Orthogonal MIMO Antennas for Compact Cellular Handsets

M. Bank, K. Slupenko, M Haridim, V. Tsingouz

Abstract- we propose a novel compact MIMO antenna system for small handsets, based on two different types of antennas –a small loop and the MB antenna. The MB antenna is an enhanced dipole antenna, which can be implemented as internal antenna in a compact cellular handset. Similar to conventional dipole, MB is an electrical antenna; and the small loop is a magnetic antenna. It is shown that using these antenna one can create a compact MIMO system, with small mutual coupling between the antennas, even when the distance between them is smaller than λ/3. We also present a new method for increasing the radiation efficiency of small loop antennas at frequencies higher than 470MHz. Simulations results show that the mutual coupling between MB and small loop antennas is low.

***Keywords*—**MIMO, LTE, cellular handset, MB antenna, small loop antenna.

I. INTRODUCTION

THIS cellular phone systems have evolved rapidly over the past several decades, during which the size and weight of the phone handsets have continuously decreased[1] .Next generation wireless devices must incorporate the MIMO technology with multiple antennas implemented in a small area .

Multiple Input and Multiple Output (MIMO) technology is the most promising, if not the last frontier, in the evolution of wireless broadband access networks. In MIMO systems, signals from multiple antennas are combined to mitigate multipath effects, to improve channel capacity, to improve network coverage, and to increase link reliability [2]. In order to explore the diversity and multiplexing gains offered by the MIMO technology, the antennas spacing must be typically half wavelength [2]

LTE is the next generation cellular phone technology that aims to achieve a high peak data rate, low latency, and high radio efficiency in addition to low cost and sufficiently high mobility characteristics [1, 2]. One important characteristic of the LTE standard is the requirement for implementing MIMO architecture.

The LTE standard refers to various frequency bands. In this paper we consider the lowest band of 698-798MHz. At these low frequencies, implementing multiple antennas in a handheld device poses significant challenge in terms of high antenna radiation efficiency,high isolation, and low mutual coupling between the antennas. Mutual coupling between the antennas is determined by separation between the antennas, measured in terms of fractions of the wavelength used. Actually, it is attributed to the constraints on the dimensions of the handset (typically around 50x100mm) and the existence of the PCB which acts as a ground plane.

This paper presents a study of an innovative MIMO antenna system for compact mobile handsets, in which the distance between the antennas is less than λ/3 and the operating frequency is about 730MHz. In order to reduce the mutual coupling between the antennas we propose to use antennas of different types – electrical and magnetic, where the former is MB antenna [3], and the latter is a small loop antenna.

MB antenna is an enhanced dipole whose radiating element is the PCB (Printed Circuit Board) of the handset. In contrast to the conventional dipole and/or monopole the MB antenna can be implemented as an internal antenna in a compact cellular handset [3].

Small loops form another antenna type. The frequency range of this antenna is generally 285 to 470MHz [4]. Due to its extremely low radiation efficiency (only 1-20%), small loops are used predominantly as receiving antennas, where signal-to-noise ratio, and not antenna efficiency, is the most important factor [5].

Besides the proposed MIMO antenna system, we present a new method for increasing the low radiation efficiency of loop antennas at frequencies beyond 470MHz.

Simulation results show that it is possible to obtain low mutual coupling between the antennas of the investigated MIMO system, even when the distance between them is much smaller than λ/3.

II. THE MB ANTENNA

The MB antenna (MBA) is a modified version of a linear antenna that allows for the radiating element

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to be implemented by the handset's PCB which acts as a ground plane at cellular frequencies. Fig. 1 illustrates the directions of the currents when the radiating trace of a monopole antenna is implemented in parallel to a ground plane. As seen in this Figure, the currents in the conducting trace and in the ground plane are anti-parallel, resulting in very low radiation efficiency because of the destructive superposition of the fields produced by these currents.

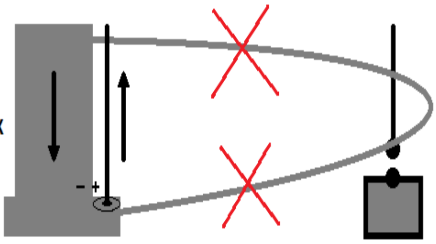


Fig. 1Monopole in parallel to ground plane.

The main idea behind the MBA is to introduce a phase shift of 180˚ in the feed path of the radiating trace (relative to the ground) so that the two currents become in-phase and flow in the same direction. In this way, the fields emanating from the trace and the ground plane will be in-phase and hence add up, resulting in high radiation efficiency similar to that of conventional monopole antennas. The phase shifter can be implemented in various ways, provided the following two requirements are fulfilled: 1) it must be realized in a non-radiating shape, 2) its electric length (corresponding to the center frequency) must be designed such that the currents in the radiating element and the ground plane are in-phase and flow in the same direction.

Fig. 2 shows schematics of the MB antenna for two different schemes of the phase shifting element. The phase shifter may consist of a simple delay line whose electrical length is λ/2, where λ corresponds to the center frequency of operation. The radiating trace as well as the delay line can be implemented either as a separate wire (outside the substrate) or as a printed line on the same substrate on which the radiating element is printed, e.g. the handset’s PCB.

The MB antenna can be designed for multi-band operation. For this purpose one should implement a number of radiating elements of different lengths fed by the same number of phase shifters each corresponding to the central frequency of one of the required bands. Fig. 3 shows a double band MB antenna.

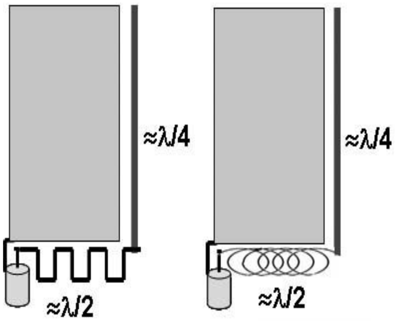


Fig.2The MB antennas using different types ofphase shifter.

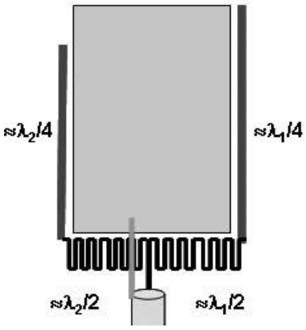


Fig. 3Multiband MB antenna.

The cellular handset PCBs may act as the substrate and ground plane for the antenna. This means that the radiating trace and the delay line, either one or both of them, can be printed on a certain area of the PCB, if this area is a pure dielectric material.

III. SMALL LOOP ANTENNA

Loop is a simple, inexpensive, and very versatile antenna. Loop antennas take many different forms such as rectangle, square, triangle, ellipse, circle, and many other configurations. The field patterns of an electrically small loop antenna are dependent on the loop area but are independent of the loop shape [5].

Loop antennas are usually classified into two main categories, electrically small and electrically large. The small loop threshold is normally defined by circumference of the loop, and is usually somewhere between one-tenth and one-third of a wavelength (there is some disagreement amongst the classic antenna texts about the small loop threshold, Balanis gives 0.1λ, Stutzman gives 0.3λ, and Kraus gives 0.33λ [5, 6, 7]).

The planar shape of the small loop antenna makes it ideal for use as a compact antenna. However, like most other compact antennas, the electrically small loop suffers from poor radiation efficiency. Because of this poor radiation efficiency, it has traditionally been limited to applications that are low-range, low data-rate communications or receive-only systems [5].

Figure 4 shows an equivalent circuit of a small loop antenna consisting of two resistors, capacitor and an inductor [8]. The radiation resistance R_{rad} , models the radio frequency energy actually radiated by the antenna. Assuming a uniform current I flowing through the loop, the power consumed by R_{rad} (i.e., the radiated power) is given by

$$P_{rad} = \frac{4}{3}\eta\pi^3\left(\frac{A}{\lambda}\right)^2|I|^2$$

where A is the loop area inside the center of trace width, and $\eta = \sqrt{\mu/\varepsilon}$ is the intrinsic impedance of the conductor [5].

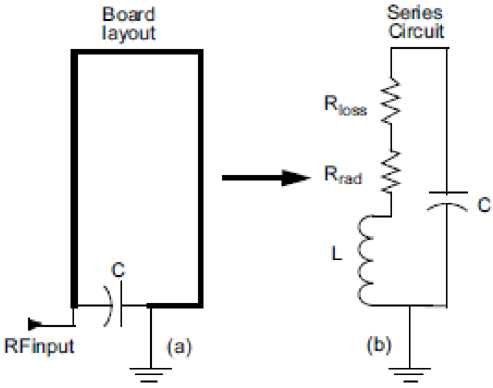


Fig. 4(a) Loop antenna physical implementation, (b) the standard loop antenna model.

The radiation resistance of the loop is given by $P_{rad} = |I|^2 R_{rad}/2 = I^2 R_{rad}$, and can be rewritten as

$$P_{rad} = \frac{8}{3}\eta\pi^3\left(\frac{A}{\lambda^2}\right)^2 = 320\pi^4\left(\frac{A}{\lambda^2}\right)^2$$

The second resistor in the model, R_{loos} , models losses, and is given by

$$R_{loss} = \frac{l}{w}\sqrt{\frac{\pi f\mu}{\sigma}}$$

where l and w are the perimeter and the width of the loop, respectively; μ and σ are the permeability and the conductivity of the conductor. This resistance is undesired, but it is an inevitable function of the antenna representing the power dissipation in the antenna. If R_{loos} is larger than R_{rad} , the antenna is inefficient, since most of the available RF power will end up as heat [8]. With current I flowing through the loop, the dissipated power is given by

$$P_{loos} = I^2 R_{loos}$$

Thus, the total power delivered to the antenna is given by the sum of the radiated power and losses:

$$P_{loos} = P_{rad} + P_{loos} = I^2\left(R_{rad} + R_{loos}\right)$$

The radiation efficiency of the loop, is given by

$$\eta_{rad} = \frac{R_{rad}}{R_{rad} + R_{loos} + R_{esr}}$$

Where R_{ESR} is the ESR of the capacitor.

The third component in the model of Fig. 4 is the loop inductance L, which determines the value of the capacitor needed for resonance. An equation to estimate the inductance of this loop with about 95% accuracy is:

$$L = \frac{l\mu}{2\pi}\ln\left(\frac{8A}{lw}\right)$$

According to this, one can calculate the value of the capacitor:

$$C = \frac{1}{4\pi^2 f^2 L}$$

Resonant frequency tuning and impedance matching between the driver and the antenna, may be much improved by tapped capacitor matching method shown in single ended form in Figure 5.

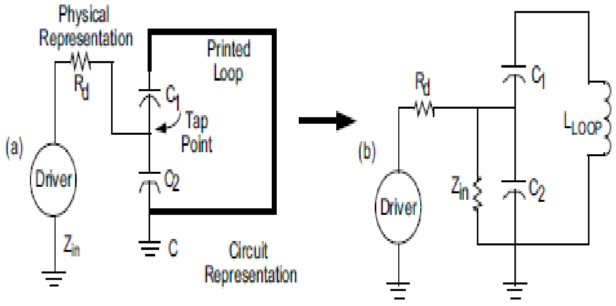


Fig. 5Single ended tapped capacitor antenna matching.

The solutions for C_1 and C_2 are given by [8]:

$$C_1 = \frac{1}{4\pi^2 f^2 L - 2\pi f\left(\sqrt{Z_{in}\left(R_{rad} + R_{loss} + R_{esr}\right)}\right)}$$

$$C_2 = \frac{1}{2\pi f\left(\sqrt{Z_{in}\left(R_{rad} + R_{loss} + R_{esr}\right)}\right)}$$

Typically C_2 is much larger than C_1. In this case, C_1 tunes the resonant frequency, while C_2 independently tunes the antenna impedance. This makes tweaking the final design much easier. For example, the antenna impedance could be decreased by increasing only C_2, without a compensating decrease in C_1 while maintaining near optimal tuning.

IV. SOLUTION FOR LOW RADIATION EFFICIENCY OF THE SMALL LOOP ANTENNA

According to the formula of C_1 one can see that increasing the antenna resonant frequency cause lowering of the capacitor. In practice, it is difficult to realize an antenna with capacitance smaller than 2-3pF, due the parasitic capacitance, which begins to affect the performance of the antenna. The capacitance can be increased by reducing the antenna inductance, but in this case, in the formula of L, it can be seen that this directly affects the antenna's effective area. As a result, the antenna will have a very poor radiation efficiency, and cannot be used as a transmit antenna.

The poor radiation efficiency problem of a small loop antenna can be solved by an additional antenna, connected to the same source, as shown in Figure 6. Along with this, each antenna is still classified as a small loop, with circumference smaller than 0.1λ-0.33λ.

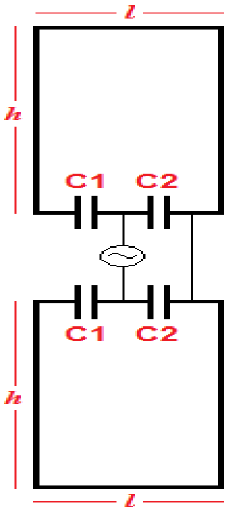


Fig. 6Model of two small loop antennas –solving the low radiation efficiency problem.

V. ANTENNA DESIGN

In order to achieve a MIMO system of high spectral efficiency, the radiation efficiency for each antenna element in the array must be maximized while minimizing their far-field envelope correlation numbers [2].

These two key challenges along with fitting two low frequency 698-798MHz LTE MIMO antennas in a small handset form factor are summarized in the following three factors:

1. Antenna efficiency - each antenna should be designed to comply with source impedance matching and radiation efficiency over an operation bandwidth (698-796MHz) exceeding 40%.
2. Near-Field Coupling - the isolation between two adjacent antennas of the MIMO system is optimized to be less than -10dB, since strong coupling between them significantly reduces their radiation efficiency and and MIMO channel de-correlation. The -10dB isolation level is considered as the threshold below which any further improvement will only increase radiation efficiency in negligible numbers which cannot justify adding this extra de-coupling complexity. Abetter antenna matching is met with -10dB isolation because of the minimized effect of mutual impedance Z_{12} and Z_{21} values between antenna ports.
3. The physical size of each antenna is selected to fit on the small board size of a smart phone device (typically around 50mm x 100mm).

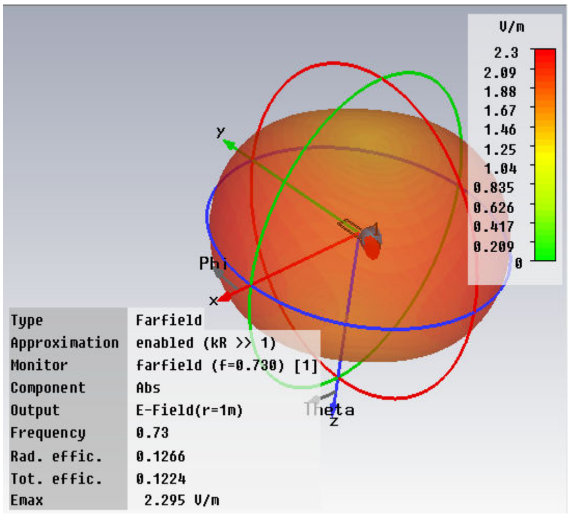
VI. SIMULATION RESULTS

The design and simulation of the investigated MIMO antenna system was carried out using the CST Microwave Studio 2010. The MB and the small loop antennas were designed for central frequency 730MHz.

A. SMALL LOOP ANTENNA

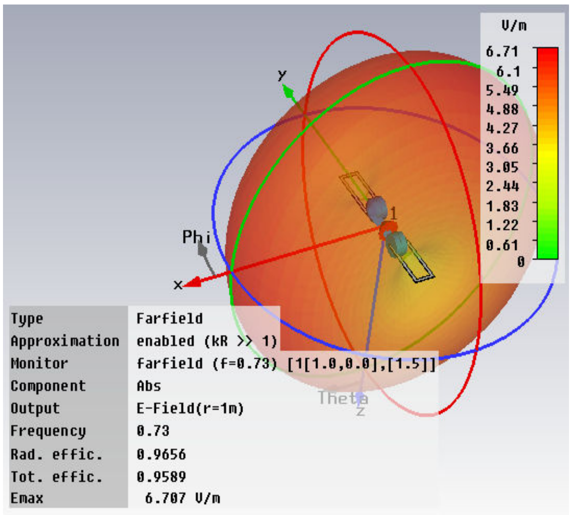
According to the equations given in Section III, one can calculate the optimal dimensions of a small loop antenna. Note that in order to fit the small loop criteria, the loop circumference must be smaller than 0.1λ-0.33λ. That is, at the resonant frequency 730MHz the circumference of the antenna must be smaller than 0.1m. According to this, the dimensions that give the maximal radiation efficiency are 12x34mm, and the track width of the antenna is 2mm. C_1 and C_2 values are 0.92pF and 43.2pF, respectively.

Figures 7 and 8 shows the far-field simulation results of the conventional and the enhanced small loop antennas, respectively. As it can be seen in these figures the total radiation efficiency of the enhanced small loop antenna is 95%, which is much higher than the conventional small loop total efficiency i.e.12%. In addition to its higher efficiency, the enhanced small loop antenna has a much larger E-field of 6.707V/m compared to that of the conventional small loop antenna 2.295V/m.



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=0.730) [1]
Component	Abs
Output	E-Field(r=1m)
Frequency	0.73
Rad. effic.	0.1266
Tot. effic.	0.1224
Emax	2.295 V/m

Fig. 7Conventional small loop antenna.



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=0.73) [1[1.0,0.0],[1.5]]
Component	Abs
Output	E-Field(r=1m)
Frequency	0.73
Rad. effic.	0.9656
Tot. effic.	0.9589
Emax	6.707 V/m

Fig. 8 – Enhanced small loop antenna.

Figure 9 shows the simulation results of the S11 characteristics of the enhanced small loop antenna. These results show a S11 of -21.58dB at the resonance frequency (730MHz).

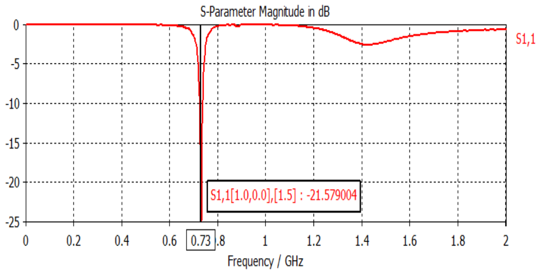


Fig. 9 – S11 simulation results of the enhanced small loop antenna.

In order to simulate the handset's PCB impact on the antenna performance, a dielectric substrate was attached to the enhanced small loop antenna, as shown in Figure 10. Table 1 shows that there is no performance degradation caused by the adjacent dielectric substrate.

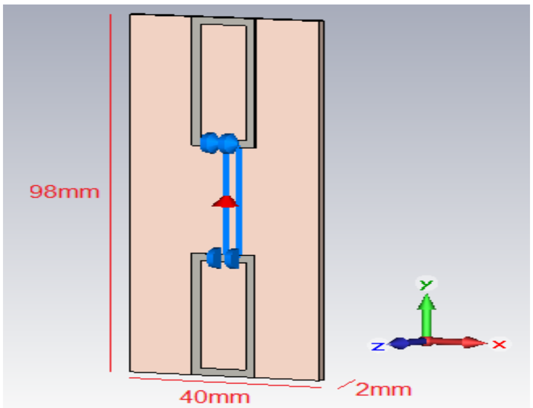
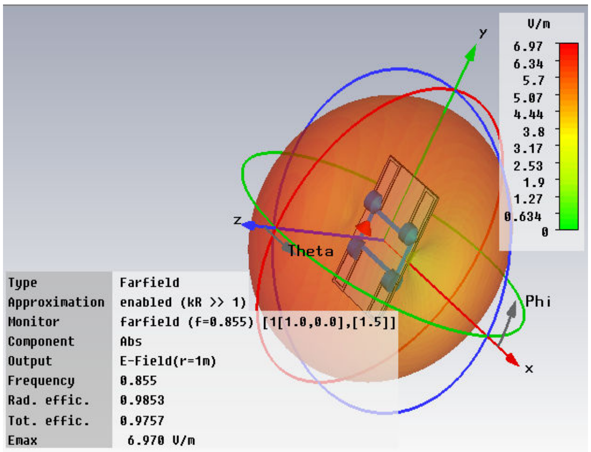


Fig. 10 Enhanced small loop antenna with adjacent dielectric substrate.

Table 1-The impactof PCB presence on the small loop antenna performance

.Antenna type	S11 [dB]	Rad. Effic.	Tot. Effic.	Emax [V/m]
Enhanced small loop	-21.58	0.9656	0.9589	6.707
Enhanced small loop with adjacent dielectric substrate	-20.11	0.9891	0.9795	6.788

From simulation results shown in Figures 11, 12 and Table 2 it can be seen that it is possible to create a compact multiband small loop antenna system, which operates as a transmitter at frequencies higher than 470MHz. The dimensions of the four-antenna array system are 2x57x104mm, so it can be implemented in compact systems, such as a mobile handset or smart phone. In addition, in order to obtain an omnidirectional radiation pattern, this configuration of small loop antennas allows a 90˚ rotation of the antenna relative to another antenna.



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=0.855) [1[1.0,0.0],[1.5]]
Component	Abs
Output	E-Field(r=1m)
Frequency	0.855
Rad. effic.	0.9853
Tot. effic.	0.9757
Emax	6.970 V/m

Fig. 11 – System of 4 small loop antennas.

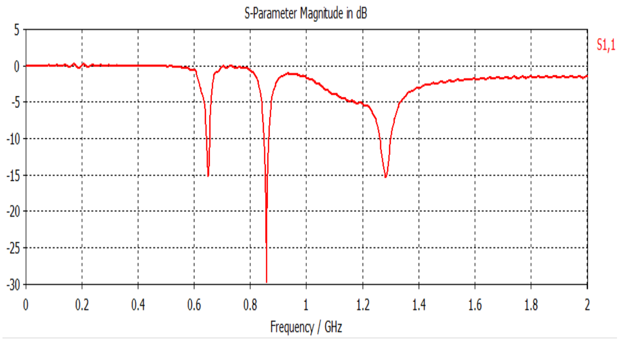


Fig. 12S11 simulation results of the 4 small loop antenna system.

Table 2-Main characteristics of the small loop multiband antenna array.

Resonant freq. [MHz]	S11 [dB]	Rad. Effic.	Tot. Effic.	Emax [V/m]
650	-15.12	0.9408	0.9125	6.695
855	-20.96	0.9853	0.9757	6.970
1270	-12.8	0.9975	0.9422	10.17

B. MB ANTENNA

As it can be seen from the presented simulation results and previous onespresented in [3], the recently proposed MB antenna seems to be well suitable for compact handsets. Simulation results for the far field performance of the MB antenna are shown in Figures 12, 13 and 14. In these simulations the required 180˚ phase shift is implemented by a typical spiral, but real MB antennas can be implemented by a compact electronic component, such as CDM-Type LTCC Chip Delay Line.

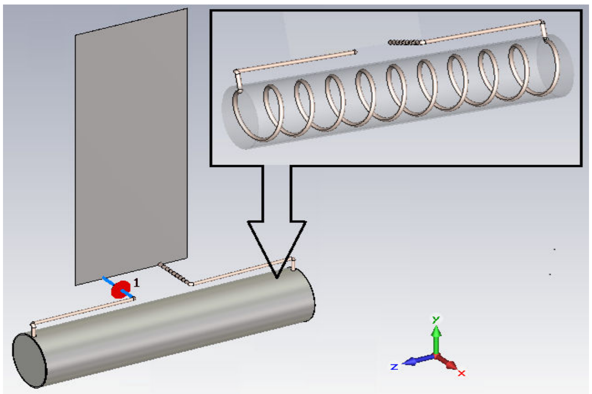
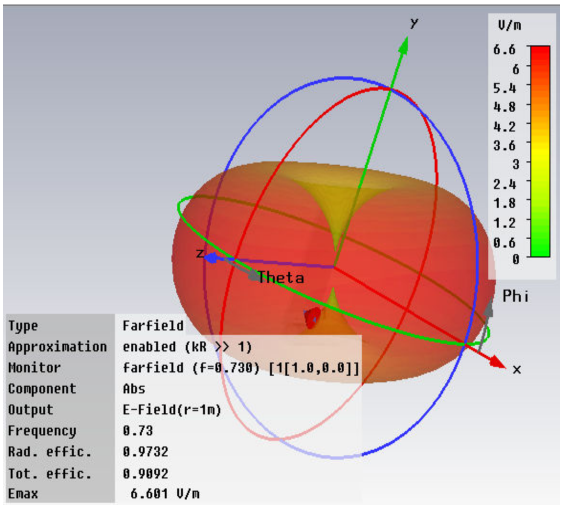


Fig. 12 MB antenna with 180˚ phase shifter implemented by a typical spiral.



```
Type            Farfield
Approximation   enabled (kR >> 1)
Monitor         farfield (f=0.730) [1[1.0,0.0]]
Component       Abs
Output          E-Field(r=1m)
Frequency       0.73
Rad. effic.     0.9732
Tot. effic.     0.9092
Emax             6.601 V/m
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Fig 13. – Simulation of MB antenna at 730MHz.

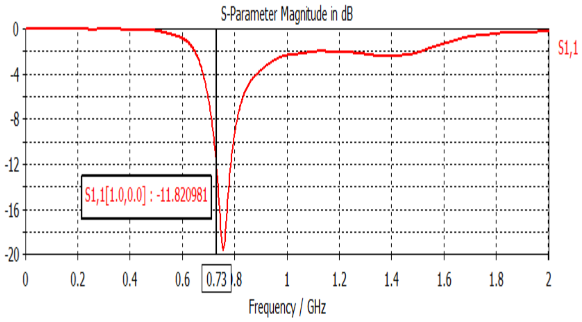


Fig. 14 – S11 simulation results of MB antenna.

As it can be seen in Figures 13 and 14, the total radiation efficiency of the MB antenna at frequency 730MHz is 90%. In addition to its higher efficiency, the MB antenna has E-field of 6.707V/m and good isolation (-11.83dB).

As in the case of a small loop antenna presented in sub-section A,the handset's PCB impact on the antenna performance is taken into account by adding a dielectric substrate attached to the MB antenna, as shown in Figure 15. From Table 3 it can be seen that there is no performance degradation caused by the adjacent dielectric substrate.

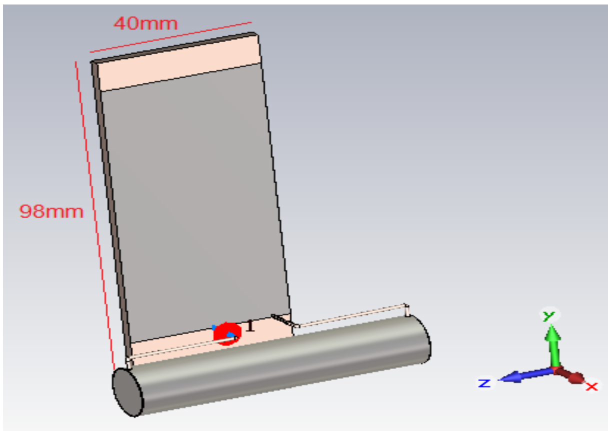


Fig. 15 – MB antenna with adjacent dielectric substrate.

Table 3 – The PCB existence impact to MB antenna performance.

Antenna type	S11 [dB]	Rad. Effic.	Tot. Effic.	Emax [V/m]
MB antenna	-11.82	0.9732	0.9092	6.601
MB antenna with adjacent dielectric substrate	-15.12	0.9784	0.9483	6.746

I. SMALL LOOP AND MBA MIMO SYSTEM

We now proceed with the design of the MIMO system consisting of the MBA and the loop antenna described above. The design is based on the simulation results for each antenna as presented in previous sections. Figure 16 shows the proposed MIMO antenna system The simulation results for this system show that the distance between the antennas can be much smaller than λ/3, for example 4mm. That is, the MIMO system is small enough to fit into a compact handset device.

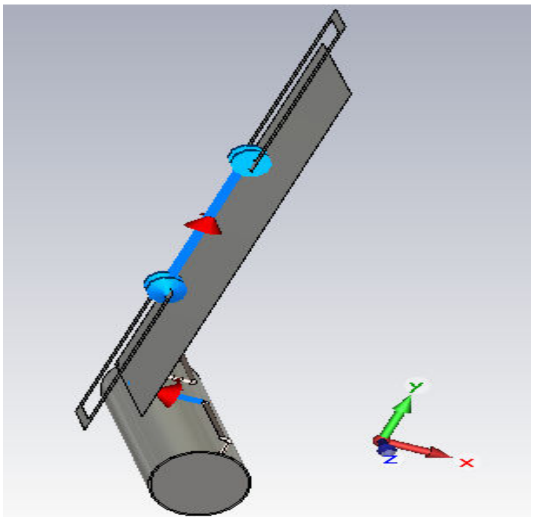
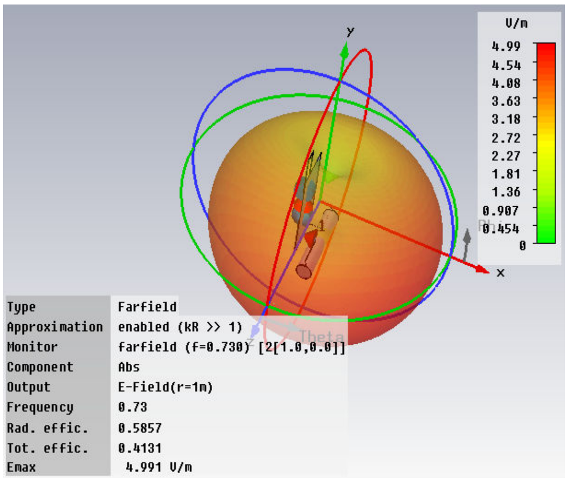


Fig. 16 – The proposed MIMO system. the distance between the antennas is 4mm.

From the far-field simulation results, shown in Figures 17 and 18, it can be seen that the total radiation efficiencies of the small loop and the MB antenna are 41% and 60%, respectively. The E-fields of the antennas are approximately the same, 4.991V/m for the small loop, and 5.529V/m for the MB.



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Type            Farfield
Approximation   enabled (kR >> 1)
Monitor         farfield (f=0.730) [2[1.0,0.0]]
Component       Abs
Output          E-Field(r=1m)
Frequency       0.73
Rad. effic.     0.5857
Tot. effic.     0.4131
Emax             4.991 V/m
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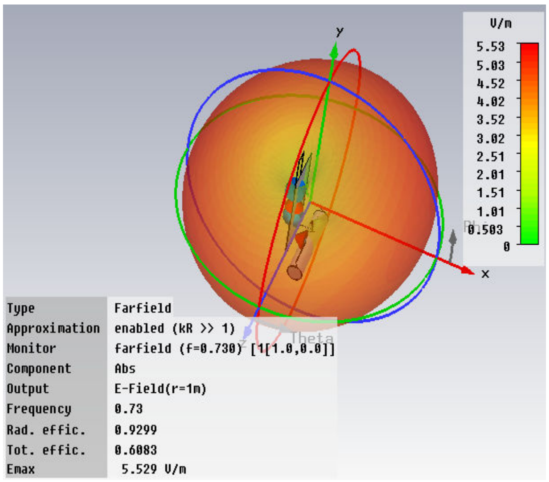
Fig. 17 – Simulation of small loop antenna placed near to the MB antenna, with a spacing of 4mm.



```
Type            Farfield
Approximation   enabled (kR >> 1)
Monitor         farfield (f=0.730) [1[1.0,0.0]]
Component       Abs
Output          E-Field(r=1m)
Frequency       0.73
Rad. effic.     0.9299
Tot. effic.     0.6083
Emax             5.529 V/m
```

Fig. 18 – Simulation of the MB antenna placed near to the small loop antenna, with a spacing of 4mm.

Figure 19 shows the simulation results for the S11 parameter of both antennas. It can be seen that the influence of eachantenna on the other is less than -10dB.

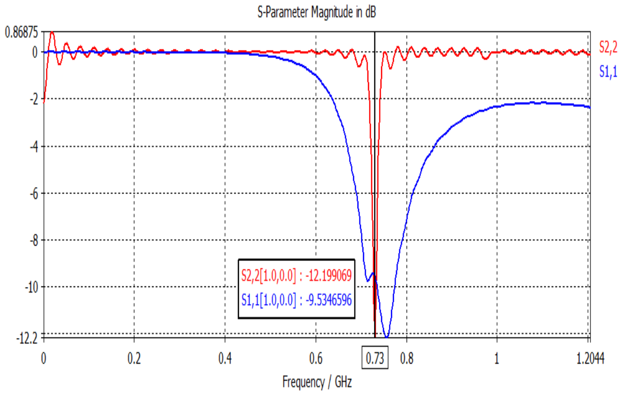


Fig. 19 – S11 simulation results of the small loop (red) and MB antenna (blue) placed near each other, with a spacing of 4mm.

This system can be further improved by combining few loop antennas, as shown in Fig. 20.

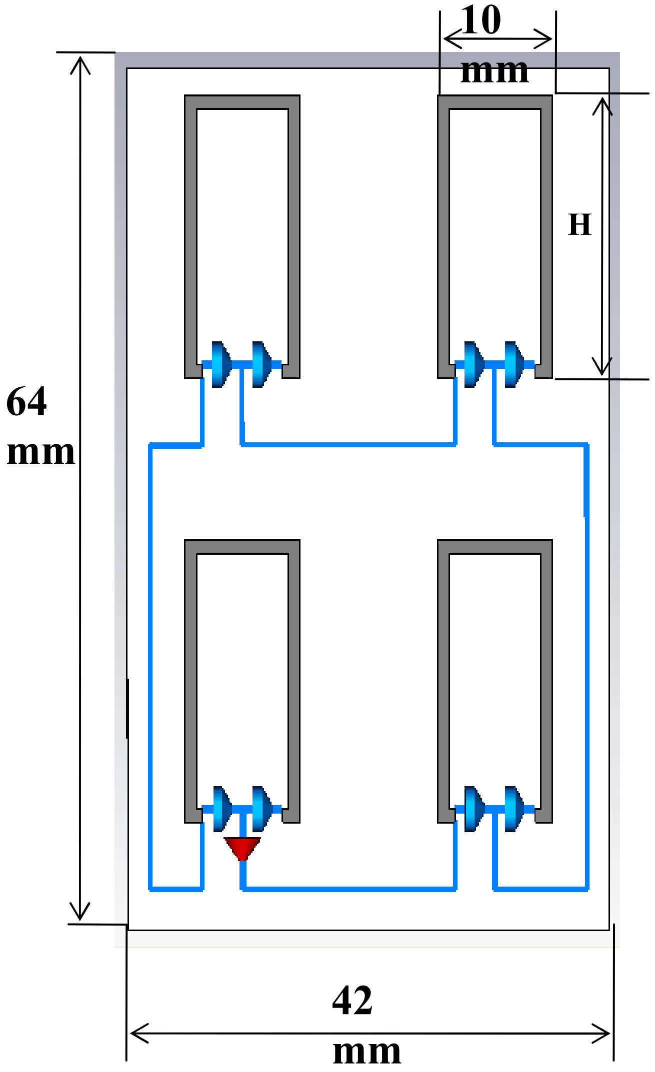


Fig. 20 Four loops antenna for portable hand set

Figures 21 and 22 show, respectively, the simulation results for the S11 parameter and the field intensity of the multi-loop antenna of Fig. 20.

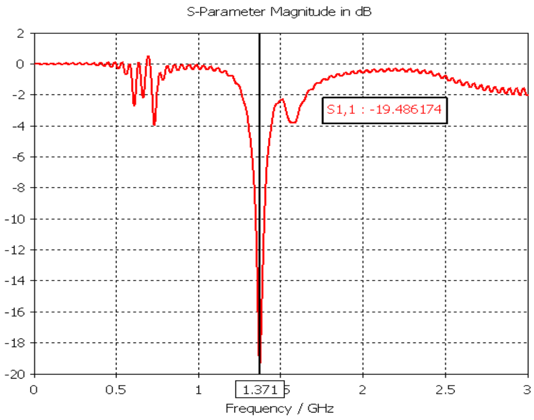
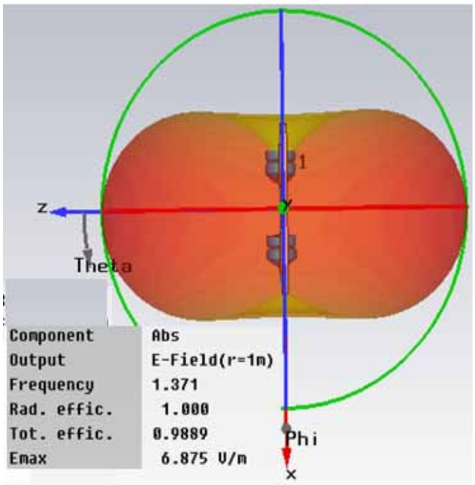


Fig. 21 Four loops antenna S11 parameter

The results show that the multi-loop antenna's characteristics are better than those of a monopole antenna, where the ladder is subject to significant mutual effects when used in the small MIMO system.



Component	Abs
Output	E-Field(r=1m)
Frequency	1.371
Rad. effic.	1.000
Tot. effic.	0.9889
Emax	6.875 V/m

Fig. 22 Four loops antenna field density on distance 1 m and source voltage 1V

It is important to note that the value of C1 (and sometimes C2) is very sensitive to the exact geometry of the antenna system. Typically, the value of C1 is much smaller than the value of C2. In our simulations the value of C1 is 0.35pF, and the value of C2 is 630pF. In addition, since the antennas are placed in the free space, there is no parasitic capacitance caused by the low value of C1. The small loop and MB port impedances are 50ohm and 75ohm, respectively.

VII. CONCLUSION

The possibility of creating a compact MIMO antenna system in a small handset based on small loop and MB antennas is proposed and investigated. Due to the fact that the small loop is a magnetic antenna and the MB is an electric one, the mutual coupling between them is low, even when the distance between the antennas is smaller than $\lambda/3$. In the presented simulations, the radiation efficiency and the antennas isolation level were investigated for a center frequency of 730 MHz. It is shown, that both antennas have radiation efficiencies exceeding 40%, and the isolation between the antennas is lower than -10dB. The dimensions of the investigated MIMO system are 40x98mm, and the distance between the antennas is 4mm, such that it is small enough to fit into the compact handset device.

We also proposed a new method for improving the radiation efficiency of the small loop antennas at frequencies higher than 470MHz. It is shown, that it is possible to obtain high radiation efficiency by using an additional antenna, fed by the same source. Moreover, this configuration of the small loop antenna can be designed for multi-band operation.

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