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CAPACITIVE RECOGNITION OF THE USER'S HAND GRIP POSITION IN MOBILE HANDSETS

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Abstract—A capacitive method for measuring hand grip position on a mobile phone equipped with a dual-band planar inverted-F antenna (PIFA) and a monopole antenna was studied using different electrode arrangements. A capacitive sensor with a dual-electrode configuration and an antenna-integrated capacitive sensor for hand grip recognition were developed. The sensitivities of the sensors were measured along the front, side and back of the phone. The dual-electrode sensor configuration exhibited its best sensitivity of 29 fF at the bottom end of the phone. The PIFA antenna-integrated sensor proved to have sensitivity of 420 fF and the monopole antenna-integrated sensor had sensitivity of 115 fF, making them both reasonable solutions for hand grip sensors in mobile applications.

1. INTRODUCTION

Mobile phones have been faced with requirements of cheap consumption product qualities. The total market has expanded, competition has diminished unit prices, and a greater need for usability, various features and smaller size have decreased product margins. Therefore, antennas need to be more economical in space consumption, more permissive of different locations in the phone, yet still have sufficient electrical performance in a stringent environment.

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Beside general antenna and phone design factors, the use of the antenna in close proximity to the user's body changes its efficiency [1–5]. The body effect normally reduces the transmission and reception power of the phone by changing antenna matching and increasing power absorption. Mobile phone antenna performance measurements using head and hand phantoms in real world usage configurations have shown that the presence of the user changes the RF performance of the phones and that antenna radiation performance is affected more by the user's hand than the head [1, 2]. Although the ground plane of the phone has a big impact for phone's ability to radiate energy, the location of user's hand and fingers is important. In the case when power absorption by the user increases, input power can of course be increased at the expense of shorter battery life and higher emissions in terms of the specific absorption rate (SAR) and hearing aid compatibility (HAC).

Power absorption and sensitivity to the user effect can be decreased by using smaller antennas, but they are inherently narrow band. Furthermore, the dimensions of the antenna cannot be reduced without deteriorating its efficiency [6]. Other techniques such as frequency-tunable antenna solutions are needed. In addition, telecommunication techniques, e.g., antenna diversity, can be used for better performance in the RF link, but they use a lot of power.

The user's effect on the antenna can be reduced or compensated using several techniques. One compensation technique involves an antenna mismatch sensor and impedance tuning of the antenna matching circuit in the desired frequency bands [7]. Several applications for tuning resonance frequencies have been introduced [8–11].

A conventional mismatch sensor utilizes a directional coupler to sense the power reflected from the antenna. Tuned antennas have to take power up to +40 dBm and retain good linearity. Inadequate matching at the antenna causes more ripple in the pass band of the RF filter, inducing extra insertion loss of 1–2 dB in addition to mismatch loss, and in these conditions the output of the RF power amplifier drops [7].

PIFAs are among the most widely used antennas in mobile terminals operating over multiple frequency bands and covering the frequency range of six telecommunication standards [16–18]. A capacitive method for evaluating the magnitude of the user's proximity effect by using a capacitive sensor integrated into a PIFA was introduced in [12]. A comparison of measured equivalent capacitance, antenna matching and total efficiency indicates that the level of the total efficiency of the dual band GSM antenna can be estimated by measuring the capacitance of the antenna, but this cannot be straightforwardly done by measuring only matching. This capacitive method additionally estimates the level of user-induced absorption. Absorption can be misconstrued in matching measurements, since as a resistive component it improves matching. In addition, the capacitive measurement method permits continuous controlling of antenna conditions in multiple antenna systems.

Capacitive proximity sensors have been used in chainsaw safety products at a 10-cm distance [19], in robot hand applications at a 0–8-cm distance [20], and for seat occupancy sensing in a car [21]. The size of the sensors has varied from $25\,\mathrm{cm}^2$ or $30\,\mathrm{cm}^2$ to $16\,\mu\mathrm{m}^2$, with operating frequencies of 80 kHz, 250 kHz and 500 kHz, respectively. The proximity effect of a human on grounded conductive objects can be distinguished with an inductive-capacitive proximity sensor [21].

This paper presents capacitive sensor configurations for sensing the user's body proximity, especially the hand grip position over the phone chassis. Recognition can be realized either by using the antenna itself as a capacitive sensor element or by using PCB (printed circuit board) electrodes as separated sensor elements. Additionally a comprehensive test method and measurement arrangements for capacitive sensors are presented. Sensor characteristics are compared in terms of the sensitivities of the sensors along the front, back and side of the phone. The best locations for electrode sensors were experimentally studied along the front of the phone.

Section 2 of this paper describes hand-induced loads on antenna performance and methods for measuring the size of loads, and also presents the antenna structures used in this study. Section 3 presents the measured capacitive and sensitivity values of a reference antenna. Finally, discussions and conclusions are given in Sections 4 and 5.

2. MEASUREMENT METHODS AND STRUCTURES

2.1. Hand Grip Load

This paper focus especially on measurement of the user's hand grip positions. Fig. 1 shows the hand grip positions used in this study. The hand grip can vary along the phone chassis between high- and low-load positions, measured at six different positions in 11 mm steps. The influence of particular grip positions on the total efficiency and matching of the antenna are presented in [12, 13]. In this study capacitive sensitivities with different electrode configurations are presented and compared using PIFA and monopole antennas. The benefits of using separated or antenna-integrated capacitive sensors are evaluated.

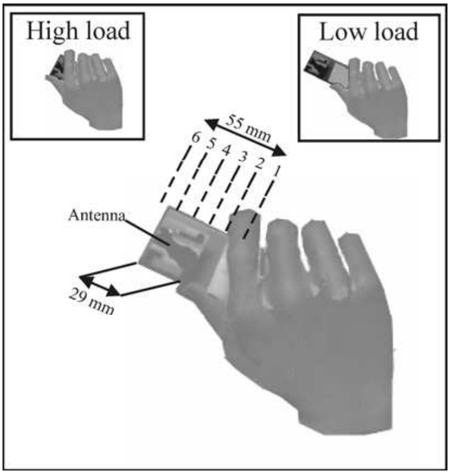

Figure 1. Hand grip position along the phone chassis varies between high- and low-load positions. Measurements consist of six grip positions in 11 mm steps, resulting in a total of 55 mm of hand movement.

2.2. Antenna Structures

Phones equipped with dual-band PIFA or dual-band monopole antennas were used as measurement platforms in this study. Figs. 2(a) and 2(b) depict a dual-band PIFA [13] and monopole antenna.

The PIFA structure includes a main antenna element for the GSM900 band and a parasitic element for the GSM1800/1900 band. It has one feed pin for the main element, one short pin for the main element and one short pin for the parasitic element The radiatortoground distance is 1 mm and the radiator is placed on top of a 40 mm × 10 mm PCB made of 0.83 mm Rogers 4003C copper laminate.

The monopole structure has one antenna element that provides the fundamental resonance frequency in the GSM900 MHz band and the first harmonic resonance frequency in the GSM1800/1900 MHz band. The monopole is formed on a 40 mm × 110 PCB and the PCB's ground plane is opened (Fig. 2(b)) behind the antenna element in order to increase the elementtoground distance.

So, the PIFA has a ground plane under the radiator whereas the ground plane is removed from under the monopole antenna. The ground plane distances and different open/short conditions of the antennas permit deviant lowfrequency responses at a capacitive sensor when the sensor is integrated into the antenna element itself.

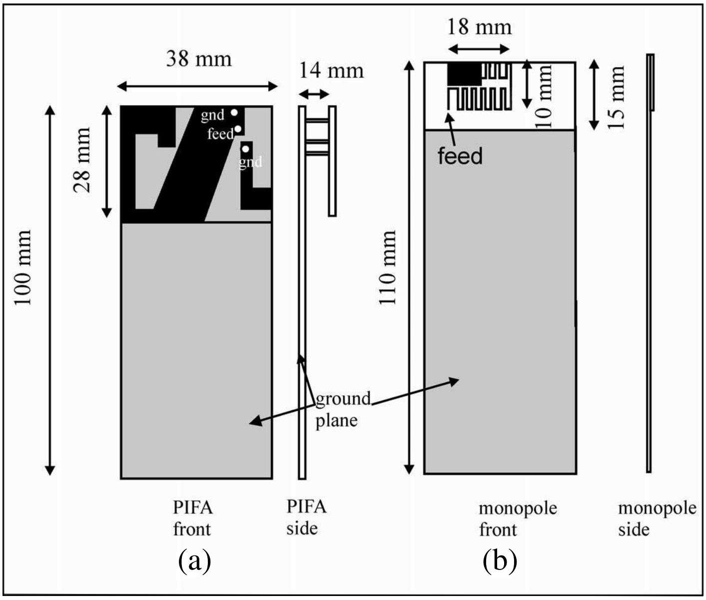

Figure 2. (a) Dualband PIFA antenna used as the first measurement platform for the sensor. (b) Dualband monopole antenna used as the second measurement platform for the sensor. The antennas have different sensor characteristics due to different radiatortoground distances, antenna areas and radiator ground conditions.

2.3. Antenna Performance in Different Hand Grip Positions

The deterioration of the antenna performance in close proximity of user's head and hand can be presented, e.g., by measuring antenna's far-field radiation patterns, total efficiencies and impedance matching in free space and with phantoms [1–4].

In this study the antenna performance is evaluated by comparing PIFA and monopole antennas. PIFA's absorption and matching losses were calculated by measuring the total antenna efficiency and antenna matching with different hand grip positions in Satimo Starlab antenna measurement chamber [4]. The loss performance at frequencies of 900 MHz and 1800 MHz are presented in [13] and Fig. 3. The absorption loss (900 MHz) starting from 1 dB at the position number 1 increased close to 7 dB at the position number 6. The matching loss starting from 0.6 dB increased up to 4 dB respectively. At 1800 MHz band, the absorption loss started from 0.2 dB and increased close to 7 dB, whereas the matching loss remains close to 1 dB in all measured

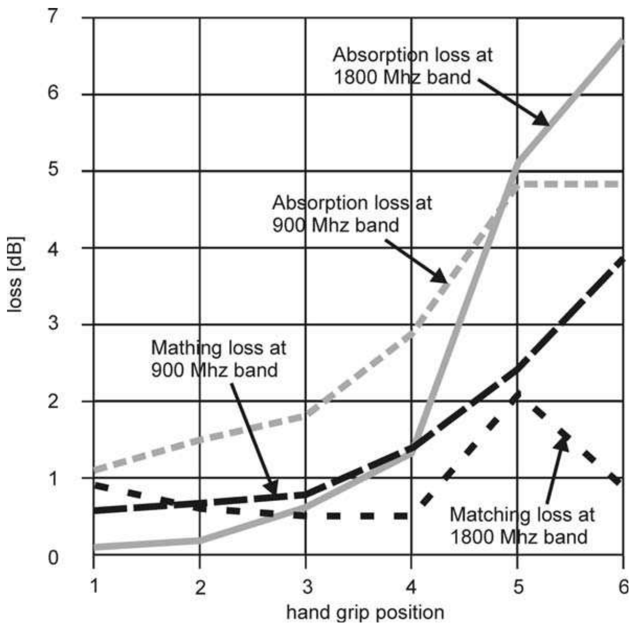

Figure 3. Hand grip induced absorption and matching losses in PIFA antenna at 900 MHz and 1800 MHz frequencies.

positions The absorption loss dominates total losses of the antenna at double higher level than the matching loss. Similar trends of losses due to hand proximity were reported in Ref. [5].

The comparison of far-field radiation patterns of PIFA in free space and with grip (location number 6) is presented in Fig. 4. The gains of the PIFA were decreased and the shape of the radiation patterns were slightly distorted due to the proximity of the user's hand to the antenna. Corresponding far-field radiation patterns of monopole antenna are presented in Fig. 5. When comparing monopole and PIFA, the same kind of overall hand grip effect is observed Measured total efficiencies of monopole antenna in free space were −0.9 dB at 960 MHz and 2170 MHz, but at the position number 6 they decreased to −6.0 dB at 960 MHz and to −2.4 dB at 2170 MHz. Corresponding hand induced losses in PIFA were 8.5 dB at 900 MHz and 7.7 dB at 1800 MHz. Both decreased antenna performances mean that there is a need for user proximity sensors, where both the mismatch and absorption losses are able to be evaluated.

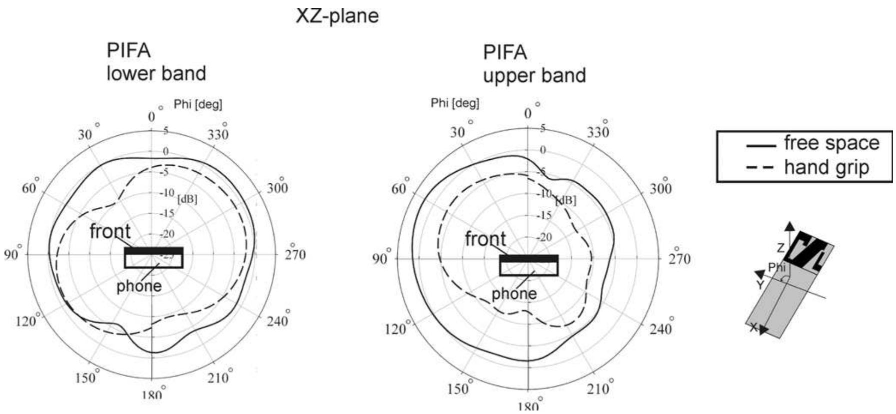

Figure 4. Measured PIFA's far-field radiation patterns of free space at 900 MHz and 1800 MHz compared to hand grip results at the same frequency points.

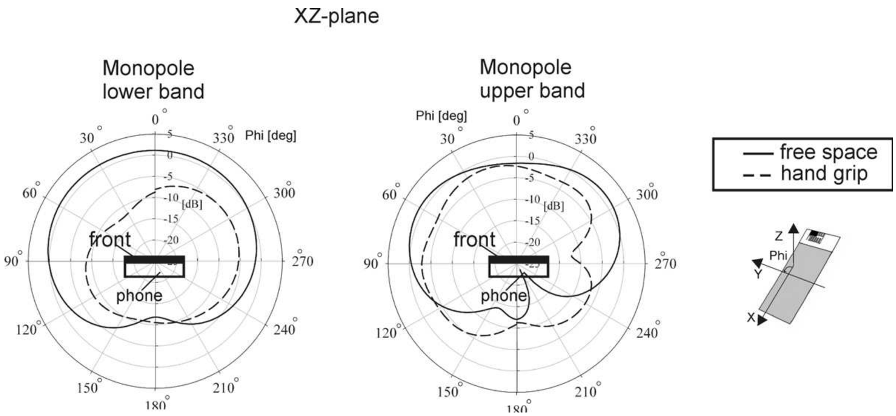

Figure 5. Measured monopole's far-field radiation patterns of free space at 960 MHz and 2170 MHz compared to hand grip results at the same frequency points.

2.4. PIFA Antenna with an Integrated Sensor

Hand grip load can be measured in a PIFA either with a sensor consisting of two electrodes (Fig. 6(a)) or with an antenna-integrated sensor (Fig. 6(b)). In the antenna-integrated sensor the second electrode is kept in a constant and shielded position on the PCB. Thus, it operates like a single-headed sensor.

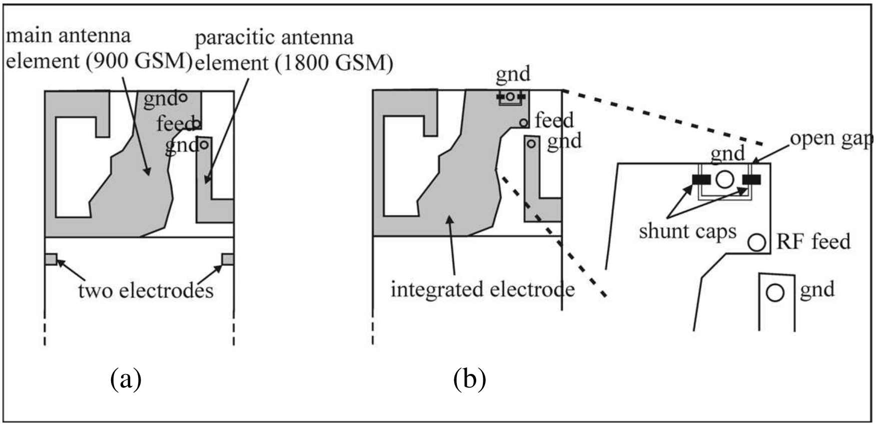

Figure 6. (a) Sensor consisting of two capacitive electrodes is designed for hand grip recognition with separated electrodes not connected on the radiator. (b) In the antenna-integrated sensor, the radiator functions as a low-frequency capacitive sensor and a high-frequency antenna at the same time. The radiator's ground pin is shunted by high-quality capacitors to block the low-frequency sensor signal.

In this study, hand-grip-induced load was measured with a commercial capacitive sensor chip (Analog Devices AD7747) physically located on the PCB of the phone. The measurements could be realized with corresponding electronics [19, 20], respectively. The chip provides 10 fF capacitance accuracy and a 10 aF resolution, which are reasonable limits for the current application. The resolution did not constrain the results in this study, and measurement noise could easily be higher than the chip's resolution. The ground plane effect (the ground is a floating plane from the sensor's point of view) was deducted from the results by using an in-chip shield function.

In the antenna-integrated sensor, the measurement signal (5 V, 16 kHz) was connected to the main element of the antenna via a 0.5 pF serial capacitor in order to achieve lower values than the maximum readable capacitance of 18 pF (limit of AD7747). The capacitor probably decreased the sensitivity of the sensor, but the decrement was not measured here. The PIFA's ground pin has to be shunted with a high-quality capacitor, since the sensor signal (16 kHz) has to be blocked from direct ground contact. A couple of 100 pF highquality capacitors fulfill the RF requirements for high pass operation (Fig. 6(b)).

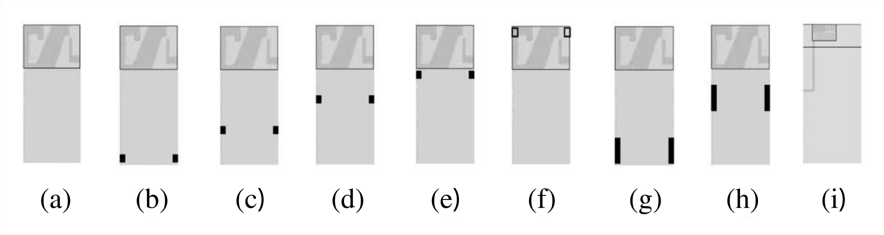

Figure 7. Studied capacitance sensor arrangements. (a) PIFA antenna-integrated sensor, (b)–(f) small capacitive electrodes for hand recognition, (g)–(h) large capacitance electrodes for hand recognition along the phone chassis, (i) monopole antenna-integrated sensor.

2.5. Capacitance Electrode Outlines

Capacitance electrodes can be realized on a PCB in several ways, which are not possible to be considered in this study. However, Fig. 7 presents some substantial cases of sensor outlines and locations along the ground plane of the phone.

In Fig. 7(a), the PIFA is measured as an antenna-integrated sensor. Then PIFA prototypes utilizing sensors consisting of two electrodes, sized 2×3 mm on the PCB, are presented in Figs. 7(b)–7(f) with varied locations along the ground plane of the phone in order to find the most sensitive placement for the electrodes. The electrode size was studied with the samples shown in Figs. 7(g) and 7(h). Parasitic load is higher and electrical field distribution is more divergent in large electrodes compared with small electrodes. In Fig. 7(i), the monopole is measured as an antenna-integrated sensor.

2.6. Measurement Arrangement

A typical antenna measurement system consists of a phone chassis, a dual-band PIFA antenna with a PCB and a hand phantom (IndexSAR, IXB-060). A corresponding evaluation setup for capacitive sensors was executed with the test arrangement (Fig. 8), which makes the setup stabile and the results reproducible over long time periods. The test arrangement was calibrated with a handsized bottle and a quantity of IndexSAR liquid (2.15 dl) A distance of 10 mm was selected as an average antenna to load distance normally used in talk mode. For calibration, the adequate electrical load of the bottle was measured with the capacitive sensor in high and lowload positions (in Fig. 8) and with the phantomhandbased system presented in Fig. 1. Thus the

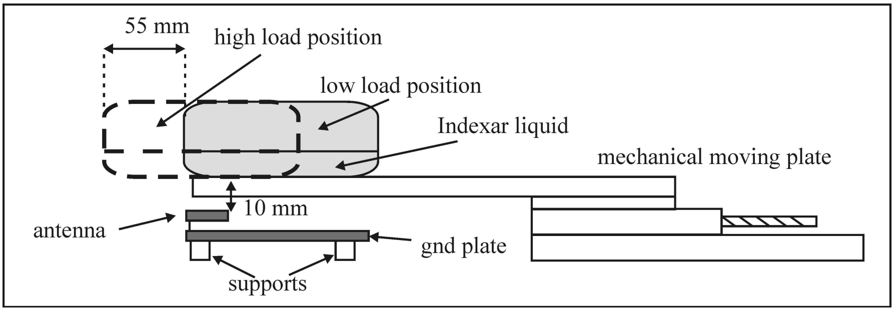

Figure 8. Mechanical test arrangement (made from plastic) for measuring sensor performance. It consists of a mechanical moving plate (motion distance of 55 mm) and a bottle of Indexar liquid (2.15 dl). The load is calibrated to be equivalent to that of the IndexSAR phantom hand presented in Fig. 1.

problem was scaled to 1-dimensional by replacing the phantom hand with the bottle of Indexar liquid and a moving plate operated with a micrometer screw.

The hand-grip-induced loads from the PIFA, the monopole antenna and the separated sensors were measured by utilizing the test arrangement, the AD7747 circuit, National Instruments I/O hardware, LabVIEW software and a laptop computer.

3. RESULTS

The performance of the capacitive sensors was evaluated by measuring initial capacitances and capacitive sensitivity values in the PIFA and monopole-integrated sensors and the separated sensors of the two capacitive electrodes.

The capacitive sensitivity in the sensor is

$$S = \frac{\Delta C}{\Delta g}, \tag{1}$$

where ΔC is the capacitance change (F) and Δg is the load position change (m).

Figure 9 presents the capacitive sensitivity results for the PIFA and monopole antennas equipped with the antenna-integrated sensor. The sensitivity results are presented in terms of hand grip positions from 1 (low load) to 6 (high load) with an antenna-to-load distance of 10 mm. The capacitance increased 115 fF in the monopole and 420 fF in the PIFA antenna between the boundary positions. To facilitate the

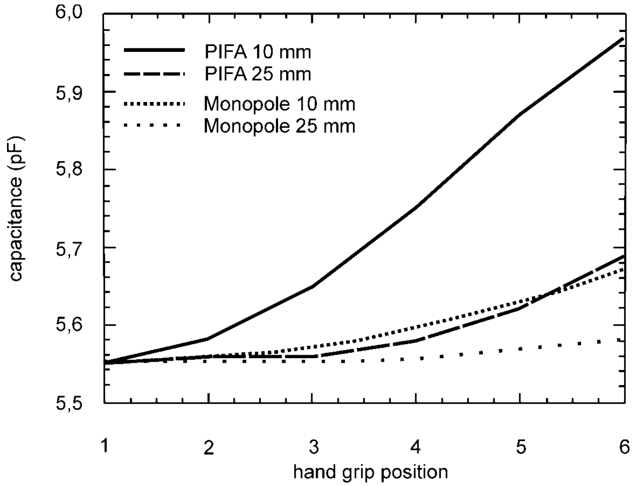

Figure 9. Capacitive sensitivity of the PIFA and the monopole antenna measured step by step from high-(6) to low-(1) load positions of the studied hand grips. Sensitivity was measured at a short (10 mm) and a long (25 mm) antenna-to-load distance.

comparison, the results were leveled to the same initial capacitance value position (5.56 pF). The initial capacitance value was 4 pF for the monopole and 5 pF for the PIFA (including a 0.5 pF serial capacitor). Both antennas' sensitivity results were proportional to the hand grip positions, but the relative sensitivity of the PIFA was 3.7 times better than that of the monopole ($\frac{420\,\text{fF}}{115\,\text{fF}} \approx 3.7$). For example, with the PIFA, position 3 can be distinguished from positions 1 and 2, but not with the monopole antenna.

Additionally, in Fig. 9, sensitivity to a far object (e.g., not a touching finger) was measured by increasing the antenna-to-object distance from 10 mm to 25 mm. The results show that the PIFA is more sensitive (130 fF) to a far object than is the monopole antenna (25 fF). Corresponding results in [20] present sensitivity of 25 fF from a 25 mm to 10 mm distance; the initial capacitance value was 8 pF. Sensitivity in [19] is weaker than that of the PIFA and monopole antenna-integrated sensor results, but for tactile sensors lower sensitivity is sufficient. Tactile sensors have to cover wide area and measure the touch, but proximity effects are not normally needed to observe.

It can be observed from Fig. 9 that the sensitivity of the PIFA at a 25 mm distance is better than the sensitivity of the monopole antenna at a 10 mm distance. So, objects not in contact with the phone cover or objects with weaker loading, such as a child's hand, can be more reliably sensed with the PIFA-integrated sensor. At sensor-to-object distances below 1 cm the capacitive sensor becomes highly nonlinear, presenting an accelerated increment in capacitive value when distance decreases [19].

The sensitivity results of the capacitive sensor utilizing two separated electrodes are presented in Fig. 10. In this study, the sensor locations were varied along the front of the phone, as shown in Fig. 7, in order to find the best position on the PCB. Contrary to antenna-integrated sensors, sensors consisting of separated electrodes are less susceptible to the risk of RF compatibility problems. The sensor electrodes were located far from each other (36 mm) in order to increase the range of electric fields above the phone. The electrodes were kept at the same level in pairs and then moved along the phone to five different locations, as presented in Figs. 7(b)–7(f). The initial capacitance value of the dual-electrode sensor was 0.3 pF in the studied setup, but the results were leveled to 5.56 pF in the figures. Sensitivity was highest at the electrode location (*b*) at the bottom end of the phone (29 fF) and it decreased as the electrode location approached the antenna. The worst electrode location was under the antenna element at the top end of the phone (*f*). Certainly, the electrode location behind the radiator is shielded by the antenna itself.

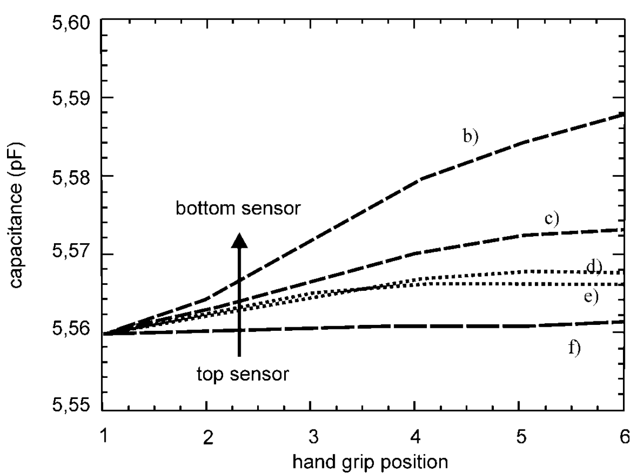

Figure 10. Capacitive sensitivities of sensors consisting of two electrodes were measured in terms of electrode positions along the phone. The most sensitive position was at the bottom end of the phone (29 fF) and the worst was behind the radiator (1 fF). Characters correspond to Fig. 7 outlines.

In addition to the location of the electrodes, the size effect of the electrodes has to be measured. Size determines the impedance level of the electrode; the larger the size, the smaller the impedance, and vice versa. Larger size induces large parasitic capacitance, which is actually deducted from the measurement results by electronics (AD7747). Sensitivity in terms of large and small size can be seen in Fig. 11. As expected, large size decreases the sensitivity of the sensor (b versus g and d versus h). Large electrodes at the bottom end and center of the phone are slightly more insensitive (5 fF) than corresponding small electrodes in particular electrode locations. Thus, large electrodes, being insensitive and space-consuming, are not useful in practical applications. A corresponding decrement in sensitivity existed in [20].

A method for further improving the performance of separated electrodes could be ground plane openings below the electrodes. Additionally, electrodes could be replaced with contact-pin-types of capacitive probes that basically should decrease impedance even more. However, the effects were not significant in the current prototypes (no screens, batteries and electronics), and the results are not presented in detail.

Since the user's fingers are located beside the phone in the talk mode, the sensor has to be sensitive to side objects. The side sensitivity

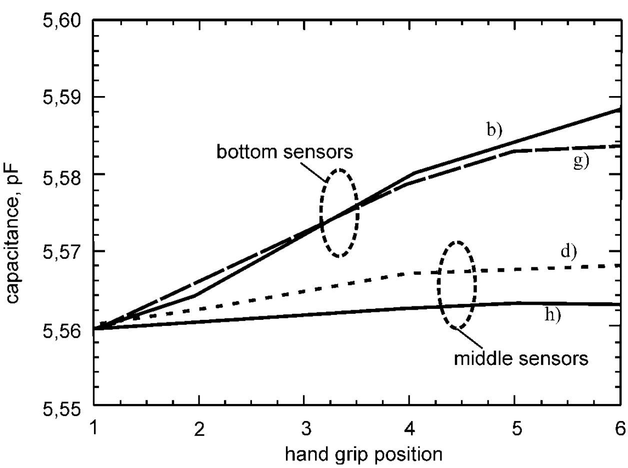

Figure 11. Electrode size effect is compared with bottom- and middle-located sensors. A small electrode sensor is more sensitive to proximity load than a corresponding large sensor (b versus g and d versus h). Characters correspond to Fig. 7 outlines.

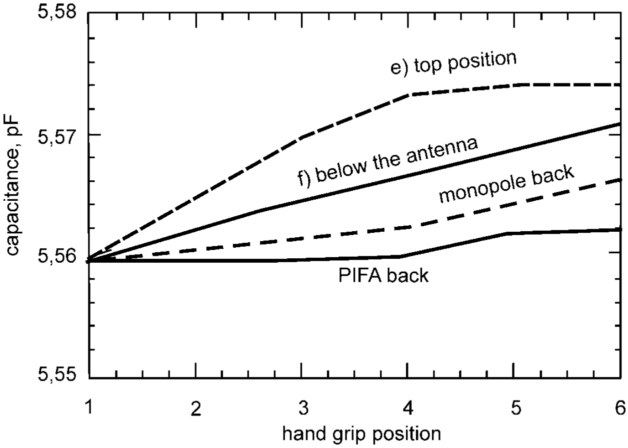

Figure 12. Dual-electrode sensor sensitivities to phone side objects, and PIFA and monopole antenna-integrated sensor sensitivities to phone background objects. Characters correspond to Fig. 7 outlines.

of the dual-electrode sensor is presented in Fig. 12 at two locations close to the radiator; on the top corners of the phone (Fig. 7(e)) with sensitivity of 145 fF, and below the antenna element (Fig. 7(f)), with sensitivity of 110 fF. The sensors were found to be more sensitive to a side object than a front object in particular locations under the antenna element, as presented earlier in Fig. 10. The PIFA shadows the front part of the phone, but a side object can be still recognized.

Antennas are normally designed in such a way that the radiation pattern faces away from the user's head and a background object has minimal influence on RF response. So, the sensor has to be immune to that background object. The effect was measured with the PIFA and monopole-integrated sensors and is presented in Fig. 12. The sensitivity of the PIFA was poor (15 fF), but the sensitivity of the monopole was only fair (60 fF), making the PIFA more reliable at this point.

4. DISCUSSION

A sensor consisting of two electrodes and an antenna-integrated sensor were evaluated as hand grip position sensors with dual-band (900/1800 MHz) PIFA and monopole antennas. The sensors were characterized especially by measuring the sensitivity of the sensor. This information is needed when measuring hand loads, as presented in [1, 14, 15]. Antenna-integrated sensors had sensitivity of 115 fF in the monopole antenna and 420 fF in the PIFA at a 10 mm antenna-to-sensor distance, followed by sensitivity of 25 fF in the monopole and 115 fF in the PIFA at a 25 mm distance, respectively. Hence, the PIFA antenna was found to be more beneficial than the monopole antenna in integrated sensor usage. The sensor consisting of two electrodes has sensitivity of 29 fF in the most advantageous location at the bottom end of the phone. The electrode size effect was only 3 fF, signifying that large size is not beneficial in proximity sensors. The dual-electrode sensor was sensitive to a side object (sensitivities from 110 fF to 140 fF) when located behind the antenna element. The sensor consisting of two electrodes had results close to the values presented in [20], which presents, e.g., initial capacitance of 8 pF with 36 fF sensitivity. In conclusion, maximum sensitivity can be reached with the antenna-integrated sensor, but sufficient operation can be realized with a sensor consisting of two separated electrodes.

Capacitive sensors can be utilized to measure user hand proximity effects on antennas by realizing them either with two electrodes or integrated into the antenna. In contrast to the mismatch control technique typically realized with a directional coupler in current mobile phones [7], a capacitive sensor has significant benefits. A capacitive sensor utilized as small electrodes does not increase RF link losses. Additionally, it can sense the proximity effect regardless of antenna matching. Matching is inconveniently deciphered when more than one electrical resonance is used in the same band [12] or when matching is modified by a resistive component, e.g., human tissue absorption. So, matching and the user proximity effect are not always proportional to each other. In multiple antenna applications, capacitive sensors can sense all antennas but a matching sensor can only sense the antenna currently in use. Capacitive sensors are cheap compared with optical sensors; they have large proximity coverage and they can be incorporated on surfaces with light weight [20]. This study does not present a complete analysis of RF signal and sensor cooperation, additive losses in the antenna caused by the sensor or only finger-induced effects; this will be done in coming studies.

5. CONCLUSION

This paper presented capacitive recognition of the user's hand grip position in mobile phones. An antenna-integrated sensor is characterized by sensitivity to hand proximity of 420 fF in a PIFA and 115 fF in a monopole antenna at a 10 mm antenna-to-sensor distance, which are much higher sensitivities than achievable with capacitive sensors designed for tactile applications such as touch screens. A sensor consisting of two separated electrodes has a sensitivity of 29 fF in the most advantageous location at the bottom end of the phone. A capacitive sensor can be utilized in phones to measure hand grip positions by realizing them either with two electrodes on a PCB or integrated into the antenna. Capacitive sensors can replace the mismatch sensors typically realized with a directional coupler in current mobile phones since the capacitive sensor can sense the proximity effect regardless of antenna matching. Matching is inconveniently deciphered when more than one electrical resonance is used in the same band or when matching is modified by a resistive component. In multiple antenna applications, capacitive sensors can sense all antennas but a matching sensor can only sense the antenna currently in use.

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