FREQUENCY-TUNABLE INTERNAL ANTENNA FOR MOBILE PHONES

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Abstract *– New approaches are needed for improving the performance of small antennas to fulfill the multiband operation requirements of future wireless mobile communications terminals. In this paper, a novel low-loss frequency-tuning circuit for mobile handset antennas is proposed. The presented design takes into account several factors that affect the practical mobile handset antenna design, such as the biasing limitations and distortion of the switching component as well as the effect of the mobile handset -sized ground plane. An antenna prototype that is capable of switching between the US cellular and GSM systems at 800-900 MHz frequency range was designed and measured. The antenna was positioned on a metallized printed circuit board (PCB) having size equal to that of a typical mobile phone. The tuning circuit, consisting of transmission line sections and an SPDT (single-pole, double-throw) FET switch, was fabricated directly on the substrate of the PCB. The designed antenna has high radiation efficiency and low distortion in both system bands.*

1 INTRODUCTION

Microstrip patch antennas are commonly used in mobile communications terminals due to their many attractive features, such as simple structure, low production cost, light weight, and robustness. Dual-frequency antenna elements are required, as today's standard mobile terminals operate in two frequency bands, e.g. GSM900/GSM1800 in Europe. It is desirable to have more universal phones that operate in multiple systems around the world, but the inherently narrow impedance bandwidth of patch antennas combined with the restricted volume for the antenna element limit their applicability in multiband phones.

One way to overcome the bandwidth limitation is to increase the effective bandwidth of the antenna element by tuning its resonant frequency, and thus the operation band, between different communication systems. This can be realized by loading the antenna with a reactive tuning component, which can be either an electrically controlled reactance or a passive reactance with a switching component. One common method is to connect a tunable reactance or switch between the patch and the ground plane, as first proposed in [1]. Another approach is to use the tuning component for connecting separate parts of the patch [2, 3]. In these cases the tuning components are typically placed at high RF voltage [1] or current [2, 3] locations to maximize the obtained frequency shift. This may result in significant losses in the tuning component [4]. Also, many important factors, which may restrict the use and performance of certain tuning circuits in mobile terminal antennas, have been given less attention in previously published designs. These limiting factors are e.g. the available dc-bias and distortion of the switching component as well as the effect of the mobile handset -sized ground plane on bandwidth [5-7].

Recently, a theoretical analysis on the minimization of power loss in frequency tuning circuits of small resonant antennas has been presented [8]. To support the theory, the design of frequency-tunable patch antennas mounted on large ground planes was demonstrated. In this paper, the same basic principles were adapted to the design of a frequency-tuning circuit for practical mobile handset antenna. A tuning circuit was added to a previously published dual-band antenna element [9] for the European GSM bands (880-960 MHz, 1710-1880 MHz) to cover also the US cellular system band (824-894 MHz) with the same antenna. The tuning circuit consisted of low-loss transmission line sections and an SPDT FET switch, which has suitable characteristics for use in real mobile phones. The antenna was positioned on a metallized PCB having dimensions 110 mm × 40 mm, thus representing the PCB of a typical mobile phone. Both simulated and measured results for the design are presented.

2 ANTENNA STRUCTURE AND DESIGN

The electrical properties of a handset antenna, especially the bandwidth, are known to depend strongly on the size of the ground plane of the device on which the antenna is mounted (phone chassis) and the position of the antenna on it [5-7]. Based on this, the total radiation bandwidth of the antenna-chassis combination is partly defined by the dipole-type radiation of the chassis currents, whose level further depends on whether the chassis is at resonance or not [6, 7]. If the chassis resonates at the operating frequency of the antenna element, the effective unloaded quality factor of the antenna-chassis combination ($Q_{0,eff}$) decreases, and the bandwidth increases strongly. When an antenna, which is positioned on a chassis having size equal to that of a typical mobile phone, is tuned from the GSM900 band down to the US cellular band, the coupling of the feed to the antenna element increases considerably. This happens because $Q_{0,eff}$ increases, as the resonant frequency of the antenna is tuned further away from the resonance of the chassis (around 1 GHz for a 110 mm-long chassis). Thus, if the antenna is matched well in the GSM900 band, the matching in the US cellular band is poor owing to clear overcoupling. On the other hand, if the antenna is matched well in the US cellular band, the matching in the GSM900 band is poor owing to clear undercoupling. Therefore, owing to the strong frequency-dependency of the coupling between the feed and the antenna element, sufficient matching in both bands cannot be obtained by simply switching the resonant frequency of a mobile handset antenna between the two systems. This significantly complicates the design of frequency-tunable antennas for mobile handsets. One way to provide adequate bandwidth for both systems is to utilize dual resonance. In the presented design, a doubly tuned resonance has been used in both system bands (see the Smith chart in Fig. 2)

The presented antenna structure was designed and theoretically studied with a method of moments (MoM) -based simulation software. Figure 1 shows the studied configuration. The used antenna element is similar to the dual-band GSM antenna presented in [9] (Fig. 1a). The total size of the antenna element was 16 mm × 38 mm × 8 mm (*length* × *width* × *height*). The widths of the three contact pins (short circuit, feed, coupling to the tuning circuit) were 1 mm. The antenna was located on a 110 mm × 40 mm × 0.79 mm RT/duroid 5870 plate ($\varepsilon_r' = 2.33$, $\tan\delta = 0.0012$), which had metallization on its backside.

The triple system band behavior was realized with a tuning circuit consisting of low-loss transmission line sections and an SPDT FET switch. The theory presented in [8] was used as a starting point for the design. The tuning circuit was fabricated on the substrate of the PCB, and a pin interconnected the antenna element and the tuning circuit. The basic idea is to connect the first tuning line having length l_1 in turn to the second tuning line having length either $l_{2,1}$ or $l_{2,2}$ (Fig. 1b) and thereby change the reactance loading the antenna. In the presented design, the antenna operates in the US cellular band when line 1 is connected to line 2,1 (State1 of the switch) and in the GSM900 band when line 1 is connected to line 2,2 (State2 of the switch).

To obtain the desired frequency bands with minimum tuning line lengths, the study was done with open-ended transmission lines. The switch was not directly connected to the antenna but separated from it by a section of transmission line. This allows low power loss in the switch, as the position of the switch is close to a current minimum. This kind of design should also lead to low distortion in both states of the switch, as the voltage over the switch remains low. The desired bands were covered with minimized losses with line lengths $l_1 \approx 0.11\lambda$ (λ@900 MHz, vertical pin 7.2 mm + a 20.3 mm-long section of line on the substrate), $l_{2,1} \approx 0.01\lambda$ (2 mm on the substrate), and $l_{2,2} \approx 0.06\lambda$ (13.5 mm on the substrate). The widths of the lines were 2.2 mm ($Z_0 = 50\ \Omega$), excluding the 1 mm-wide vertical coupling pin. Alpha's low-voltage SPDT FET switch AS193-73 [10] was used as a switching component in the design. It was modeled in the simulations by an S-parameter block including the chip and the package (from the manufacturer).

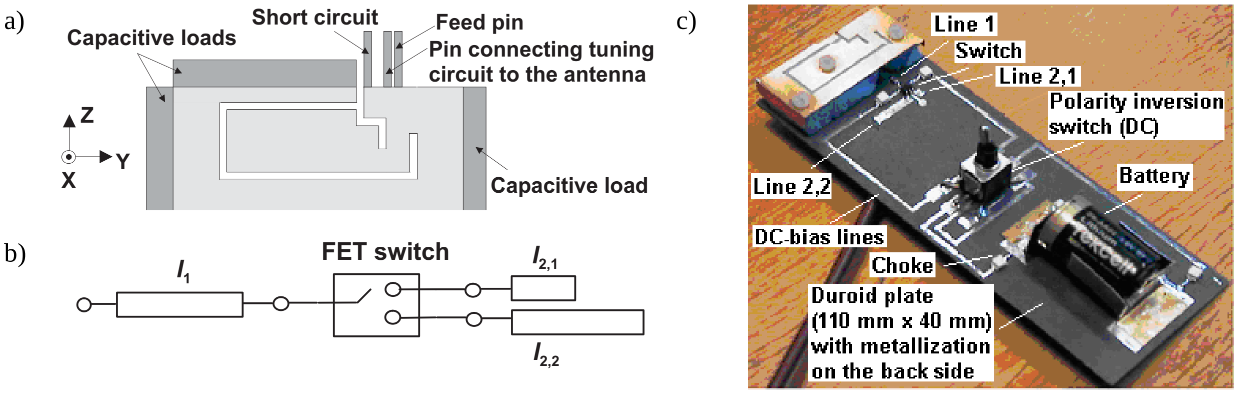
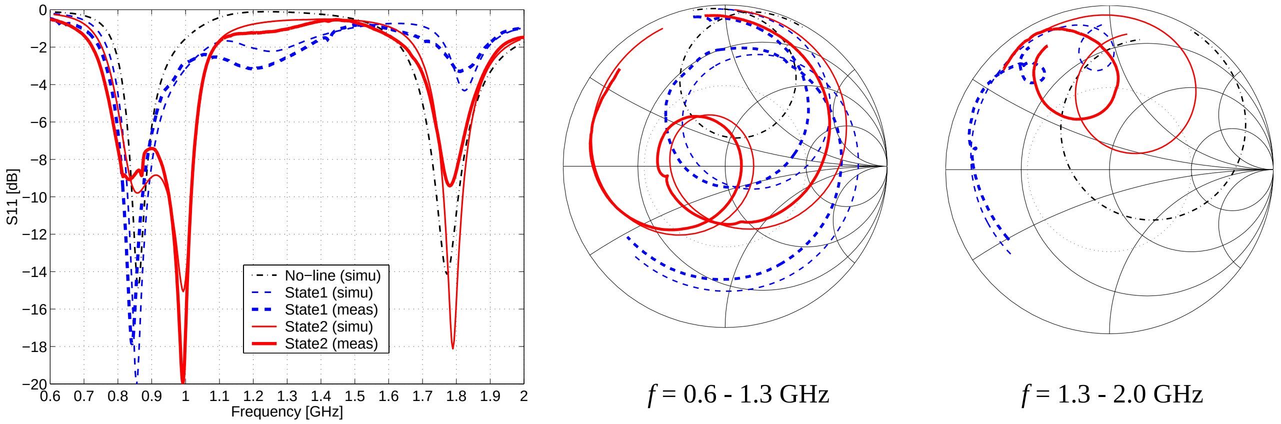


Figure 1. *Studied antenna structure, a) Antenna element (to scale), darkened parts are bent down, b) Structure of the tuning circuit, c) Photograph of the prototype.*

A prototype antenna (Fig. 1c) was constructed by photoetching the patch, capacitive loads, and contact pins from 0.2 mm-thick sheet of tin bronze (96 % copper and 4 % tin, effective conductivity $\sigma_{eff} = 0.192 \times 10^7$ S/m). A piece of Styrofoam was placed below the antenna to support the structure. The tuning lines, which were made of copper (thickness 35 μm, $\sigma_{eff} = 1.45 \times 10^7$ S/m), were etched on the PCB. For easier prototyping, the tuning lines were located only partly below the antenna, but they could have been bent totally below the antenna element without degrading the performance. The line 1 was dc-decoupled from the switch with a blocking capacitor of 100 pF. A 3.6 V battery, with a switch for the inversion of the polarity, was used as a supply voltage for the FET switch. The dc-lines were fabricated directly on the duroid, and chokes were added to the dc-lines near the switch and near the battery.

3 RESULTS

Figure 2 shows the frequency responses of reflection coefficient when no tuning circuit is connected to the antenna (No-line) and with the tuning circuit in both states of the switch (State1 and State2). The length of line 2,2 ($l_{2,2}$) of the prototype was adjusted slightly by shortening it by 2 mm compared to the original design. The measured frequency bands ($L_{retn} \geq 6$ dB) are 796-909 MHz (State1) and 785-1034 MHz (State2). The US cellular and GSM900 bands are covered with over 7 dB matching with the switch in State1 and in State2, respectively. The latter state (State2) would actually cover both system bands, however, to improve the matching in the lower band, and thus also the total efficiency of the antenna, the other state of the switch (State1) was utilized as well. It can also be noted that the antenna can be used concurrently in the European GSM900 and GSM1800 systems, as coupling the tuning circuit to the antenna does not destroy the performance in the GSM1800 band with the switch in State2. Furthermore, the antenna performance in the GSM1800 might be improved by slightly modifying the upper band element of the antenna, but in this study the upper band was not of main interest.

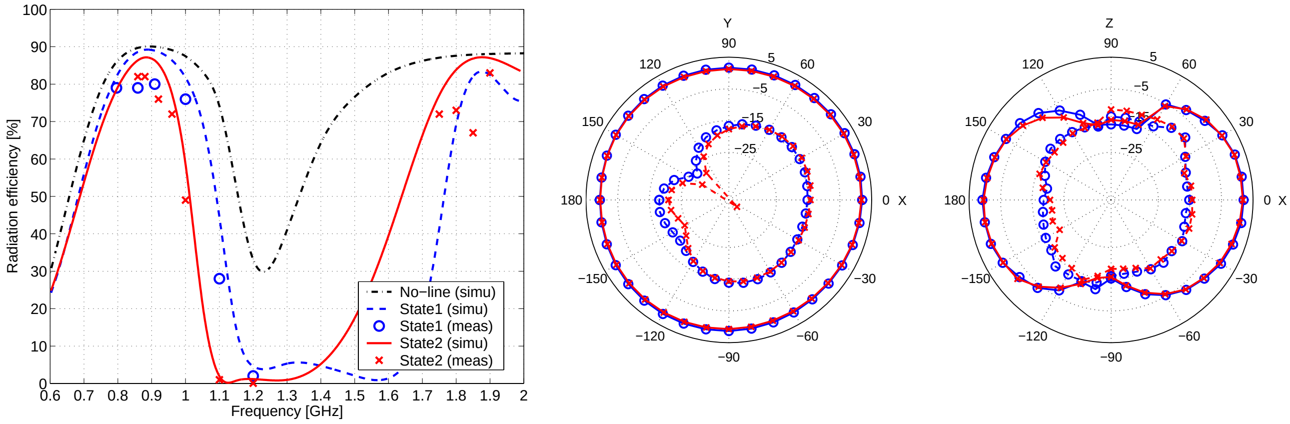


f = 0.6 - 1.3 GHz

f = 1.3 - 2.0 GHz

Figure 2. *Simulated and measured frequency responses of reflection coefficient for the prototype antenna. Dotted circle on the Smith chart represents L_{retn} = 6 dB.*

The radiation efficiency ($\eta_r = P_{in} / P_{rad}$, does not include losses due to mismatch) of the prototype was measured with the 3D pattern integration method. The measured efficiency is above 79 % in the US cellular band and above 72 % in the GMS900 band. The simulated values are above 85 % and 78 % in the US cellular band and GSM900 band, respectively. The radiation efficiency of the antenna without the tuning circuit was not measured, but the simulated values are above 88 % in the original frequency band ($L_{retn} \geq 6$ dB). These results indicate that the losses caused by the tuning circuit are small. The small discrepancy between the measured and simulated results can be attributed to the uncertainty of the measurement set-up. However, the general trends in the simulated and measured radiation efficiencies as a function of frequency are similar (Fig. 3a). Radiation efficiency in the GSM1800 band was not measured when the switch was in State1 because the simultaneous operation of the US cellular and GSM1800 bands was not of interest.



a)

b)

Figure 3. *a) Simulated and measured radiation efficiencies for the prototype antenna, b) Measured cuts of the radiation patterns (—— E_θ, --- E_ϕ) at 859 MHz with the switch in State1 (o) and at 920 MHz with the switch in State2 (x) including the effect of mismatch loss. Antenna orientation is given in Fig. 1a. Radial unit is dBi.*

The measured cuts of the radiation patterns are shown in Fig. 3b at the center frequencies of both system bands (859 MHz with the switch in State1 and 920 MHz with the switch in State2). The patterns are very similar in both states of the switch. They are almost omnidirectional and resemble those of a half-wave dipole, indicating that the chassis currents have a significant contribution to the radiation [6, 7]. As expected, the radiation patterns of the prototype were predicted well in the simulations (not shown in Fig. 3b for clarity).

The linearity of the prototype was studied with the two-tone intermodulation distortion measurement. The intermodulation products generated by the prototype were measured at several frequencies and in both switching states. The results were similar in all cases. In both states of the switch the 3rd order input intercept point $IIP_3 > 64$ dBm (using equation $IIP_3(\mathrm{dBm}) = P_{in}(\mathrm{dBm})-0.5IMD_3(\mathrm{dBc})$, $P_{in} = 30$ dBm/tone). Also the levels of the harmonic frequencies generated by the prototype are low (below –81 dBc) in both switching states ($P_{in} = 33$ dBm, only one source frequency).

4 CONCLUSIONS

A novel, low-loss frequency-tuning circuit for mobile handset antennas was presented. To demonstrate its performance, an antenna prototype that is capable of switching between the US cellular and GSM systems at 800-900 MHz range was designed and measured. The results show that an additional band of operation could be added to an existing dual-frequency antenna design with a simple tuning-circuit that causes only a small amount of additional losses and distortion.

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