A Systematic Approach for Port-Decoupling of Closely Separated Antennas

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***Abstract*—A design approach for decoupling closely separated antennas is discussed. This design methodology is particularly useful when the available real estate is very limited, and modifying the ground plane is not a viable practical option- a situation that is typically encountered when designing smartphones. In addition, the design guidelines are applicable for multi-element arrays, resulting in the possible realization of large compact arrays, which is desirable for saving chipset cost when targeting mm-wave applications.**

***Index Terms*—**Antenna Decoupling, Neutralization Line, 4G smartphones, LTE/MIMO Antenna, WiFi Antenna, mm-Wave Arrays.

I. INTRODUCTION

Deployment of smart antenna systems is beneficial for advanced communication systems that require a miniaturized handheld package which provides a high data rate and good coverage. A smart antenna system is one in which the quality of communication system is enhanced by incorporating appropriate signal processing schemes into a set of transmit/receive antennas [1]. This is the case for many emerging wireless systems, whether operating in the sub-6 GHz range or at millimeter wavelengths. In either case, There is a clear need for minimizing the overall system size. Many sub-6 GHz systems target consumer handheld devices, where size is limited to a certain volume, while integrated mm-wave systems are in-quest for small volume compact on-silicon arrays, to enable low-cost solutions. Thus, in many applications, antennas must be placed in close proximity of each other. This introduces significant mutual coupling effects which usually deteriorate the system performance and/or introduce complixities in the associated signal processing algorithms. To address the design issues pertaining to compact antenna array systems, a synthesis method whose objective is to reduce the mutual coupling effects between the array elements is addressed. In this paper, the technique is demonstrated through the design of a diversity antenna system. Results for the measurements of the mutual coupling are presented, along with patterns for different excitations. It should be pointed out that the proposed synthesis method is general and can be applied to guide the design procedure of many related problems.

Many interesting techniques have been previously proposed to lower the mutual coupling between antennas. These include:

(i) using some form of slots in the ground plane [2][3][4][5][6] (note that this solution is not valid for devices equipped with screens, since these screens have metal backing rendering the slots ineffective);

(ii) shaping the ground plane [7][8][9][10] (usually the shaping is introduced near the PCB edges, thus avoiding the screen issues encountered with slots in the PCB. However, such a solution has its practical challenges since it may require multiple PCB releases before the final antenna design is achieved);

(iii) Adding a network at the feed port [11][12][13][14][15] (widely adopted due its practicality, but typically suffers from limited degrees of freedom resulting in a limited bandwidth);

(iv) incorporating metamaterials/EBG-inspired structures [16][17] (which requires significant increase in area, an issue for both portable devices, and on-chip mm-wave designs);

(v) using a neutralization line [18][19], which is perhaps the most practical solution to date.

II. PROPOSED METHOD

The technique proposed herein means to minimize coupling utilizes the fact that the antenna array may be viewed as a multi-port circuit, as shown in Fig. 1, where each antenna is represented by a generalized scattering matrix. In a conventional array of two antennas, port 1 represents the physical feed. A part of the input power from the feed is radiated in free space or launched into a surface wave and/or leaky wave, while a portion of the input power at one port is coupled to the other feed-port of the second antenna. The latter mechanism lowers the system efficiency. Thus, one's design target is to minimize such power transfer. One possible approach to lowering such mutual coupling is to establish an additional path from one antenna to the other. Through proper design of an out-of-phase coupling path, it is possible to realize a null in the coupled power at the feed-ports, thus effectively port-decoupling the antenna elements.

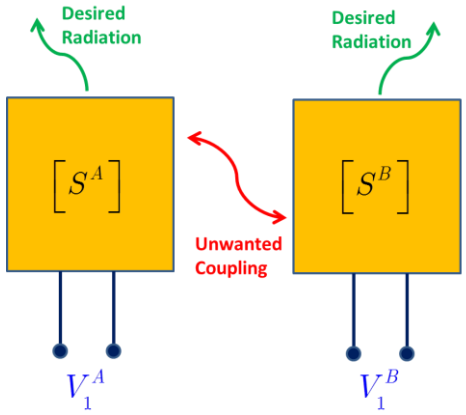

Fig. 1. Circuit model for two coupled antennas.

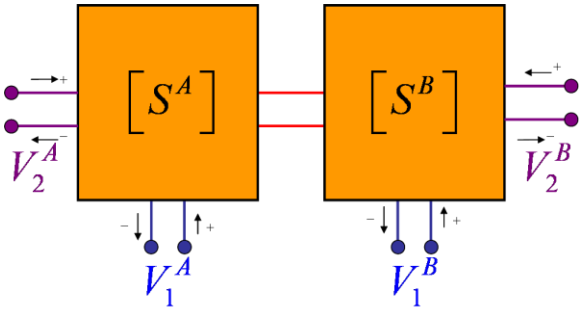

Fig. 2. Two-port circuit model for two coupled antennas.

Fig. 2 depicts a possible network representation. In this two-port circuit model, radiation is treated as a "desirable" loss in the network, with the target being the synthesis of a circuit/printed structure connecting both antennas and countering the existing mutual coupling between the feed ports.

Generally, for a four-port model such as the one in Fig. 2, the governing system of equations may be expressed as [20]:

$$\begin{bmatrix} \begin{bmatrix} V_1^{A-} \\ V_1^{B-} \end{bmatrix} \\ \begin{bmatrix} V_2^{A-} \\ V_2^{B-} \end{bmatrix} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} & \begin{bmatrix} S_{13} & S_{14} \\ S_{23} & S_{24} \end{bmatrix} \\ \begin{bmatrix} S_{31} & S_{32} \\ S_{41} & S_{42} \end{bmatrix} & \begin{bmatrix} S_{33} & S_{34} \\ S_{43} & S_{44} \end{bmatrix} \end{bmatrix} \begin{bmatrix} \begin{bmatrix} V_1^{A+} \\ V_1^{B+} \end{bmatrix} \\ \begin{bmatrix} V_2^{A+} \\ V_2^{B+} \end{bmatrix} \end{bmatrix} \quad (1)$$

which can be re-written as:

$$\begin{bmatrix} [V_P^-]_{2\times1} \\ [V_C^-]_{2\times1} \end{bmatrix} = \begin{bmatrix} [S_{PP}]_{2\times2} & [S_{PC}]_{2\times2} \\ [S_{CP}]_{2\times2} & [S_{CC}]_{2\times2} \end{bmatrix} \begin{bmatrix} [V_P^+]_{2\times1} \\ [V_C^+]_{2\times1} \end{bmatrix} \quad (2)$$

or alternatively as:

$$[V_C^-]_{2\times1} = [S_{conn}]_{2\times2}^{-1} [V_C^+]_{2\times1} \quad (3)$$

where $[S_{conn}]_{2\times2}^{-1}$ is the scattering matrix representing a physical network connecting ports "2" in each of the networks.

The reduced two-port network can be derived from this general network equation to get:

$$\begin{bmatrix} V_1^{A-} \\ V_1^{B-} \end{bmatrix} = [S_0]_{2\times2} \begin{bmatrix} V_1^{A+} \\ V_1^{B+} \end{bmatrix}$$

$$= \left[[S_{PP}]_{2\times2} + [S_{PC}]_{2\times2} \left[[S_{conn}]_{2\times2}^{-1} - [S_{CC}]_{2\times2} \right]^{-1} [S_{CP}]_{2\times2} \right] \begin{bmatrix} V_1^{A+} \\ V_1^{B+} \end{bmatrix} \quad (4)$$

which may be re-written as:

$$\begin{bmatrix} V_1^{A-} \\ V_1^{B-} \end{bmatrix} = [S_0]_{2\times2} \begin{bmatrix} V_1^{A+} \\ V_1^{B+} \end{bmatrix} \quad (5)$$

with a desired overall matrix $[S_0]$, such that:

$$[S_0] = \begin{bmatrix} S_{11}^A\big|_0 & 0 \\ 0 & S_{11}^B\big|_0 \end{bmatrix} = \begin{bmatrix} S_{11}^A\big|_0 & 0 \\ 0 & S_{11}^A\big|_0 \end{bmatrix} \quad (6)$$

where $S_{11}^A\big|_0$ ($S_{11}^B\big|_0$) denotes the scattering parameters at the physical input port of antenna A (B). It is evident, then, that we need to synthesize a lossless connection matrix $[S_{conn}]_{2\times2}$ to maximize the overall efficiency and achieve the desired overall matrix through [21]:

$$[S_{conn}]_{2\times2} = \left[[S_{CC}]_{2\times2} + [S_{CP}]_{2\times2} \left[[S_0]_{2\times2} - [S_{PP}]_{2\times2} \right]^{-1} [S_{PC}]_{2\times2} \right]^{-1} \quad (7)$$

Thus, for a passive, lossless, and symmetrical connection network, the connection matrix itself can be written as:

$$[S_{conn}] = \begin{bmatrix} \left|S_{conn}^{11}\right| e^{j\varphi_{conn}^{11}} & \sqrt{1-\left|S_{conn}^{11}\right|^2}\, e^{j\left(\varphi_{conn}^{11} - \frac{2m+1}{2}\pi\right)} \\ \sqrt{1-\left|S_{conn}^{11}\right|^2}\, e^{j\left(\varphi_{conn}^{11} - \frac{2m+1}{2}\pi\right)} & \left|S_{conn}^{11}\right| e^{j\varphi_{conn}^{11}} \end{bmatrix} \quad (8)$$

By varying $\left|S_{conn}^{11}\right|$ and $e^{j\varphi_{conn}^{11}}$, one can easily construct the "Return Loss" and "Insertion Loss" Maps, which can be used to calculate the return and insertion loss levels at the antenna ports by using (4).

Fig. 3 shows a return loss map for two closely coupled microstrip patch antennas, while Fig. 4 presents the insertion loss map for the same antennas. If we assume a hypothetical passive, lossless, and symmetrical connection network, then

these maps identify two important pieces of information. First, the best return loss we can achieve in this case is around 25dB, while it is 21dB for the insertion loss. Second, if we put both of these maps together, then it becomes evident that a

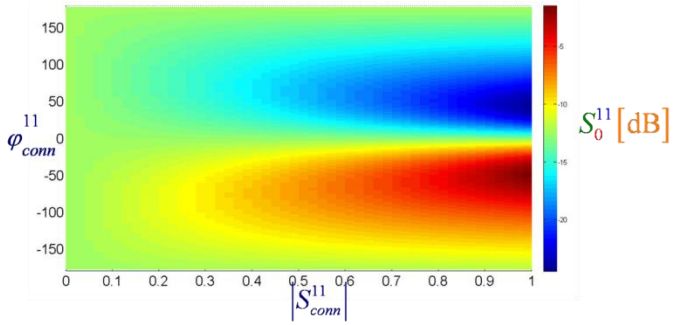

Fig. 3. Return loss map.

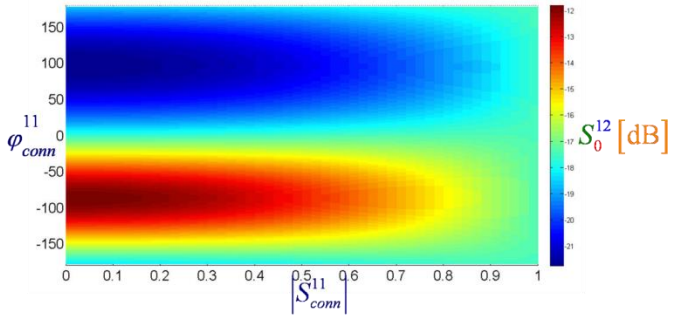

Fig. 4. Insertion loss map.

connection matrix, where $\left|S_{conn}^{11}\right|=1$, and $\varphi_{conn}^{11}\cong 45^0$, would result in a good de-coupled scenario in which a return loss of 25 dB and an insertion loss of around 18dB would be realized. In general, this technique is quite useful for:

(i) Rapidly assessing every "tapping" location for realizing a connection network which would decouple any coupled set of antennas.

(ii) Rapidly defining the best possible connection matrix, which can be used to define a hard limit on the expected performance.

(iii) Allowing a feasibility study pertaining to the realization of such a connection matrix.

(iv) Significantly reducing the number of simulations and optimization cycles needed to design a de-coupled system.

It is to be noted that using a passive, lossless, and symmetrical connection network is only useful for simplifying the analytical calculations of the "Return Loss" and "Insertion Loss" maps. That is: (4) is quite general, and can be used for active and/or lossy cases.

Fig. 5 and Fig. 6 show two very simple implementations of the proposed connection network. In Fig. 5, the connection is established by interconnecting the two patches with two printed strips. The target is to null the coupling at a single frequency. Another design is shown in Fig. 6, where coupling is minimized by adding simple non-connected stubs to the patches. The design target was to keep the coupling below 10dB for wider range of frequencies. We note that these examples show mutual decouplings in the H-plane. One

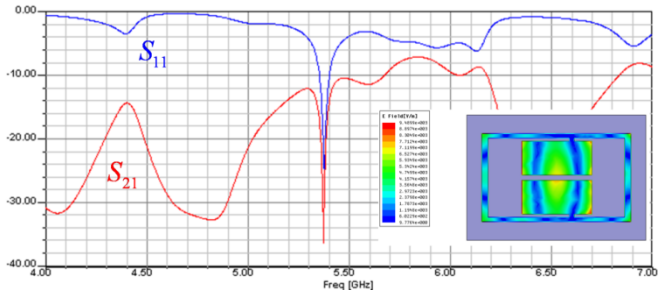

Fig. 5. Mutual de-coupling achieved by connecting the two patches.

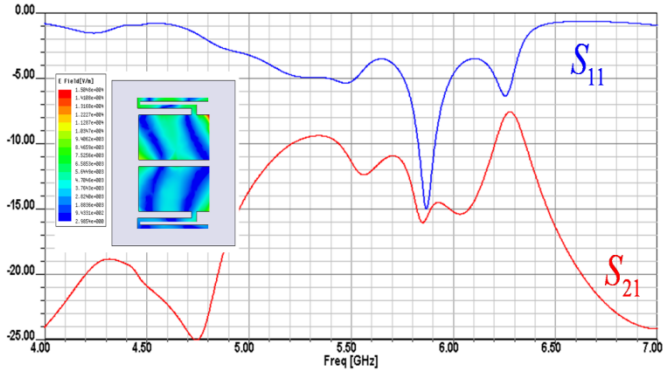

Fig. 6. Mutual de-coupling achieved adding a meander stub to each patch.

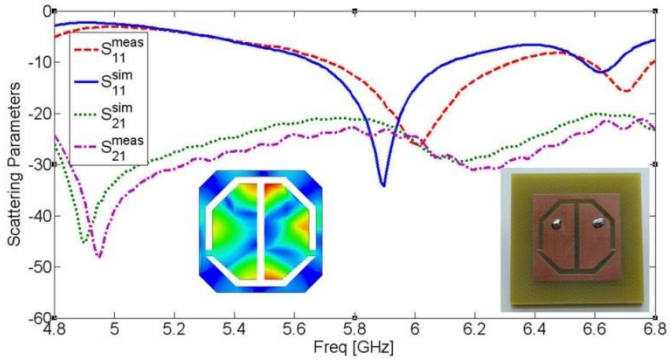

Fig. 7. Measured and simulated results for the proposed compact diversity antenna.

should note that the current distribution on the resulting configuration of antennas is different from that of the original two-coupled antennas. However, this is acceptable in many modern designs, where the primary target is to maintain diversified field patterns, along with an acceptable level of radiation efficiency.

Another design for wide band operation is shown in Fig. 7, where the coupling is minimized by adding two stepped impedance lines, a technique which is widely known and commonly used in passive filter designs [20]. However, instead of designing them following the traditional filter design methodology, they are synthesized based on the above

connection matrix concept in order to mitigate the coupling mechanism between the patches. Thus, the structure in Fig. 7 has two modified rectangular patches connected with stepped impedance lines, forming a squared-shaped structure with a side length of 3.2 cm over a ground plane of 4.8X4.8cm on a

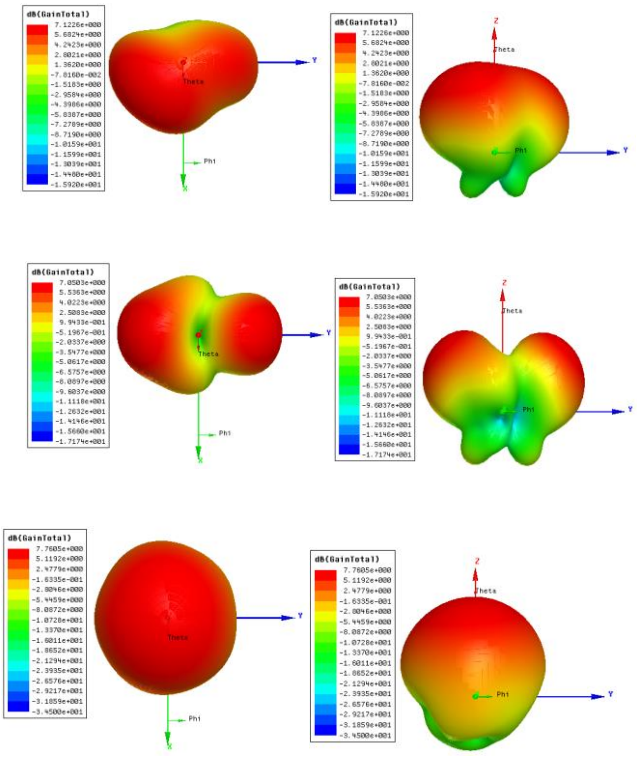

Fig. 8. Gain [dB] for different sets of excitations $\{\text{Top}(1\angle 0^0),(0\angle 0^0)\}$, middle$\{(1\angle 0^0),(1\angle 0^0)\}$ & $\{\text{bottom}(1\angle 0^0),(1\angle 180^0)\}$

118 mil FR4 substrate. Note that the measurements agree reasonably well with the simulations, and that the resulting mutual coupling is approximately -20dB around the measured center frequency of 6 GHz, with a return loss of VSWR<2 covering the frequency range of 5.719-6.309GHz with a bandwidth of 9.81%.

The optimized antenna in Fig. 7 is fed with two coaxial feed ports. The excitation mechanism can be a switched-type in nature, thus allowing the activation of one or both ports, with fixed amplitude and phase. Alternatively, one may consider operating the antenna in the adaptive array mode, where the amplitudes and phases are allowed to vary. By inspecting the three-dimensional gain patterns of the antenna in Fig. 8 and Fig. 9, we can clearly observe its ability to create a sum/difference pattern. which makes it quite a simple antenna for deployment in switched-beam smart antenna systems.

III. Decoupling Using Lumped Elements

During the course of this work, it was noticed that the coupling maps for many antennas indicate that we can simply use a single inductor or capacitor to decouple two highly coupled antennas. For the sake of illustration, let us assume that we have two closely placed microstrip patch antennas (Fig. 10). Each patch has the dimensions of 64mmX50mm and is printed on a 3mm FR4 substrate. The edge-to-edge separation is 3 mm, the ground plane is 120mmX150mm, and the coupling is about -6dB. Fig. 11 shows that there exists considerable

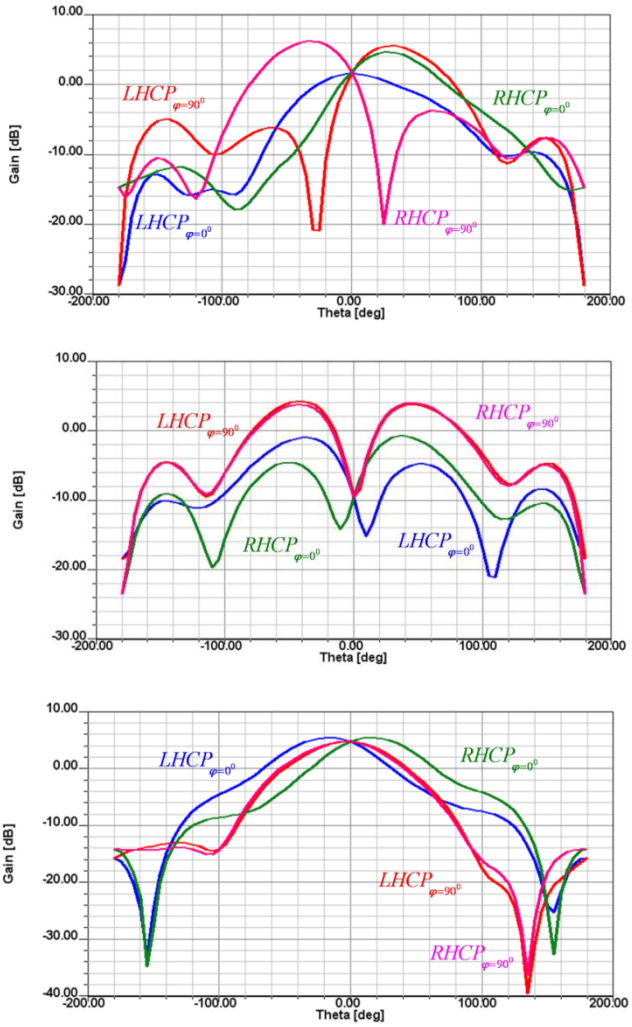

Fig. 9. LHCP/RHCP gains for different excitations $\{\text{Top}(1\angle 0^0),(0\angle 0^0)\}$, middle$\{(1\angle 0^0),(1\angle 0^0)\}$ & $\{\text{bottom}(1\angle 0^0),(1\angle 180^0)\}$

coupling between the two antennas. If the ports are placed on the outer sides at the center of the patch edges (Fig. 12), the results would look similar to those shown in Fig. 13.

Applying the proposed algorithm, it is possible to generate the return and insertion loss maps shown in Fig. 14. If we change the location of the ports to 25mm from the edge, we have a new map. Fig. 15 shows the return and insertion loss maps at 1.114GHz. One may observe that a possible solution occurs at 0.5 and -180 degrees, with S_{11} of -20.17dB and S_{12} of -16.53dB. The map at 1.05GHz is shown in Fig. 16. This should help in assessing potential de-coupling on a considerably wide operational bandwidth.

Alternatively, placing the connection ports on the inside edges of the patch antennas inside, we realize the topology shown in Fig. 17, with its maps depicted in Fig. 18. The latter maps show that, at 1.104GHz, a suitable solution exists at 0.9 and -100 degrees, where S11 is -36.42 dB and S21 is -28.23 dB. Hence, one can easily synthesize a network configuration

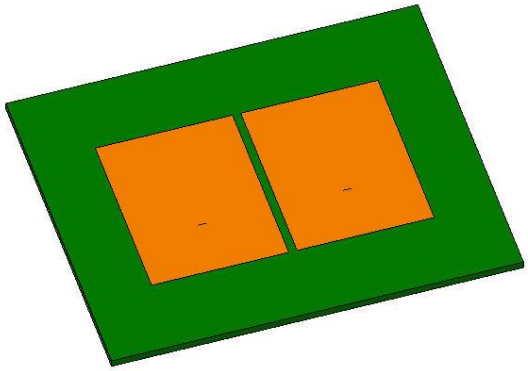

Fig. 10. Two closely separated patches.

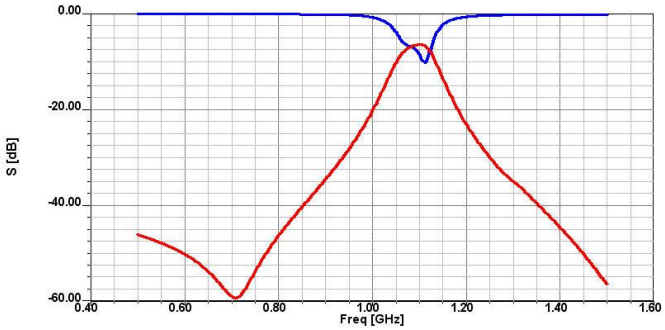

Fig. 11. Coupling between the two patches.

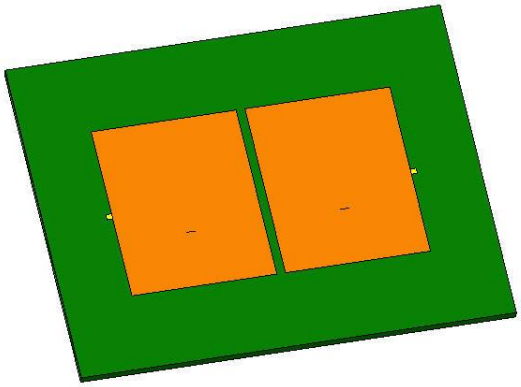

Fig. 12. Patches with auxiliary ports on the outer sides.

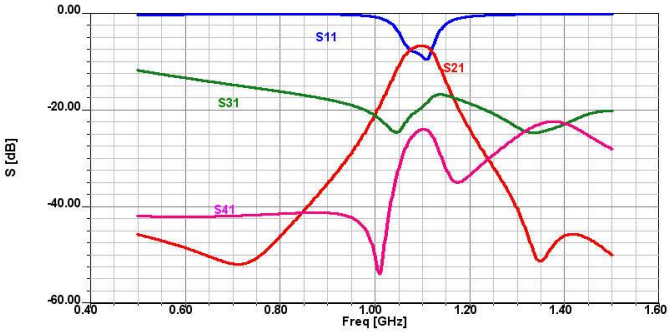

Fig. 13. Results for the four-port simulation.

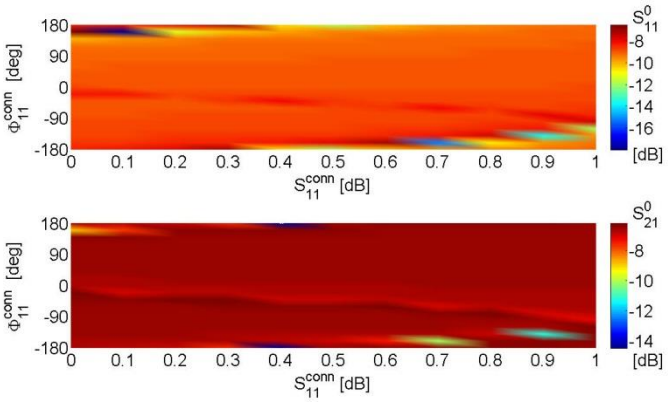

Fig. 14. Return and insertion loss maps for auxiliary ports at center of patches.

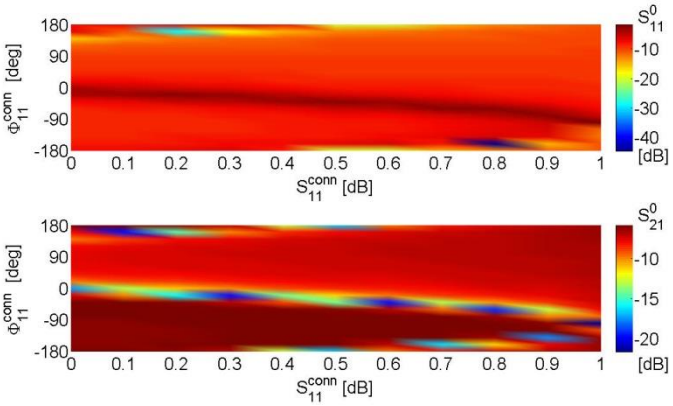

Fig. 15. Return and insertion loss maps for auxiliary ports at 25mm from edge of patches.

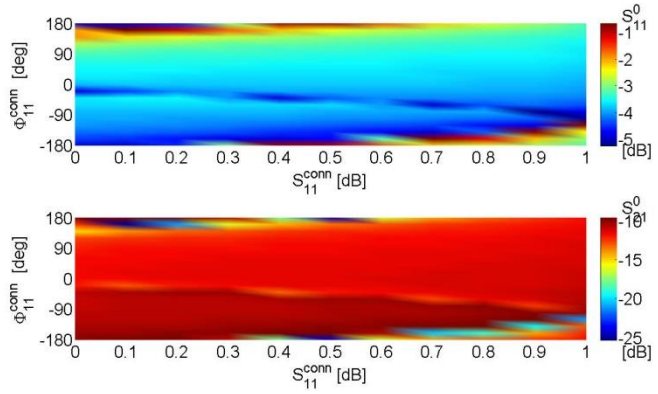

Fig. 16. Return and insertion loss maps at 1.05GHz.

which is close in performance to the required connection matrix (In this work, the synthesis has been carried out using Agilent ADS [25]), as shown in Fig. 20, with its impact on the antenna scattering parameters shown in Fig. 21).

We should point out that the previous results were obtained by direct synthesis. That is, the "Return/Insertion loss" maps were used to find the best solution at a given frequency. For wider band de-coupling, different maps should be developed at each frequency of interest. Fig. 21 shows a possible wideband de-coupling design.

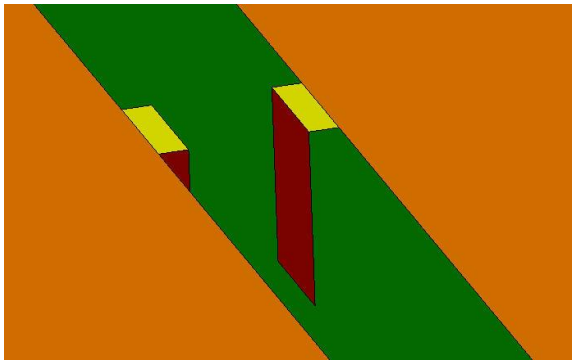

Fig. 17. Using the auxiliary ports at the near edges.

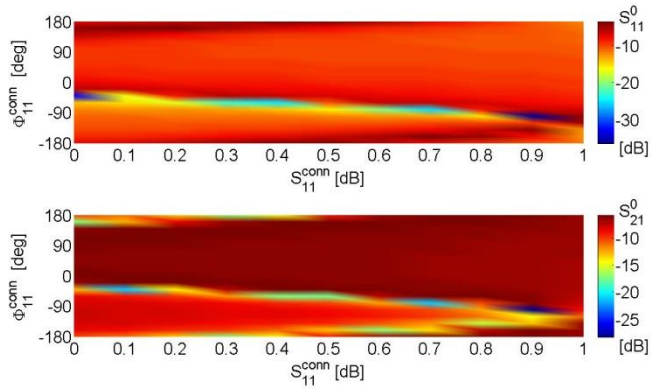

Fig. 18. Return and insertion loss maps for inside ports.

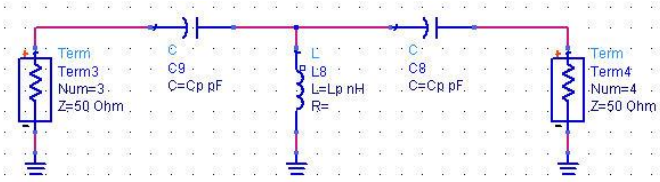

Fig. 19. Synthesizing a connection matrix.

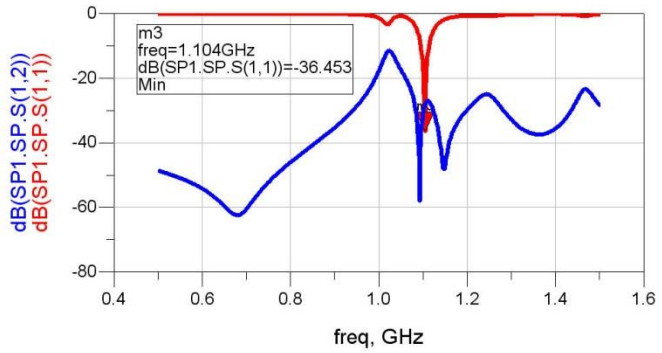

Fig. 20. Results for direct synthesis of the connection matrix.

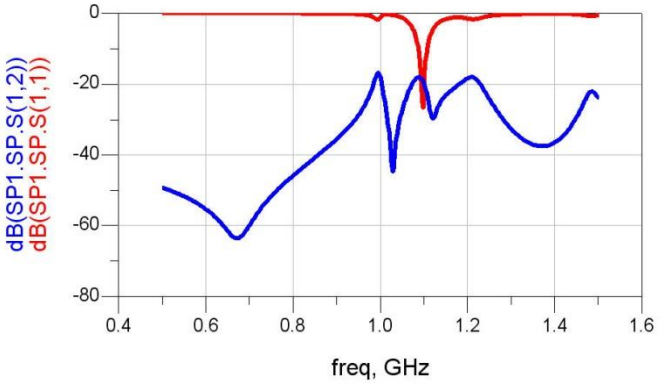

Fig. 21. Results for wide-band decoupling.

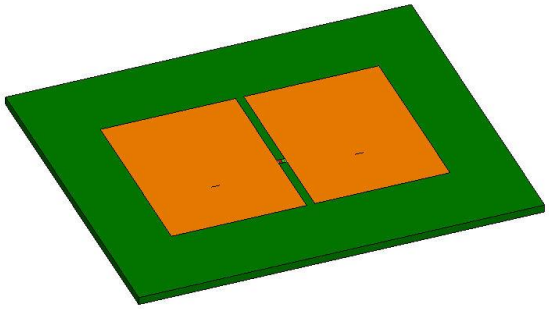

Fig. 22. Modeling LC network in full wave simulators.

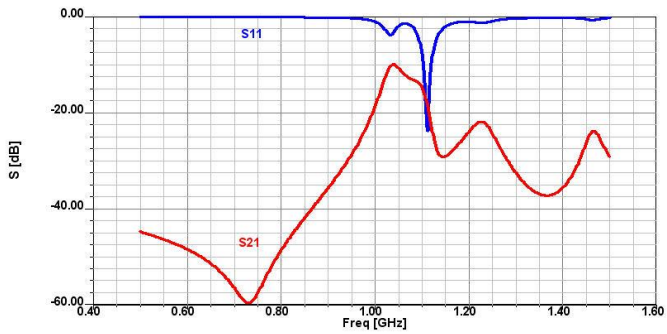

Fig. 23. The resulting antenna scattering parameters.

To verify the predictions for the de-coupling behavior, full wave numerical simulations have been performed using various commercially available field-solvers, e.g. FEM solvers in HFSS [22], FDTD solvers in SEMCAD [24], or MOM/hybrid techniques available in FEKO [23]. If we use the network developed in Fig. 20, with its CAD as shown in Fig. 22, the results plotted in Fig. 23 correlate well with those derived by using a circuit simulator utilizing the impedance maps (as shown in Fig. 20). The corresponding resulting patterns for odd and even excitations are shown in Fig. 24.

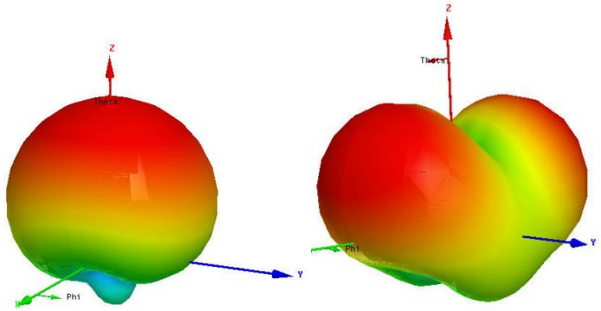

Fig. 24. Resulting pattern for odd and even excitations at the antenna physical ports.

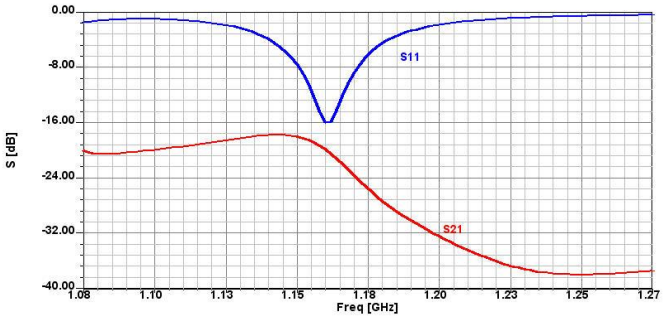

Fig. 25. Using a single capacitor at the patch's outer sides to decouple the patches.

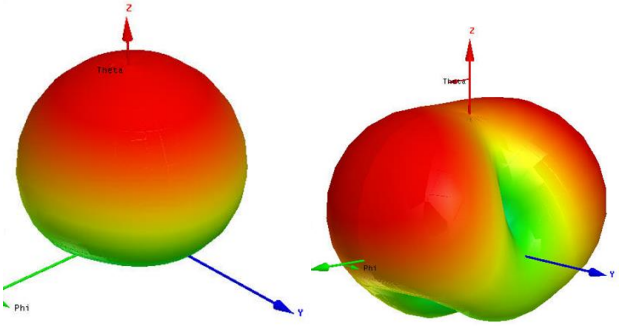

Fig. 26. Odd and even pattern results when using a single capacitor at each patch.

Studying the return and insertion loss maps further, one will observe that there is no physical solution at 25mm from the edge using a single capacitor or inductor. However, if a capacitor is placed at the outer sides of the patches, we can see in Fig. 25 that a 4pF capacitor can fulfill our design requirements. The resulting odd and even mode patterns are shown in Fig. 26.

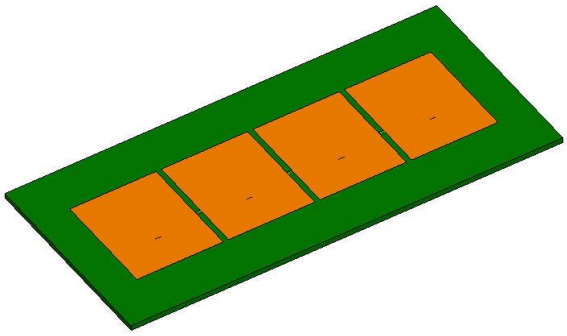

Fig. 27. A four-patch antenna system with decoupling ports on the inner edges.

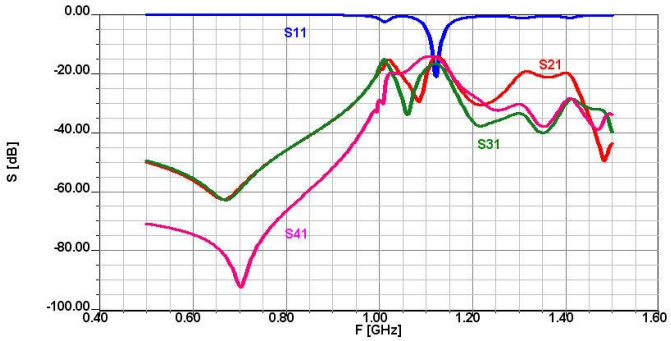

Fig. 28. Resulting coupling between the four patches.

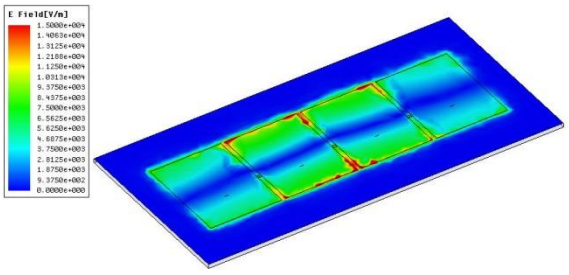

Fig. 29. Field distribution at excitation using {1,-1,-1,1}.

IV. Arrays of Multi-coupled Patches

The proposed technique can be easily applied to any antenna system which is comprised of more than two elements. For

example, the design strategy has been applied to a four-patch antenna system as shown in Fig. 27. Its corresponding relevant results are summarized in Fig. 28, Fig. 29, and Fig. 30, demonstrating the applicability of the technique. One should note that although pattern diversity is realized through such a port de-coupling technique, it does not physically decouple the patches (current distribution for an element in the array is significantly different from that which exists when the element stands alone). This typically deprives the designer from being able to use traditional array theory analysis (element factor+array factor). Still, for many compact portable applications, this is an acceptable tradeoff to achieve the desired performance while working with a compact volume.

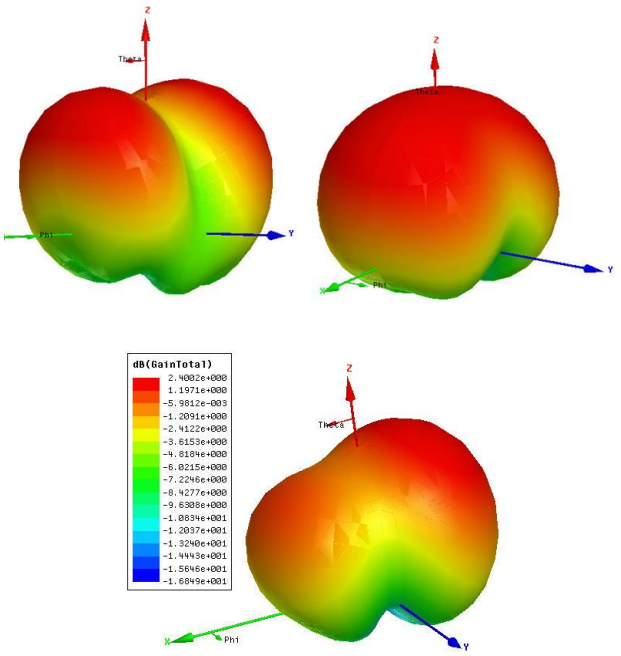

Fig. 30. The resulting gain when exciting using {1,-1,-1,1} (top left) and {1,-1,1,-1} (top right), and exciting at a quadrature phase difference between the four ports.

V. Discussions

In this communication, a technique for port-decoupling of multi-coupled antennas has been discussed. Compared to available techniques, the proposed approach has the advantage of minimizing the coupling while working with a minimum volume, and without requiring an alteration to the ground plane configuration. This is an advantage to many integrated mm-Wave systems. The technique is also generally applicable to 3D antenna designs, such as those typically available in 4G smartphones. For example, Fig. 31 presents a CAD pictorial of a possible realization of two decoupled antennas on a smartphone form-factor operating in the 2.4/5GHz band along with the resulting decoupling shown in Fig. 32.

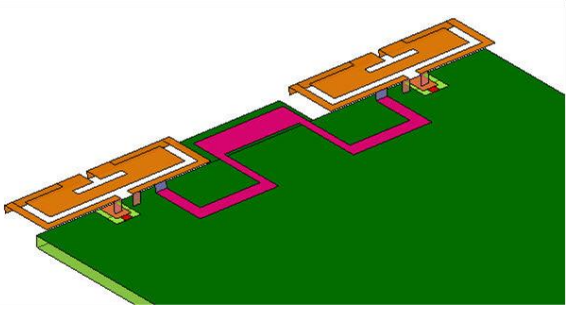

Fig. 31. Antennas for WLAN applications.

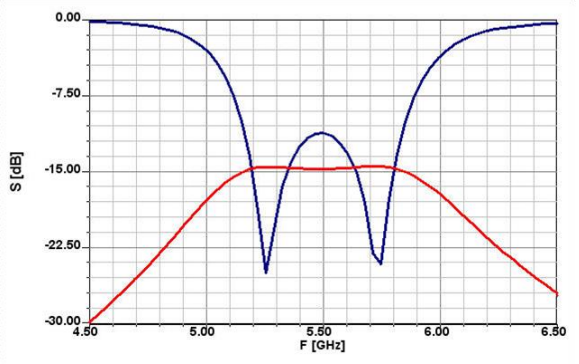

Fig. 32. Response of the antenna system at the high WLAN band.

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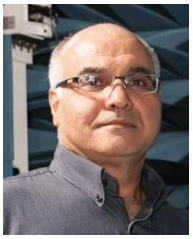

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Dr. Safavi-Naeini has led several international collaborative research programs with research institutes in Germany, Finland, Japan, China, Sweden, and the USA.