# MULTIBAND SLOT ANTENNAS FOR METAL BACK COVER MOBILE HANDSETS

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**Abstract**—New multiband integrated slot antennas for mobile handsets are presented for GSM, DCS, PCS and WCDMA, GPS and WIFI 2.4 GHz. Prototypes, both simulated and measured, are realised in the metal back cover away from the hand. Perturbations due to tissue proximity are simulated using a CTIA compliant hand phantom.

## 1. INTRODUCTION

Most mobile communications devices now fall into two distinct groups. The first group includes Wideband Code Division Multiple Access (W-CDMA) and Evolution-Data Only (EVDO) type simple telephone handsets and feature phones, and the second group includes mobile computing devices such as Pocket PC (PPC) and Palm which have been called communications enabled personal data assistants (PDAs). Out of these groups have emerged two extremely popular technologies one of which is the smartphone and the other tablet. For antenna engineers a welcome side effect of these changes has been a slowing of the previous demand for smaller phone footprints and it is now reasonable to assume that smartphones will have a diagonal dimension of at least 10 cm to allow for a touchscreen. Antenna engineers in

general have found the problems of radiating elements very close to the body a difficult one. The inductive and lossy nature of biological matter at the frequencies used for popular mobile communications tends to cause detuning and loss of $Q$ [1]. Further, the rates of change of detuning and $Q$ vary as a function of distance from the skin's surface and as a function of frequency. This frequency dependent nature of perturbation is a particular problem for multiband antennas held close to the ear and face. The authors of [2] and [3] discuss perturbations due to the proximity of metal items near mobile phone antennas. Despite the drawbacks metal box type phone covers are particularly popular in smart phones. For laptop computers, where space is less restricted, several designs for slot antennas incorporated into the metal shielding of the case have been researched [4, 5].

In this paper, two novel slot antennas are built on the two ends of a full metal back covered smart phone. One antenna covers GSM 850/900 (824–960 MHz), DCS (1710–1880 MHz), PCS (1850–1990 MHz) and WCDMA (1920–2170 MHz) and the other covers GPS and WIFI 2.4 GHz bands. Simulations and measurements are presented for these antennas. An industry standard phantom hand is also included in our experiments. In addition a brief discussion on the wideband matching of slot antennas is also included.

The rest of this paper is structured as follows. In Section 2, a discussion of the shape of our proposed slot antenna and its associated feed structure is presented. The contents of Section 3 deal with the practical aspects of implementing the theory discussed in Section 2. Section 4 contains details of two antennas with both simulations and measurements. Finally Section 5 includes detailed conclusions on the results in the paper as well as suggested improvements to design.

## 2. CONSIDERATION OF THE SLOT SHAPE AND FEED STRUCTURE

For small antennas $Q$ factor is a useful parameter for judging performance. By considering the energy relationship $Q$ can be expressed as

$$Q = 2\pi \frac{\text{average stored energy}}{\text{energy loss per cycle}} \tag{1}$$

where for an antenna the stored energy accounts for the reactive near field while the energy loss represents losses and useful radiated electromagnetic energy [6–8]. $Q$ factor is inversely proportional to an antenna resonance bandwidth $(\Delta f)$ [9, 10]. When resonant at
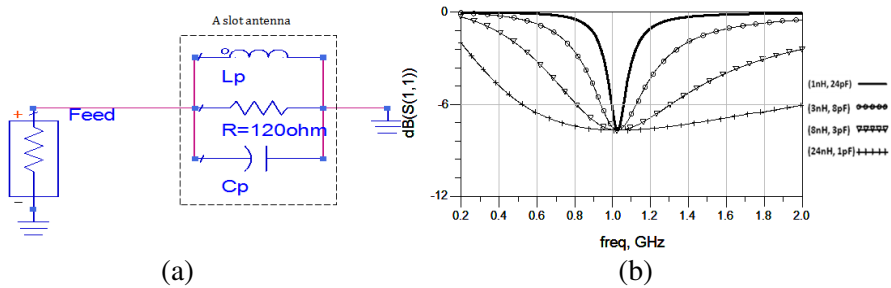
**Figure 1.** Simulations of a parallel circuit with a set of reactances. (a) A parallel circuit. (b) Simulated $S_{11}$.

$\omega = \omega_0 = 2\pi f_0$, the antenna $Q$ factor can also be expressed as

$$\frac{\Delta f}{f_0} = \frac{1}{Q} \tag{2}$$

In relation to the prototypes designed later on we see that a slot antenna can be treated as a band pass filter which consists of a parallel resonant circuit [11, 12]. Both the slot shape and feed will have significant impacts on the bandwidth of a slot antenna so both will be considered here. The parallel circuit shown in Figure 1(a), its $Q$ computed from Equation (3) is shown below:

$$Q = \omega_0 C_p R = \frac{R}{\omega_0 L_p} \tag{3}$$

where $C_p$ and $L_p$ are the capacitance and inductance of the parallel circuit. From Equations (2) and (3) it can be seen that the capacitance $C_p$ is inversely proportional to the bandwidth and the inductance $L_p$ is proportional to the bandwidth. Bandwidth can be increased using a larger $L_p$ and a lower $C_p$. Four representative parallel circuit pairs of $L_p$ and $C_p$ values were simulated using Agilent's advanced design system (ADS). The results are shown in Figure 1(b).

In design of the slot antenna, wider apertures tend to increased inductance and decreased capacitance [13–15]. This is not a desirable solution for full metal covered smartphone since the appearance would be disrupted.

Further increases in bandwidth can be achieved by superposition of resonances. For a slot antenna this can be achieved by adding a matching circuit in series with $L_s$ and $C_s$. Figure 2 shows the circuit, the frequency response and $S_{11}$. To avoid detuning the antenna, the series circuit should have roughly the same resonant frequency. This

response can be inspected using Equation (4).

$$f_0 = \frac{1}{2\pi\sqrt{L_pC_p}} \approx \frac{1}{2\pi\sqrt{L_sC_s}} \Rightarrow \sqrt{L_pC_p} \approx \sqrt{L_sC_s} \tag{4}$$

For frequencies slightly lower than $f_0$, the parallel one is inductive while the series one is capacitive and they compose a new series resonance $f_{0l}$. For frequencies slightly higher than $f_0$, there will be another resonance $f_{0h}$. Proper adjustment of $L_s$ and $C_s$ can control the spectral distance between these three different resonances and when they are close enough they show a wideband performance that is shown in Figure 2.

In Figures 1 and 2, it is 120 ohm rather than a better matching that is used because a properly bigger resistance than 50 ohm will be helpful to apply the series $LC$ matching to $f_{0l}$ and $f_{0h}$. We may explain this in two reasons: Firstly as the resistance of $f_0$, 120 ohm is good enough to get the return loss better than $-6$ dB; Secondly resistances of $f_{0l}$ and $f_{0h}$ (Series resonance) are lower than that of $f_0$ (Parallel resonance. Please refer to Figure 2(c)), so properly choosing a bigger resistance for $f_0$ will make sure that $f_{0l}$ and $f_{0h}$ locate around 50 ohm. For slot antenna designs shown in following sections, the initial resistance of $f_0$ can be controlled by appropriately shifting the feed structure along the slot [16].
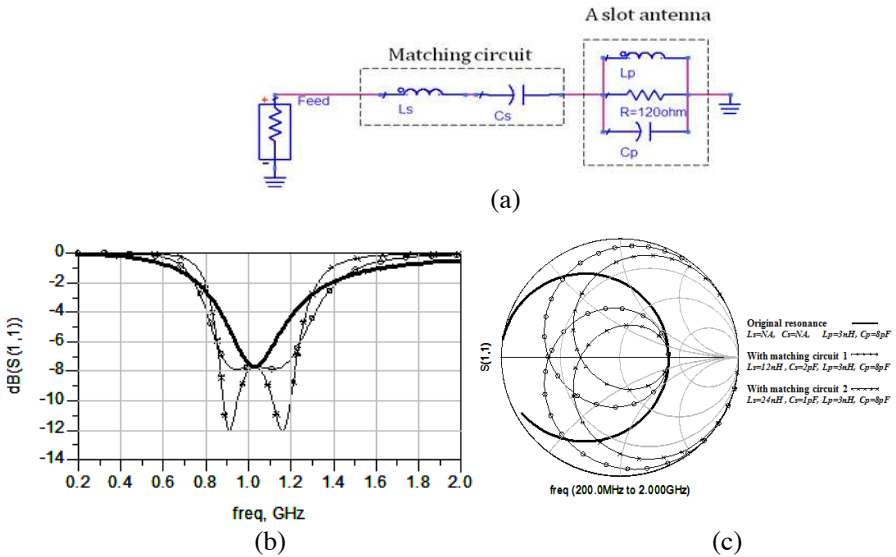


**Figure 2.** Simulations of a parallel circuit with matching circuits. (a) A parallel circuit with a matching circuit. (b) Simulated $S_{11}$. (c) Simulated smith chart.

## 3. PRACTICAL FEEDS FOR A SLOT ANTENNA

In practice, the length and width of the feed will also influence $L_s$ whilst the coupling between the feed and the antenna will alter $C_s$. If necessary an extra inductor can be used to achieve a larger range of $L_s$. To verify the tuning effects of such a feed structure, a simple slot antenna built on a FR4 board was simulated in CST shown in Figure 3(a). The original design shows the slot is fed by a conventional T shape feed while the matched design is fed with a smaller feed structure and an additional series inductor valued 20 nH. A smaller area of feed structure decreases the coupling between the feed and the antenna, and together with a higher inductor helps to increase the bandwidth. This is shown in Figure 3(b) where the T-feed and the reduced feed size are compared.
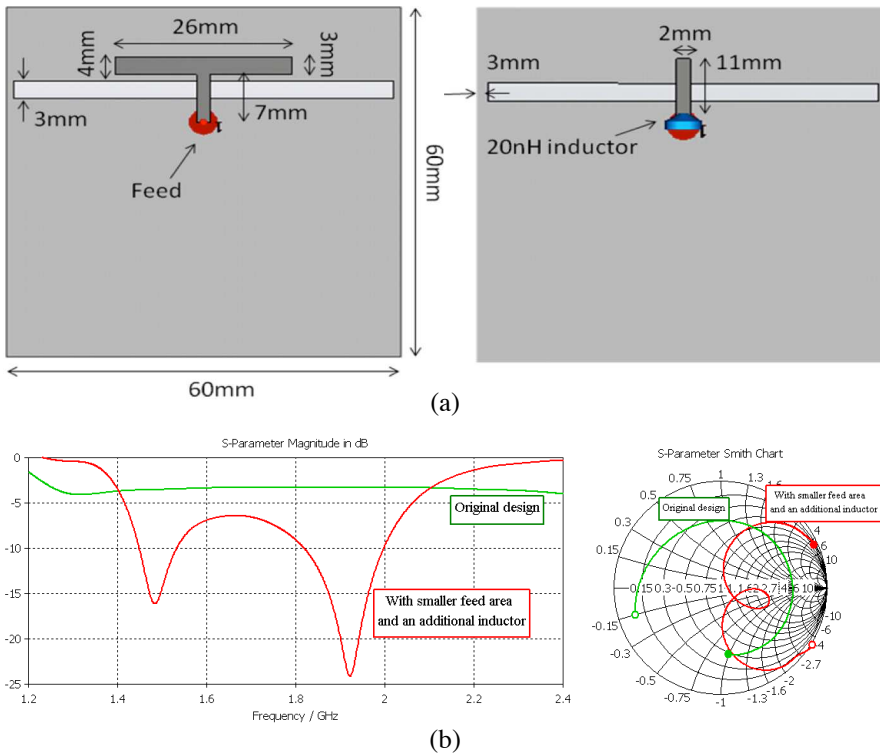


**Figure 3.** Impacts of feed structures on the resonances of a slot antenna. (a) T-feed and simple feed augmented with a 20 nH inductor. (b) Simulated $S_{11}$ results and Smith Chart.

For most slot antennas, it will be sufficient to use different feed size to get the $C_s$ by varying the coupling between the feed and the antenna. But sometimes we do need an extra inductor to get a desired $L_s$. The typical values of $L_s$ vary from a few nanohenries to tens of nanohenries. We should carefully use a big inductor because of its losses. To match a multiband slot antenna, the values will be further restricted since a big $L_s$ impacts high frequencies much more than low frequencies.

## 4. ANTENNA DESIGN, CONSTRUCTION AND CHARACTERISTICS

In our design, antennas are set at the two ends of a rectangular smartphone. For current smartphone designs, which tend to have a
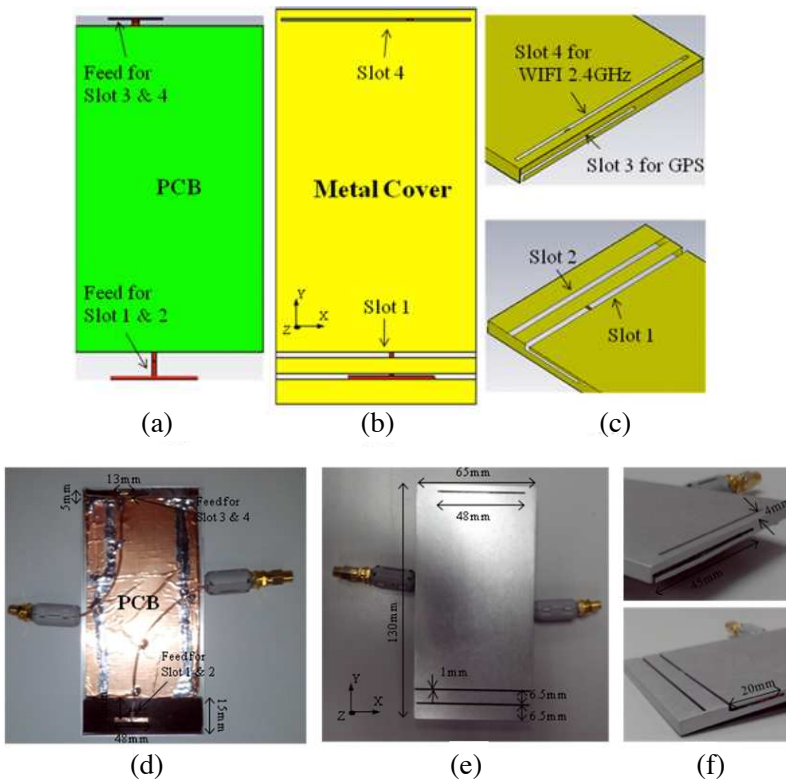
**Figure 4.** CST simulation model and prototype of the metal cover slot antennas.

diagonal of 10 cm or more, the two ends are relatively resistive to the hand impact since in a normal grip the hand covers the ends less. In Figure 4, the design of the cover with the cellular systems antenna at the bottom and the GPS/WIFI 2.4 GHz combo antenna at the top is shown. For the main antenna, two slots each are opened symmetrically to $Y$-axis for a good appearance. The longer one works at GSM850/900, PCS and WCDMA and the shorter one will cover the DCS band. Although wider slots are helpful for enhancing bandwidth, for aesthetic reasons we have made them to be only 1 mm wide. Excitation via a strip line with a substrate on the internal side of the back cover can be realised. Alternatively a feed can be made on the main PCB as is the case for many mobiles. However such a layout may cause some unpredictable resonances produced by separated back cover and main PCB. To reduce the possible interferences, conductive connections between the PCB and metal
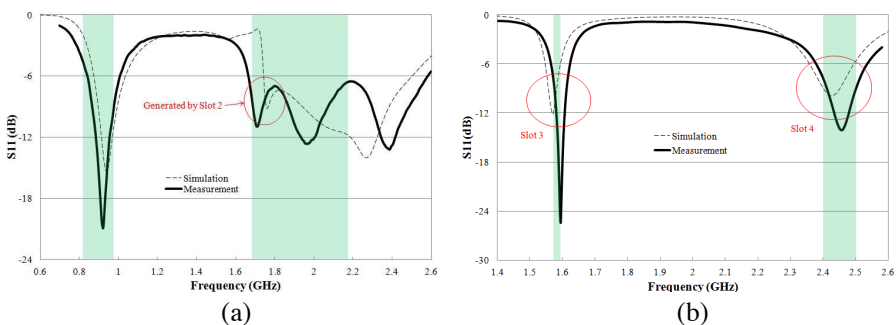


(a)                              (b)

**Figure 5.** Simulated and measured return loss for the metal cover slot antennas. (a) $S_{11}$ for main antenna. (b) $S_{11}$ for combo antenna.
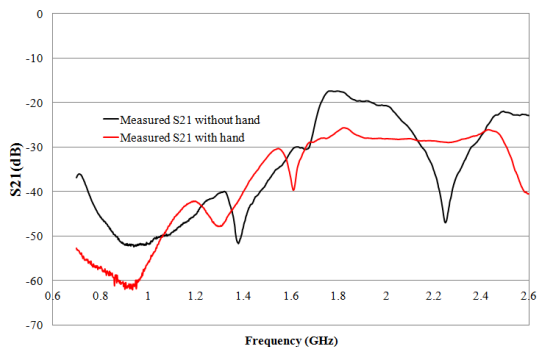


**Figure 6.** Measured isolation for the metal cover slot antennas.

back cover should be introduced by pogo pins and even a double-sided adhesive conductive tape between the shielding cans on the PCB and the back cover. Both simulated and measured results show good −6 dB performance of the antenna across all of the specified bands. The measured free space efficiencies also show the antenna has a good performance. The combo antenna also consists of two slots while slot 3 is a 1/4 wavelength slot [17, 18]. The feed is set in the same way as for the main antenna to tune the resonance of the combo. Simulated and
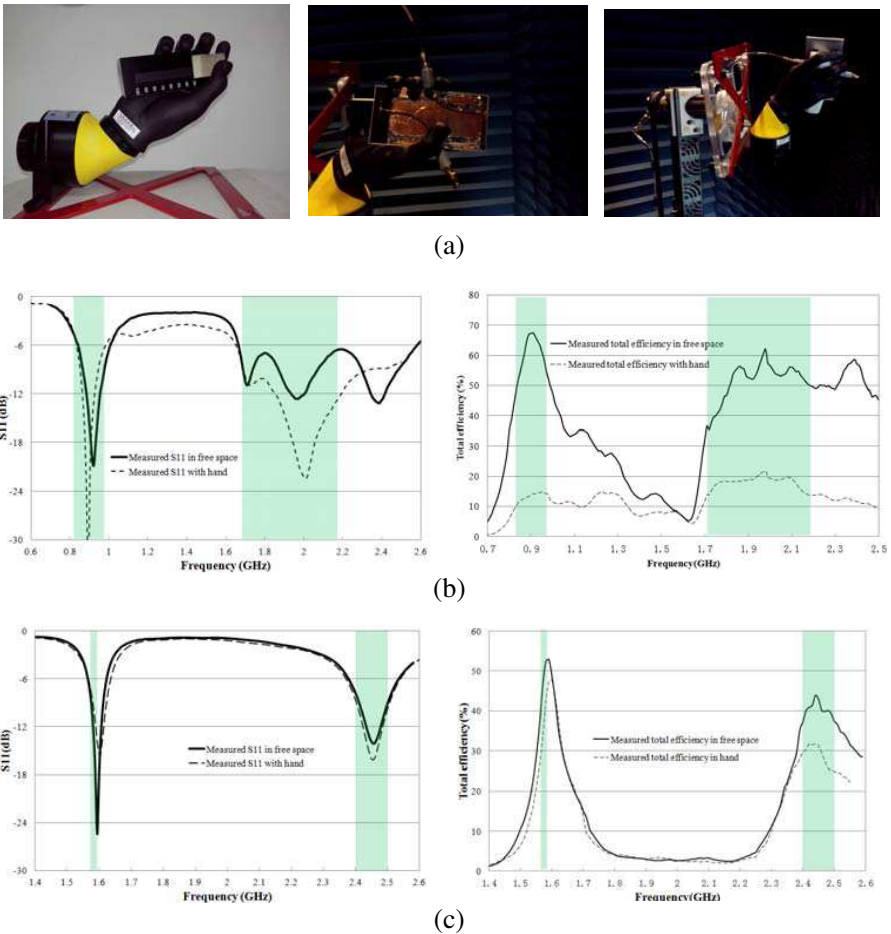


(a)



(b)



(c)

**Figure 7.** Measured hand effects on antennas' total efficiency. (a) Measurement of the metal cover antenna held in hand. (b) Measured hand effects on main antenna. (c) Measured hand effects on combo antennas.

measured return loss is shown in Figure 5. Since both the main and the combo antennas are using the metal cover as the primary radiation part, it should be noted that a high isolation is needed to keep antennas working properly. From the measured $S_{21}$ results shown in Figure 6 we found the isolation to be better than $-15$ dB in all bands. Compared with the measurement in free space, hand effects drop the $S_{21}$ to be less than $-25$ dB due to the power absorption by the hand.

Antennas' free space performance was first measured in an ETS chamber and then the hand effects were measured using a CTIA (Cellular Telecommunications Industry Association) certificated hand shown in Figure 7(a). This phantom hand can mimic a real hand with similar permittivity and loss at different frequencies. The smartphone was gripped in a data mode as shown in the Figure 7(a). From the measured return loss and efficiency comparisons shown in Figure 7, it can be seen that in common with all typical devices the hand has significant impacts on main and WIFI antennas. The tissue losses have led to a deepened $S_{11}$ and reduced total efficiency. GPS antenna is relatively stable since it is furthest to the hand. Far field patterns of the total radiations in free space and by the presence of the hand were also measured and shown in Figure 8. Obvious hand effects,
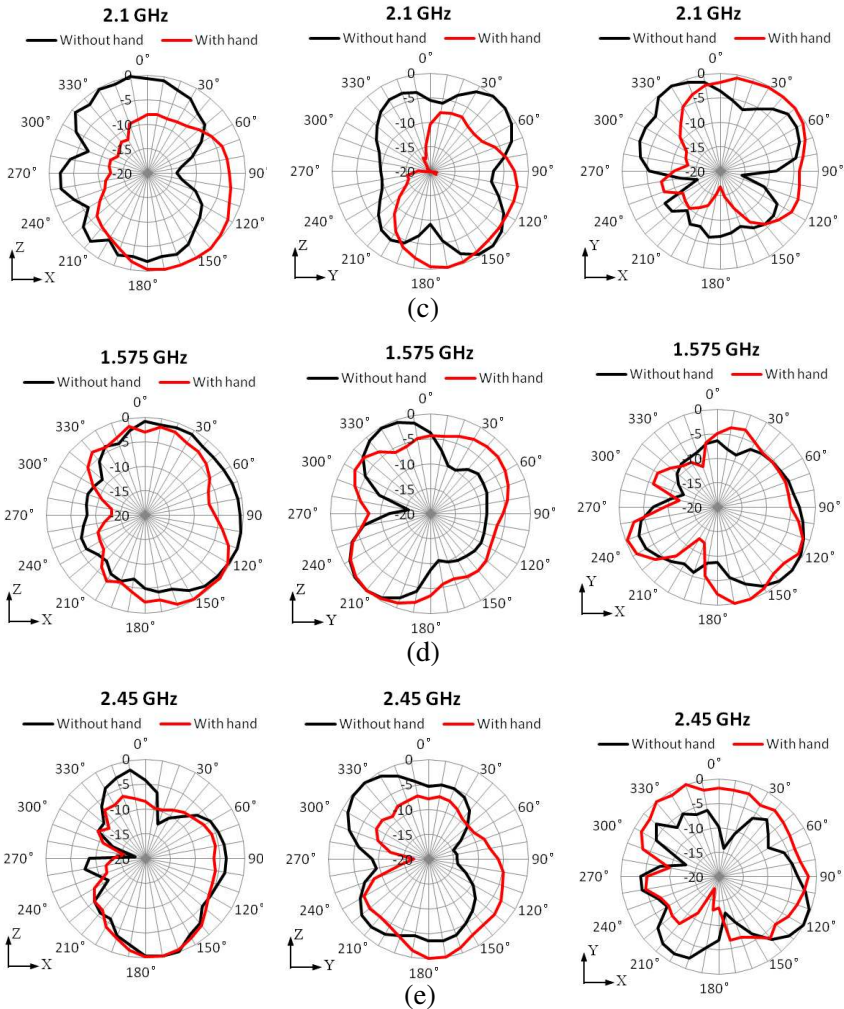


(a)

(b)
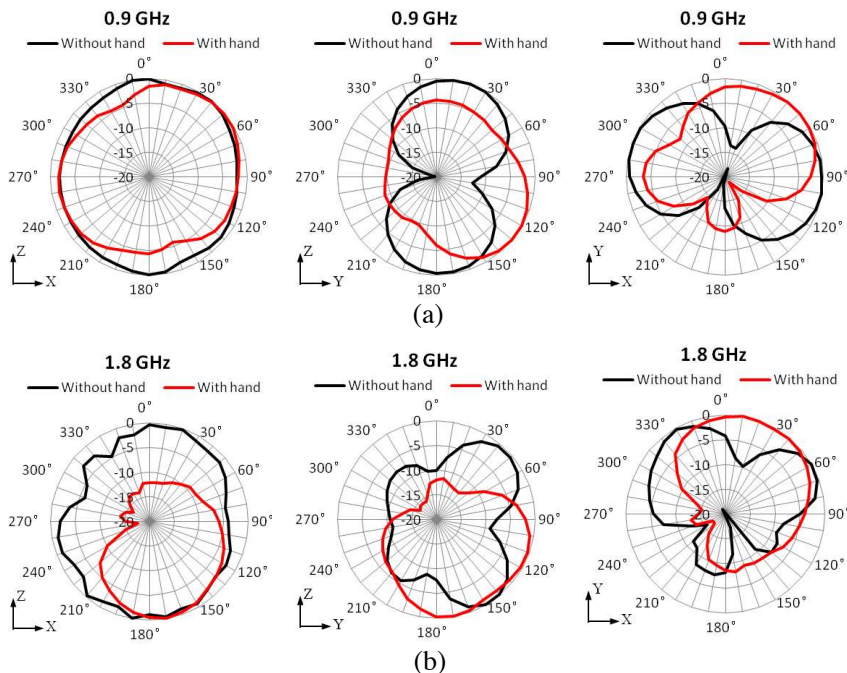
**Figure 8.** Comparisons of the total radiations measured with and without hand.

especially at main antenna bands, can be found from the distorted patterns compared to the results without hand. The coordinate refers to Figures 4(b) and (e).

## 5. CONCLUSIONS

In this paper, we have presented two novel antennas integrated into the metal cover of a smartphone. In addition, it was shown how the slot antenna could be effectively matched using a simple tee and mutually coupled line enhanced with an inductor. The enhanced matching technique allows for improvements in bandwidth. Working antennas were created for the GSM 850/900, DCS, PCS, WCDMA and GPS/WIFI 2.4 GHz bands. Comparisons of the effects of proximity of the hand on $S_{11}$, $S_{21}$, efficiency and radiation pattern with and without a phantom hand were also discussed and the results of this show that in common with typical implementation mobile phone antennas efficiencies do drop sharply when the antenna is being held in the hand. Further work for this research would include the addition of a thin transparent cover to the phone to increase isolation between the antenna and the hand and a parametric study of bandwidth improvements as a function of slot width and inductive loading.

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