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Tx-Rx Isolation Exploiting Tunable Balanced - Unbalanced Antennas Architecture

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***Abstract*—The duplex filter is probably still the most expensive component in mobile handsets for the significant Transmitter (Tx) - Receiver (Rx) isolation required. This paper suggests to relax or even replace the duplex filter by equipping the Tx and the Rx with two separate antennas. The two antennas are different in the sense that one is balanced and the other is unbalanced. By properly controlling the two arms of the balanced antenna, impressive Tx-Rx isolation is obtained by canceling the coupling trans-impedance between the two antennas.**

I. Introduction

The miniaturization trend of future mobile phones necessitates a universal co-design between the radiating antennas and the RF frontend. In such joint design, some components will provide other functionalities different from their conventional functionalities while redundant components should be removed. In this paper we propose to re-use the wireless antennas and employ them for RF filtering. Specifically, we aim at isolating the Tx from the Rx in a frequency division duplex (FDD) systems, thus relaxing or dispensing with costly and bulky duplexers. Although recent SAW filters occupy a smaller area, they provide limited performance [1]. The problem scales dramatically when considering multi-band systems, where a bulky bank of switched duplex filters will be required.

In this paper, we gain Tx-Rx isolation by reducing or canceling the coupling trans-impedance between the two antennas. The advantages of separating the Tx antenna from the Rx antenna have been illustrated in [2] and [3]. In such work, the antenna separation was mainly intended to provide some initial moderate level of isolation, followed a conventional filtering mechanism.

To tackle the problem of mutual coupling, feeding networks have been proposed, the so-called decoupling and matching networks. A method that is used in many of the publications on the subject of reducing mutual coupling, is the one named in [5] as multi-port conjugate match or simply a decoupling network. There are multiple ways of implementing such a network and the same concept is named differently depending on implementation method. It has been called throughout literature an eigen mode feed network in [6], mode decomposition network in [7], optimal Hermitian match in [8], decoupling and decorrelating network in [9], hybrid-coupler in [10] and finally, a multi-port conjugate match. All of the aforementioned have the role of jointly minimizing coupling and input return loss. However, apart from the added ohmic losses, the main drawback of this method is the fact that when the distance between the radiating elements decreases (the coupling between them increases) the bandwidth of the system is significantly decreases as well [5].

The use of a particular antenna structure in which the coupling is canceled through the radiation mechanism is discussed extensively in the literature. Another example is the parasitic element method where an added passive element is used in between the active ones to induce and extra coupling path that will cancel the initial one as shown in [11]. In a similar way, the neutralization line as in [12] and [13], is used to cancel the trans-impedance between the ports at a single frequency. Other methods include the modification of the ground plane as in [14] or the use of cross polar elements and orthogonal radiation mods, as in [15].

The authors of [16] and [17] propose a design with balanced antennas in order to limit the use of the ground plane of the printed circuit board (PCB) in the radiation mechanism. Combined with a secondary antenna that makes full use of the ground plane, a good level of decoupling can be achieved.

In this contribution, a feeding network is chosen to create specific excitation vectors for a two port antenna so that a field cancellation is achieved at the secondary antenna. When excited, the two port antenna has a radiation mechanism similar to a balanced element however, the obtained decoupling level is much higher due to the active cancellation. Furthermore, by employing this architecture, a reconfigurable and dynamic decoupling mechanism is achieved. The following section will highlight this principle by a concrete design and the relevant results obtained with it. Finally, in the last section the conclusions and finale remarks are presented.

II. Discussions and results

As a starting point for the discussions, the structure from figure 1 has been chosen. It is a three element MEA. Two of the elements, the monopoles, are folded and meandered from minimizing the occupied volume. However, when these elements are fed differentially (a balanced feeding with the excitation signal dephased by 180 degrees) they become a balanced antenna. The third element is a dual band planar inverted F antenna (PIFA) which is coiled around itself and placed on a Polytetrafluoroethylene (PTFE) dielectric substrate for stability and size reduction. The ground plane

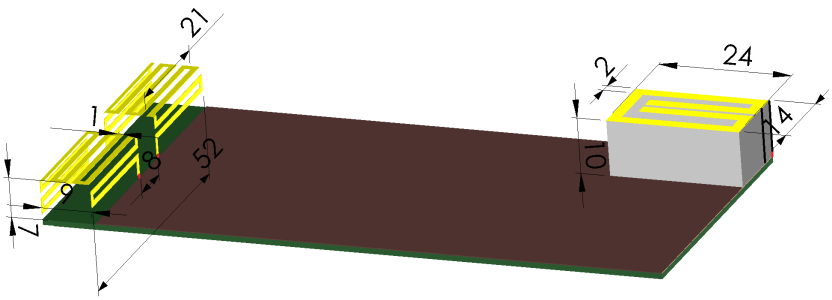

Fig. 1. The numerical model of the structure. The excitation ports are marked with red.

is etched on standard one mm thick FR-4. Among the design criteria were compactness, simplicity and low band operation. The resonant frequency of each element is around 810 MHz, as it can be seen in the simulated results plotted in figure 2. The simulation has been carried out using the Aalborg University in-house FDTD (Finite-Difference Time-Domain) electromagnetic solver, choosing a uniform griding and a space cell size of 0.5 mm.

There is a strong coupling between each of the elements, especially between the two monopoles as indicated by the high magnitude of S_{21}. However, the isolation that is the focus of this paper is the one between the monopoles and the PIFA. The mechanism to minimize the coupling between antenna elements, proposed in this contribution, is inspired from the principals of beam-forming or beam-steering. Instead of modifying the excitation vectors of an array to obtain a desired far-field radiation pattern, this principle is applied to modify the near-fields distribution. The working principle is similar to the case corresponding to a balanced antenna and an orthogonal unbalanced antenna in which case they will be inherently decoupled. In other words, just by choosing the right phase shift of the excitation signals of two elements in MEA fed balanced, one can create a orthogonality of the near-fields, thus achieving unprecedented level of isolation.

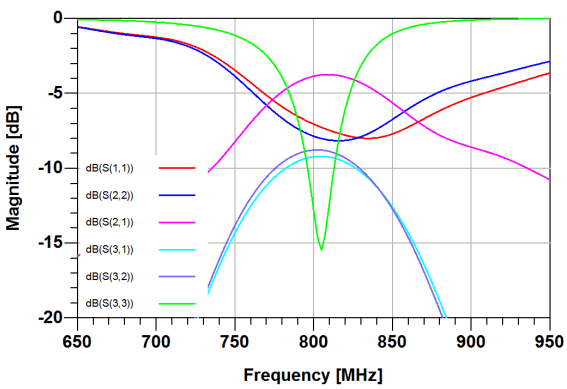

Fig. 2. The S parameters simulated for the antenna structure from figure 1. Only some of the parameters are shown due to reciprocity. Ports 1 and 2 correspond to the two monopoles and port 3 is exciting the PIFA.

For a symmetric coupling between the elements of the balanced antenna and the secondary antenna, a phase difference of 180 degrees between the signals that drive the balanced element will create a null in the direction of any third antenna that is placed on the symmetry axis. However, a completely symmetric environment is very unlikely to be encountered in practice especially if we consider the user‘s interaction with the handset. Therefore, for an antenna system such as the one shown in figure 1, the phase difference required for isolation will be close to 180 degrees and it will vary in time depending on many factors such as the frequency and near-field environment. Potentially, thought a feedback algorithm, it can be constantly updated so that the isolation requirements are satisfied thus making this isolation mechanism very robust and agile.

The main advantage of this isolation method is that it can be implemented in the baseband module without modifying the RF engine. In addition, due to the relatively low cost of silicon, modern transceiver design employs a balanced architecture for distributing the requirements on the power amplifiers and this decoupling technique can be directly integrated in a balanced system because two antenna elements are needed. Actually, it could make some of the modern transceiver's output stages redundant, such as the balanced to unbalanced conversion which adds to the balanced transceiver's losses.

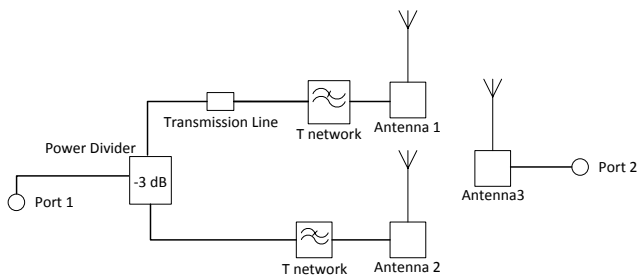

Fig. 3. The block diagram of the complete system, antenna plus feeding network.

To verify the principle presented and for simplifying the prototype's manufacturing, a feeding network has been chosen instead of a digital implementation. The network generates the necessary excitation vectors through microwave circuits which are printed on the back side of the PCB. In figure 3, the block diagram of the system is presented. First, the signal from the input port is split in two waves with equal amplitude, then they are delayed differently, one with a T network plus a transmission line and the other with just a T network. The

microstrip transmission line offers the gross phase difference (about 160 degrees) and the fine tuning is done with the help of the identical T networks which consist of two tunable capacitors from 0.6 to 2.5 pF and a fixed inductor of 9 nH. The obtained signals are connected to the input ports of the two monopoles from figure 1 .

The complete system, feeding network and antennas are simulated by a hybrid method. The effect of the feeding network has been simulated with a method of moments based code from Agilent Technologies ($ADS^{®}$). The behavior of the antenna has been imported through its S parameters. The layout for the feeding network is plotted in figure 4.

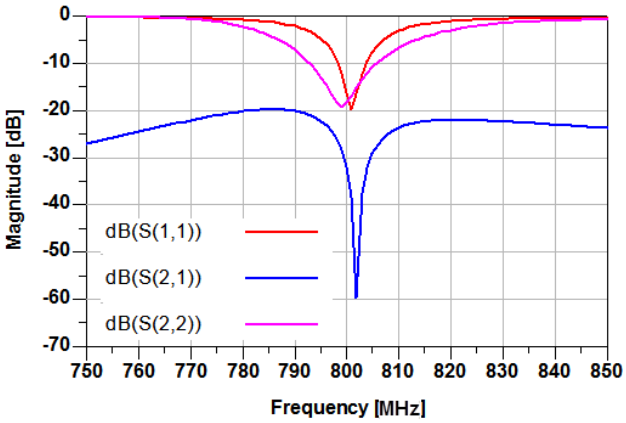

Fig. 5. The S parameters simulated through the hybrid method. The 3 port antenna becomes a 2 port network due to the balanced feeding of the monopoles.

The results of this hybrid simulation are plotted in figure 5. An impressive isolation level can be observed given the fact that the capacitors were tuned with 0.125 pF steps. For a deeper null, a much finer resolution is needed. However the isolation bandwidth is relatively narrow because the response of the antennas is also narrow-band. Cancellation is achieved only at one frequency however, the coupling between the antennas varies quickly with frequency. Nevertheless, a significant decoupling improvement is seen over the whole band.

As a result of this new feeding, the two monopoles become a balanced antenna that no longer uses the ground plane for radiation. Therefore, the input impedance it will be much more robust against the user's presence, as it was shown throughout literature. Nevertheless, the isolation disturbance in the near-field can be compensated by changing the phase difference of the excitation signals for the balanced element, as it can be seen in figure 6, where just one of the capacitors from the T networks is varied in its whole tuning interval.

The efficiency of the feeding network has been investigated. In the simulation all possible sources of losses have been included such as mismatch loses, conductive and dielectric losses in the microstrip, in the lumped components, even expected losses due to soldering have been included. The results of the simulation are plotted in figure 7. To calculate the total efficiency of the antenna, the only thing that has to

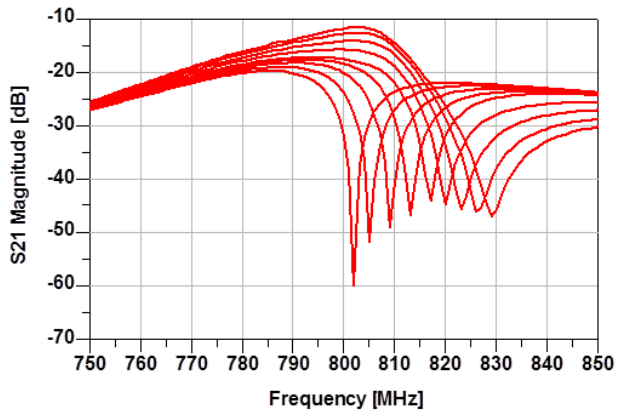

Fig. 6. The S_{21} response when just one capacitor is varied form 0.6 to 2.5 pF.

be included is the thermal losses in the antenna elements, which have been simulated to be around 1.5 dB at the resonating frequency, not shown here. Thus, the expected total efficiency of the balanced element is around -3 dB. The second antenna, a PIFA in this case, but it can be any type of antenna, will behave as it is expected. It has to be mentioned that its efficiency will be affected slightly, depending on the initial coupling level between the MAS elements, because the isolation is achieved at the ports. The radiating elements are still coupled so currents are running on the balanced element which means thermal loss. However, this is valid only for the unbalanced element because, when the balanced element is excited, the PIFA is in the null of its near-fields so no current will run on it.

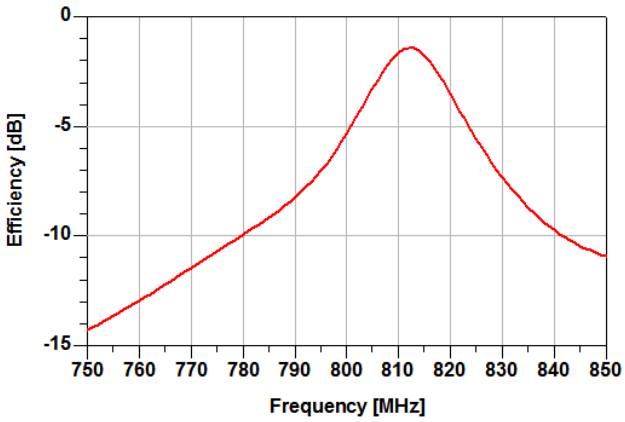

Fig. 7. The simulated efficiency of the feeding network .

III. Conclusion

A novel Tx-Rx isolation has been attained by tuning a balanced Tx antenna in a balanced-unbalanced antenna architecture. The isolation mechanism has been evaluated in the worst case scenario where the duplex frequency was set

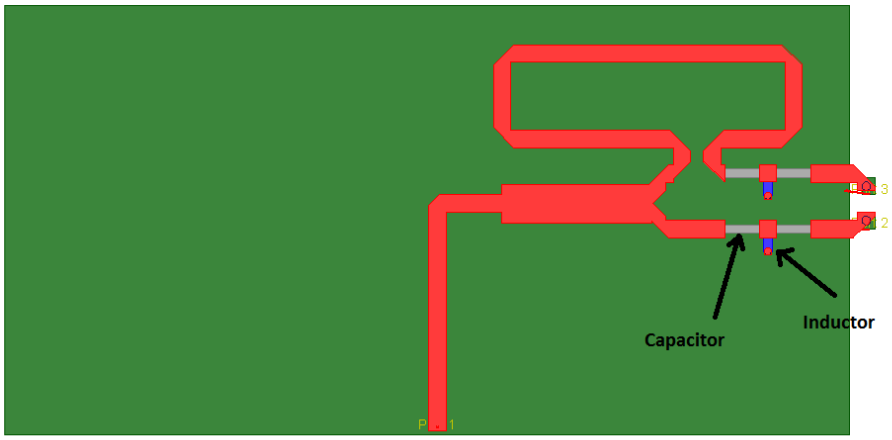

Fig. 4. The layout model of the feeding network used in the method of moments simulation. Red represents top layer whereas green represents the bottom layer with FR4 in between.

to zero. The agility of the antenna architecture has been demonstrated, though no attempt has been made to optimize the presented architecture for frequency tuning.

Acknowledgements

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