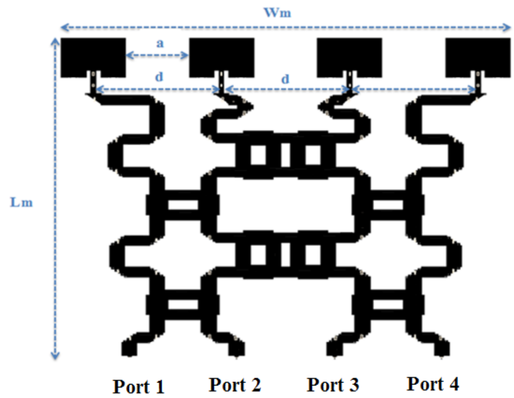

Figure 4. Final geometry of the proposed switched beam smart antenna at 5.8 GHz

Table 1. The principal parameters of the proposed smart antenna at 5.8 GHz

Parameter	Lm	Wm	d	a
Value (mm)	90.61	96.54	25.8	11.6

3.2. Results and discussion

Figure 5 shows clearly that all the reflection coefficients S_{11}, S_{22}, S_{33}, and S_{44} (of the four input ports) of the proposed smart antenna are below -10 dB at the resonance frequency 5.8 GHz. The parameters S_{11}, S_{44} are -24.7 dB and the parameters S_{22}, S_{33} are -20.8 dB, which means good impedance matching. Figure 6 and Figure 7 illustrate respectively the simulated radiation patterns (2D polar) and 3D gain pattern of our smart antenna at 5.8 GHz using the CST software (Computer Simulation Technology).

We observe that the proposed smart antenna produces four orthogonal beams in the required directions. In fact, when the ports 1, 4, 3 and 2 are excited by an RF signal, the antenna ponting angles are respectively symmetrical with respect to the axis. These angles are +15°/-15° and +39°/-39° respectively for the ports 4/1 and 2/3. When the port 1 is excited, the maximum gain of our smart antenna is around 17.98 dB at 5.8 GHz. Table 2 shows a comparison between the performances of our smart antenna and these of the proposed transmitting antennas for a MPT system. We can say that our smart antenna exhibits better performances in terms of gain, return loss and bandwidth in comparison with other proposed transmitting antennas for a MPT system. It is clear that our switched beam smart antenna can be used as a transmitting antenna in a MPT system at 5.8 GHz.

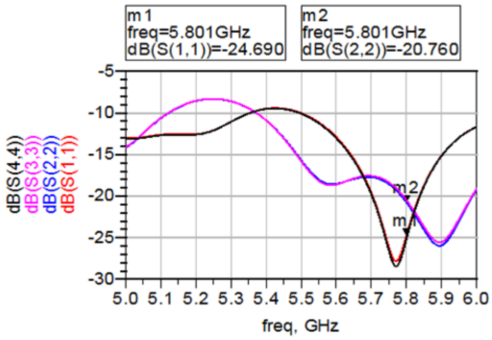

Figure 5. Simulated return losses of the proposed smart antenna

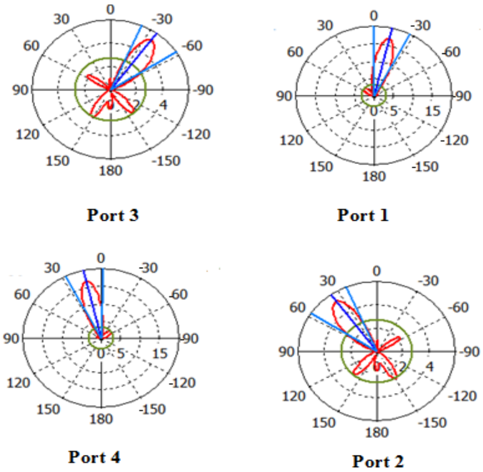

Figure 6. Main beams directions produced by the proposed switched beam smart antenna at 5.8 GHz (CST Software)

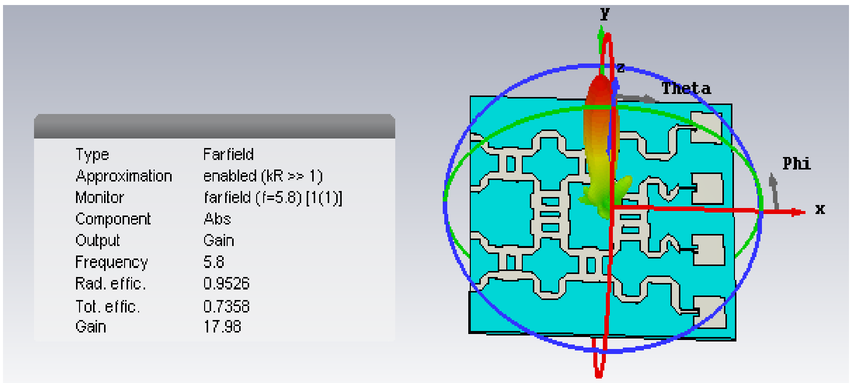

Figure 7. Simulated 3D gain pattern of the proposed smart antenna at 5.8 GHz (CST Software)

Table 2. Comparison with other proposed transmitting antennas for a MPT system

Reference	[2-3]	[5]	[this work]
Frequency (GHz)	5.8	2.45	5.8
Transmitting antennas	Anntenna Array of sixteen patchs	Horn antenna array	Antenna array of four patchs alimented by a 4x4 Butler Matrix
Simulated gain (dB)	16.8	14.37	17.98
Simulated S_{11} (dB)	-19.19	-17.1	24.69
Simulated bandwidth (MHz)	130	_	More than 500

3.3. Fabrication and measurments

3.3.1. Fabricated prototype

We have manufactured the proposed smart antenna in microstrip technology to confirm the validity of its design and verify its performances. It is printed on the commercial substrate FR4 (εr=4.4, h=1.6 mm and tanδ=0.02). Figure 8 illustrates the fabricated prototype of this smart antenna (the SMA connectors are used as feeding ports).

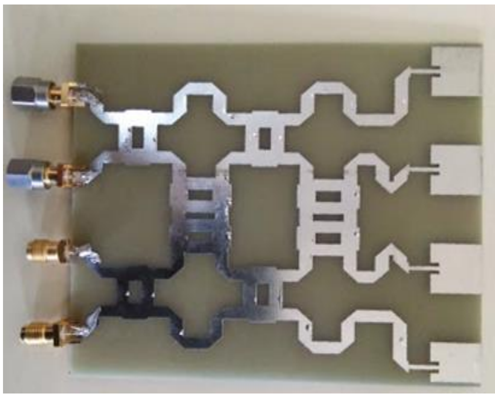

Figure 8. Fabricated prototype of the proposed smart antenna alimented by a 4x4 Butler Matrix

3.3.2. Comparison between the simulated and measured results

We have measured the reflection coefficients of our smart antenna in order to validate its fabricated prototype. The measurements of reflection coefficients were performed using the ANRITSU vector network as shown in Figure 9. The Figures (10, 11, 12 and 13) present respectively the comparisons between the simulated and measured S-parameters (S_{11}, S_{22}, S_{33} and S_{44}**)** of the proposed smart antenna. The Table 3 presents the comparison between the simulated and measured results.

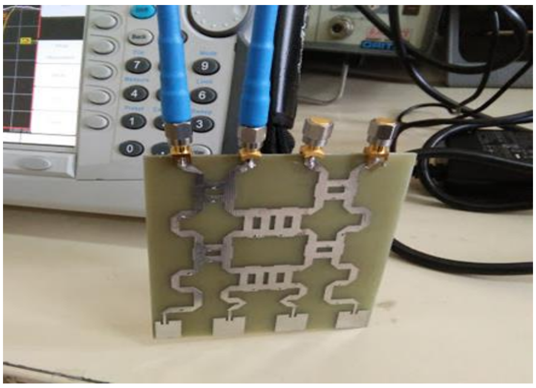

Figure 9. Measurement of the smart antenna reflection coefficients

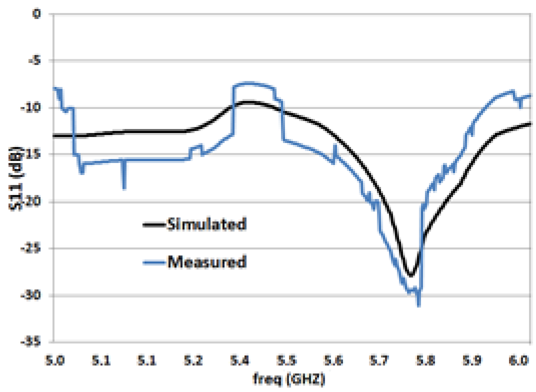

Figure 10. Comparison between the simulated and measured S_{11} (port 1 is excited)

We observe that the measured reflection coefficients (S_{11}, S_{22}, S_{33} and S_{44}) of the proposed smart antenna are less than -10 dB (good impedance matching) at 5.8 GHz. Thus, the fabricated prototype of this antenna presents good results although there are some differences between the measured and simulated results. On one hand, these differences are certainly dues to the fabrication imperfections and to the connectors soldering. On the other hand, they can be also explained by the experimental conditions. In fact, the measurements were not performed in an anechoic chamber. Consequently, they are many multiple paths because of the presence of walls and other metallic objects.

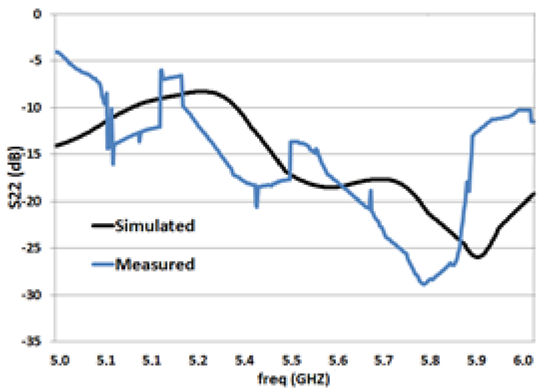

Figure 11. Comparison between the simulated and measured S_{22} (port 2 is excited)

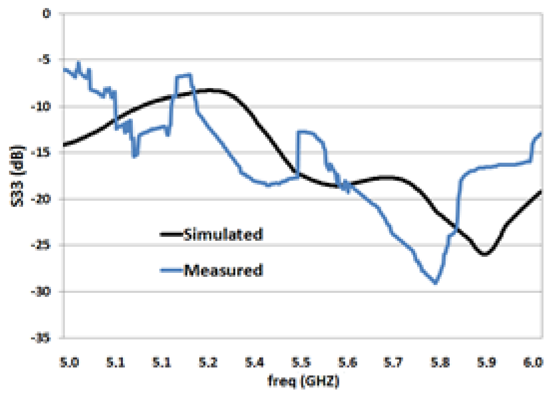

Figure 12. Comparison between the simulated and measured S_{33} (port 3 is excited)

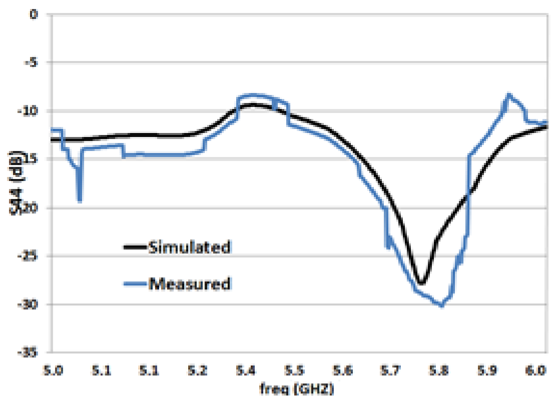

Figure 13. Comparison between the simulated and measured S_{44} (port 4 is excited)

Table 3. Comparison between the simulated and measured reflection coefficients of the proposed smart antenna

Results	Simulation	Measurement
S_{11} (dB) At 5.8 GHz	-24.7	-20.6
S_{22} (dB) At 5.8 GHz	-20.8	-28.3
S_{33} (dB) At 5.8 GHz	-20.8	-28.8
S_{44} (dB) At 5.8 GHz	-24.7	-29.4

4. CONCLUSION

In this paper, a planar design, simulation and implementation of a switched beam smart antenna alimented by a 4x4 butler matrix at 5.8 GHz has been presented. The simulated results show that the proposed smart antenna offers interesting performances in terms of return losses and gain. It is capable to produce four orthogonal beams in the directions (± 15°, ± 39°). Furthermore, the return losses of this antenna have been confirmed by experimentation. Therefore, it is clear from the simulated and measured results that our smart antenna is suitable for wireless power transfer application at 5.8 GHz.

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