Progress In Electromagnetics Research C, Vol. 23, 219–231, 2011

FEASIBILITY STUDY OF ANTENNA INTEGRATED CAPACITIVE SENSOR IN OPERATIONAL MOBILE PHONE

S. Myllymaki [1, *], A. Huttunen [1], V. K. Palukuru [1], H. Jantunen [1], M. Berg [2], and E. Salonen [2]

[1]Microelectronics and Material Physics Laboratories, University of Oulu, P. O. Box 4500, FIN-90014, Finland

[2]Centre for Wireless Communications, University of Oulu, P. O. Box 4500, FIN-90014, Finland

Abstract—An antenna integrated sensor implementation for hand or finger proximity recognition is developed. Capacitive sensor was installed on the antenna of functional Nokia 6021 phone. The sensitivity of the phone with planar inverted F antenna (PIFA) integrated sensor was measured with active TRP (total radiated power) and TIS (total isotropic sensitivity) measurements. Phone active measurements were performed with/without data cables and compared to reference phones. Passive cable phone measurements were compared with active measurement results. TRP results had no significant decrements due to integration compared with the reference phone. Some TIS channels suffered from detrimental effects due to interfering signals, which were measured with a spectrum analyzer.

1. INTRODUCTION

A close proximity of user's head and hand drops the efficiency of the mobile phone antenna. Because of that, the output power has to be increased, which additionally causes shorter battery life and higher emissions in terms of the specific absorption rate (SAR) and hearing aid compatibility (HAC). The handhold positioning along the phone (calling mode) and the finger positioning over the antenna (browsing mode) are the physically alternative loads inducing these inconvenient effects on the phone [1–5, 11].

Received 6 July 2011, Accepted 22 August 2011, Scheduled 30 August 2011

* Corresponding author: Sami Myllymaki (samby@ee.oulu.fi).

The user's effect can be reduced by using, e.g., with known compensation techniques involving antenna mismatch sensor and the impedance tuning of the antenna matching circuit in the desired frequency bands [6]. Several research papers for tuning resonance frequencies and enhancing matching have been introduced [7–9]. Additional method used for finger compensation is studied in [19].

In our previous work, a method for evaluating the user's proximity effect by using capacitive sensor was introduced [10]. The total efficiency of the dual GSM band antenna was proportional to the capacitance of the antenna, but it was not proportional to the antenna matching in all tested cases. The sensor antenna integration and performance from different point of views are published in [16–18].

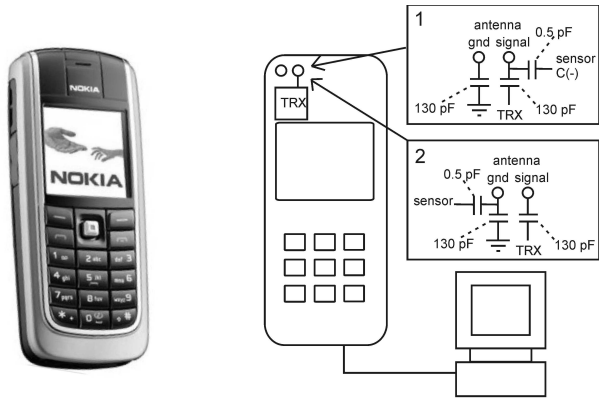
In contrast to the mismatch sensor technique typically realized by directional coupler in current mobile phones [6], the capacitive sensor has some benefits. Capacitive sensor senses the user proximity effect regardless of antenna matching. The matching can be complexly changed when more than one electrical resonance is used in the same band or when matching is modified by a resistive component such as human tissue absorption. In multiple antenna applications capacitive sensors can sense all antennas in the system, whereas the matching sensor is able to sense only one antenna. The characteristic of the capacitive sensor saves both time and energy since the communication signal is not used for sensor purposes.

This paper presents the antenna integrated capacitive sensor solution manually implemented in *online and operational* Nokia 6021 phone, since there has been a raised question what is the real effect in the rf chain if sensor signal is existed in the antenna. The effect of the antenna induced user load was presented on the load gauge on laptop's screen. The radio signal study is completed by measuring the TRP and TIS as active RF measurements. The results were compared with the passive antenna measurements of corresponding phone equipped with the cable for antenna alone measurements. Additionally spectrum analyses from measurement circuit was arranged in order to further explain active phone measurement results.

The Section 2 describes details of the system to measure the antenna capacitance. Section 3 presents TRP and TIS measurement results compared with passive antenna and spectrum analyzer measurements. Conclusion is given in Section 4.

2. ANTENNA INTEGRATION

Figure 1(a) shows Nokia 6021 phone and Fig. 1(b) the phone implemented capacitance measurement system. PIFA operating at



(a) (b)

Figure 1. (a) Nokia 6021 phone. (b) Antenna's capacitance measured with sensor system (options 1 and 2) consisting of capacitance circuit, measurement electronics and computer for collecting data.

narrow low band and wide upper GSM bands was equipped with commercial capacitance measurement chip (Analog Devices 7747). The phone was opened and following system was implemented on the RF signal route. The capacitance measurement system can be shunted either on the RF feed line (option 1 at Fig. 1(b)) or on the ground pin (option 2 at Fig. 1(b)) having different impedances: 50 ohm (option 1) and very small (option 2). Owing to the maximum readable capacitance of AD7747, a serial capacitor of 0.5 pF had to be used in order to limit the maximum output capacitance under 18 pF. The input of the sensor was equipped with a low pass filter (10 μH inductor and 0.5 pF capacitor in serial). RF lines towards the TRX (transceiver) and antenna ground were equipped with two high-Q 130 pF capacitors (Murata) to pass RF signal but block the low frequency (16 kHz) sensor signal. The ground plane of the phone was extracted from results by a shield function of AD7747. The shield means that the copy of the measurement signal is fed in the same time to the ground plane, following with the deduction of measurement and copied signal. So the results have only measurement capacitance change (hand to ground plane capacitance is extracted). The sensor system was mounted on a single PCB, data supplied by a cable via National Instruments I/O hardware to LabVIEW software and finally to the gauge on the laptop's screen. The measurement circuit placed on single PCB is placed on the top of the phone (Fig. 2(b)). The measurement signal is fed by using a cable to the connection circuit built on the backside of phone's PCB (Fig. 2(a)), which is presented in detail in Fig. 2(c).

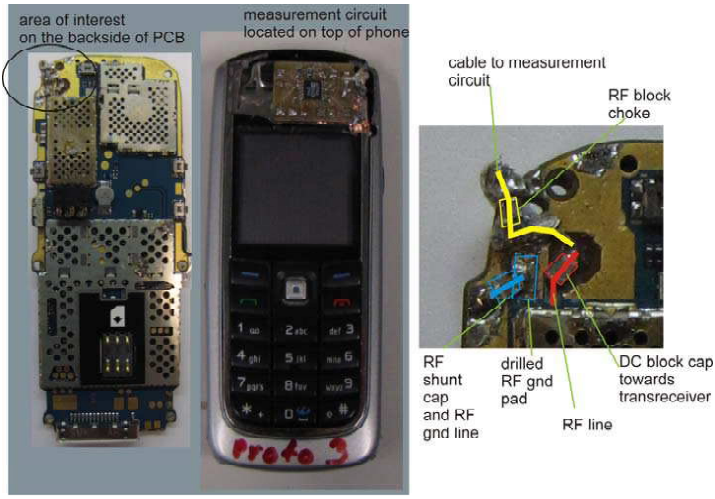


Figure 2. A photograph picture from prototype phone. (a) Backside of PCB was used for measurement signal and RF connections. (b) Topside of phone was used for AD7747 circuit. (c) Connection includes cable to antenna pin line (yellow), antenna pin to TRX line (red) and RF gnd line (blue).

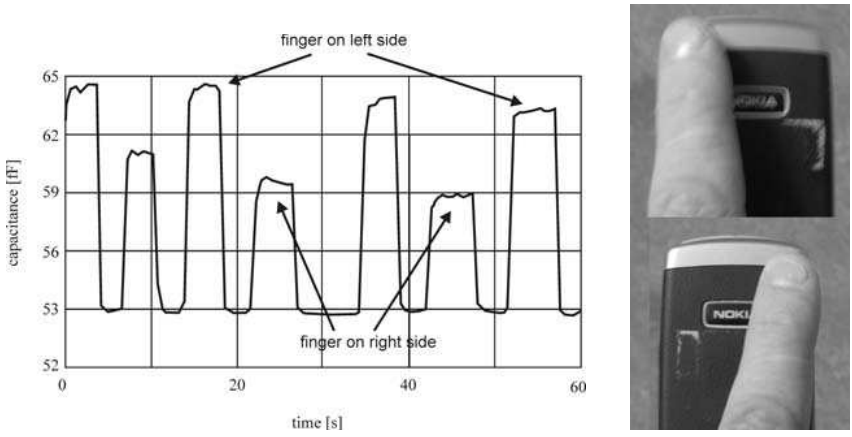


Figure 3. Capacitance output response measured in user's hand, index finger in turns located on right and left side of antenna. Measured finger locations on the backside of the phone are presented in detail.

Measured capacitive output is presented in Fig. 3. 6021 phone was in user's hand and the index finger was placed in turn over the right or left side of the antenna. Finger/no-finger affected levels can be clearly extracted from each other's. Real time finger detection can be straightforwardly realized by using this system.

3. MEASUREMENT

3.1. Measurement Setup

The quality of presented integration was evaluated by measuring TRP and TIS of Nokia 6021 at Satimo Stargate antenna measurement chamber (www.satimo.com). Additionally antenna's total efficiency was measured with cable phone 6021 with Satimo Starlab measurement chamber. Measurements were performed with two Nokia 6021 phones. The first phone was kept without modifications working as a reference #1. The sensor was implemented in the second phone with a mechanical on/off switch system.

Active measurements were performed with two phones: reference 6021, modified 6021 with circuit on and circuit off. The measurements were repeated three times. In the first measurement capacitance values were collected by data cables during TRP/TIS measurements. Second measurements were performed with the battery operated and the results were compared with ref #1. Third measurements were performed also with the battery but compared with the *same 6021* without modifications (ref #2). By changing ref #1 to ref #2 the production variance existing between individual 6021s was excluded from the results. TRP and TIS were measured at GSM 900/1900 MHz bands with three channels per each.

Following cases were measured:

First measurements with data cables:		
Reference 6021		ref#1
Modified 6021	circuit on/circuit off	ref#2
Second measurements with battery:		
Reference 6021		ref#1
Modified 6021	circuit on/circuit off	ref#2
Third measurements with battery:		
Modified 6021	(circuit removed)	ref#2
Modified 6021	circuit on/circuit off	ref#2

3.2. Active Measurements

Phone's TRX can be disturbed by the capacitive measurements. The effect can be evaluated by measuring the total radiated power P_{rad}, which the integral of the radiation intensity $U(\theta, \varphi)$ over the far-field sphere of the antenna. It can be expressed as

$$P_{rad} = \int\int_{4\pi} U(\theta, \varphi) \sin\theta d\theta d\varphi, \tag{1}$$

where θ and φ are antenna rotation planes [12].

P_{rad} is measured after setting the phone at its maximum available power. GSM900 radio is limited to 2 W (33 dBm) and GSM1800/1900 radio to 1 W (30 dBm). Available output power changes if capacitive system has strong effects. Among the losses inside the phone, hand and head can decrease TRP results 2 dB at 900/1800 MHz frequencies [13].

Most network operators are using TRP goals of 23 dBm at GSM900 and 24/24.5 dBm GSM1800/1900 [14].

For example, transceiver's 33 dBm (GSM900) output power is decreased by transmission line, components on pcb and matching losses amount of 4 dB. In order to reach TRP target (23 dBm), the antenna average gain should be −6 dB or more.

Mean received power A of the phone can be expressed in absolute terms as

$$\overline{A} = P_{BS,\lim}^{(ref)} \cdot G^{(ref)} \cdot \overline{P} = P_{BS,used} \cdot C_C \cdot e_{tot}, \tag{2}$$

where $P_{BS,\lim}^{(ref)}$ is the output power of base station for BER limit ($< 2.4\%$) in reference position, $G^{(ref)}$ is the transmission factor for the chamber in the reference position including gain of the mobile phone antenna, P is relative mean received power of phone for a full sequence of the call, $P_{BS,used}$ is the output power of base station used during power measurement, C_C is calibration coefficient for chamber average transmission and cable losses, and e_{tot} is the total efficiency for the mobile phone antenna. The total efficiency e_{tot} includes impedance mismatch relative to 50 ohm, losses in the antenna itself and losses in the near-in environment such as a head phantom. The mean sensitivity of a phone in a multipath environment, including the antenna is given by

$$\overline{S} = S_{rec}/e_{tot}, \tag{3}$$

where

$$S_{rec} = P_{BS,\lim}^{(ref)} \cdot G^{(ref)} \tag{4}$$

is the receiver sensitivity, i.e., the absolute power level at the receiver of the phone, excluding any antenna, when the BER is at the specified

limit. It then follows from (2)–(4) that the mean sensitivity of the phone including the antenna can be expressed as

$$\overline{S} = C_C \cdot P_{BS,used} \cdot \frac{1}{\overline{P}}. \tag{5}$$

Additionally reasons for poor sensitivity on a single channel or a small number of channels are due to receiver in-band noise or spurious signals from the transmitter itself being radiated back into the receiver [15].

The receiver sensitivity can be measured with the transmitter set to the maximum allowed output power. Network operators are using TIS goals of −100 dBm at GSM900 and −101 dBm at GSM1800/1900. Theoretical value for maximum conducted sensitivity is −109 dBm at 900/1800/1900 frequency bands [14].

For example, a network operator has set signal strength target greater than −100 dBm (GSM900). Cellular module sensitivity is around −109 dBm, therefore the device can sustain 9 dB in loss on the antenna, transmission lines and other PCB components still reaching the requirements. Thus if 4 dB loss is consumed in the transmission lines and components, there are 5 dB left for antenna requirements, which is equivalent to the antenna average gain of −5 dB.

3.3. Measurement Results

TRP results presented in Table 1 are organized by presenting three different measurement sessions at the top level. Every session consists of a reference result and a capacitance on and capacitance off results. Six channels of GSM 900/1900 MHz bands were presented in rows. The first measurement session was performed with data cables between the computer and the phone, whereas the second measurement session was performed without the cables. Hence the effect of sensor signal cables might be distinguished. Untouched 6021 was used as reference in measurements 1 and 2. Third measurement session was copy of the second except that the same 6021 was used both for reference and on/off modified phone.

First of all, the option 1 (Fig. 1) was compared with option 2 in order to define which of them should be used in further measurements. The average TRP and TIS at option 1 were both 2 dB weaker than at the option 2, which was selected as preferred measurement topology.

By reading the results at Table 1, the 900 MHz band, the modification caused 1.5–2.7 dB TRP deterioration compared with reference when capacitance data cables were used ("data cables used", Table 1). After excluding cable effects TRP deterioration was 1.1–1.5 dB ("no cables, ref #1", Table 1) and after excluding the product variation TRP deterioration was decreased to 0.1–0.4 dB ("no cables,

Table 1. Total radiated power results [dBm] of Nokia 6021 phone measured from reference phone and modified phone with sensor on/off states.

	data cables used			*no cables, ref #1*			*no cables, ref #2*		
[MHz]	ref	on	off	ref	on	off	ref	on	off
880.2	29.5	28	28.2	29.55	28.45	28.22	29.01	28.87	29
897.4	29.3	26.8	27.2	29.2	27.83	27.62	28.63	28.38	28.33
914.8	28.1	25.4	25.5	28.61	27.15	27	28.18	27.75	27.84
	1			2				3	
1850.2	27.4	27.9	28.0	26.98	27.45	27.21	26.69	26.88	26.62
1880	27.5	28.0	28.0	27.21	27.37	27.3	26.97	26.76	26.63
1909.8	27.6	27.5	27.4	27.2	26.88	26.63	26.42	26.12	25.98

Table 2. Total isotropic sensitivity results [dBm] of Nokia 6021 phone measured from reference phone and modified phone with sensor on/off states.

	data cables used			*no cables, ref #1*			*no cables, ref #2*		
[MHz]	ref	on	off	ref	on	off	ref	on	off
880.2	–103.6	–101.2	–101	–104.47	–102.5	–102.82	–103.7	–102.78	–102.86
897.4	–103.9	–101.9	–101.7	–104.77	–103.21	–103.38	–104.3	–103.09	–103.23
914.8	–103.2	–101.7	–101.3	–103.35	–99.6	–101.84	–102.7	–96.91	–100.43
1850.2	–104.6	–103.8	–104	–102.98	–103.29	–104.28	–102.5	–102.58	–102.68
1880	–104.5	–101.3	–103.1	–102.97	–103.44	–104.57	–102.9	–102.94	–103.07
1909.8	–104.1	–103.4	–103.5	–103.3	–103.45	–104.38	–103.2	–103.19	–103.31

ref #2", Table 1). The final results are close to measurement system repeatability of 0.3 dB.

Corresponding TRP deterioration at 1900 MHz band was under ±0.5 dB. On/off state margin was under ±0.3 dB in all channels.

In conclusion, the cable effect and product variation effect were clearly observed in TRP results. The sensor is applicable to real phone usage. All results are far away from limits of network operators (23 dBm at GSM900 and 24.5 dBm GSM1900).

TIS results are presented in Table 2 organized in the same way as TRP measurements. Modification caused local interferences in two channels. Channel 914.8 MHz suffered up to 5.8 dB deterioration with the operating capacitive circuit than the reference phone.

Additionally sensor's signal dropped 3.5 dB between on/off circuit states. Corresponding deterioration with value of 3.2 dB was observed on 1880 MHz channel. TIS limits of −100 dBm at GSM900 and −101 dBm at GSM1800/1900 were not reached at GSM900 band but exceed at GSM1900 band.

According to the Equation (3) the mean sensitivity can be decreased when the total efficiency e_{tot} is changed. The total efficiency includes impedance mismatch, losses in the antenna itself and losses in the near-in environment such as a head phantom. These losses can be increased by the option 2 used in this research. TIS were measured with cables, without cables and battery operated, which can change the antenna matching and efficiency and convey extra loss in PCB environment (4 dB loss mentioned in previous example calculations). However, previous losses do not fully explain why there are differences between on/off states.

At first, reasons for TIS deterioration were evaluated by measuring total efficiency results (i.e., cable phone) of the antenna (Fig. 4 with measured channels are labeled). Those passive measurements were performed in three cases with one phone: sensor in on/off states and without the sensor. The results show that the lower band was tuned downwards compared with the measured channels. Therefore measured (TRP, TIS) band was not located on the best radiation

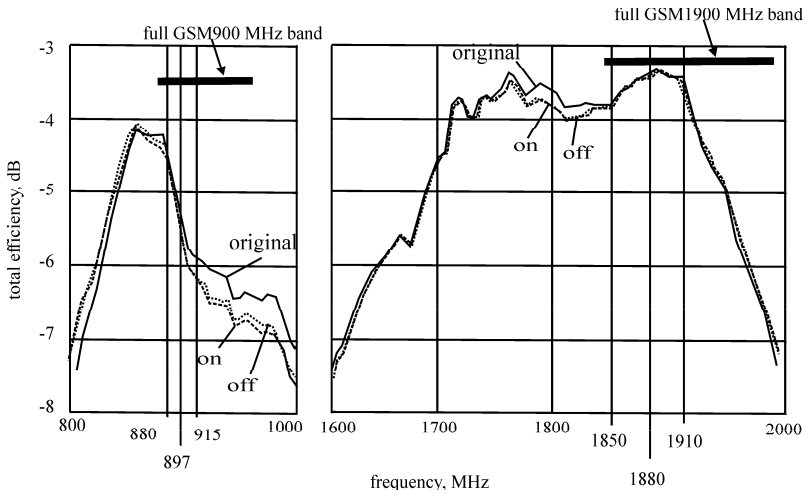


Figure 4. Measured total efficiency of Nokia 6021 antenna. Reference 6021 phone working as a reference and modified 6021 with sensor at on/off states.

band. Higher band was also tuned but still survived on the band. So the modification changed the total efficiency results but the effect between on/off states was found to be small. However, TIS results had significant deterioration in two channels when the sensor was switched on compared to the off-switched state. Passive antenna measurements did not present adequate results.

The device was studied and measured with spectrum analyzer since the poor sensitivity on a single channel or channels can be caused by in-band noise or spurious signals coming from used capacitive measurement circuit AD7747 not designed for RF applications. In order to avoid signals transmitted inside (EMI shield) to the device it was covered with a metal cage. Hewlett-Packard 8594E (9 kHz–2.9 GHz) spectrum analyzer was used with sample bandwidth of 1 kHz, tested different sweep times (200 ms–50 s) and different frequency spans in order to observe all resonances inside the sensitivity limit of used analyzer. Low frequency output spectrum can be seen in Fig. 5. When capacitive circuit was switched off, the 50 Hz main current caused weak resonance multiplies seen in the figure. Instead of that, the measurement circuit after switching on, has multiplies with stronger effects on the output. They were vanished to noise at MHz frequencies. High frequency output spectrum was presented in Fig. 6. The weakest channel at 914.8 MHz was carefully studied. A resonance peak of −102.5 dBm was measured at 915.1 MHz. Additionally another resonance was existed at 914 MHz. Both of them vanished after switching off the circuit. Obviously due to these interfering signals the TRX was disturbed as presented in [15].

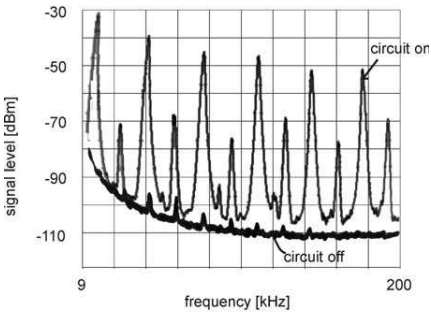


Figure 5. Low frequency output spectrum of tested device measured at circuit on/off states.

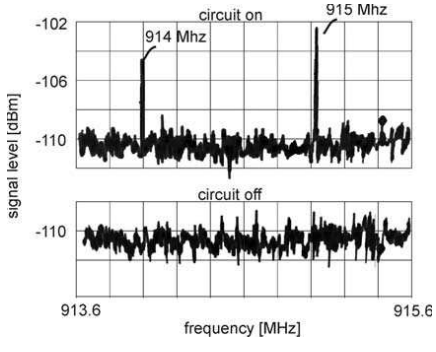


Figure 6. High frequency output spectrum of tested device measured at circuit on/off states close to interfered channel of 914.8 MHz.

Current setup was built by implementing capacitance measurement system in used phone. The realization is not optimal from RF signaling point of view. To test the low frequency operation was the primary object. The capacitance chip was assembled on the separated PCB on the top of the phone, with a coaxial cable used to connect PCBs together. Following research should be arranged in a way that a single commercial GSM chip such as Silicon Labs Si4905 GSM/GPRS would be used on the laboratory made PCB module consisting the capacitive circuit and proper connection lines. Thus the total system can be controlled at first by using RF simulators but additionally in following measurements, where several optimized prototypes are used.

4. CONCLUSION

As a feasibility study, the capacitive sensor for hand or finger proximity recognition was integrated on the antenna of Nokia 6021 phone. During the call, the antenna induced user load effect was able to be presented as the antenna load gauge on the screen of the laptop. A deterioration of radio signal caused by the sensor was evaluated by TRP and TIS measurements. TRP signal detrimental effect was very small, whereas TIS signal suffered interfering effects amount of 5.8 and 3.2 dB at 915 MHz and 1880 MHz. The results show that capacitance sensors can be used as user proximity sensors integrated into mobile phone antennas although small signal deterioration might exist at low signal strengths. Interfering spurious signals from capacitance circuit should be removed in following studies by using more robust RF system integration.

REFERENCES

1. Pelosi, M., O. Franek, M. B. Knudsen, M. Christensen, and G. F. Pedersen, "A grip study for talk and data modes in mobile phones," *IEEE Trans. on Antennas and Propagation*, Vol. 57, No. 4, 856–865, Apr. 2009.
2. Krogerus, J., J. Toivanen, C. Icheln, and P. Vainikainen, "Effect of the human body on total radiated power and the 3-D radiation element of mobile handsets," *IEEE Transactions on Instrumentation and Measurement*, Vol. 56, 2375–2385, Dec. 2007.
3. Berg, M., M. Sonkki, and E. Salonen, "Experimental study of hand and head effects to mobile antenna radiation properties," *Proc. 3rd Eur. Conf. on Antennas and Propagation (EuCAP 2009),* 437–440, Berlin, Germany, Mar. 23–27, 2009.

4. Li, C.-H., E. Ofli, N. Chavannes, E. Cherubini, H. U. Gerber, and N. Kuster, "Effects of hand phantom and different use elements on mobile phone antenna radiation performance," *Antennas and Propagation Society International Symposium*, 1–4, Jul. 2008.
5. Ofli, E., C.-H. Li, N. Chavannes, and N. Custer, "Analysis and optimization of mobile phone antenna radiation performance in the presence of head and hand phantoms" *Turk. J. Elec. Engin.*, Vol. 16, No. 1, 67–77, 2008.
6. Ranta, T. and R. Novak, "Antenna tuning approach aids cellular handsets," *Microwaves & RF*, 82–92, Nov. 2008.
7. Komulainen, M., M. Berg, H. Jantunen, E. T. Salonen, and C. Free, "A frequency tuning method for a planar inverted-F antenna," *IEEE Trans. on Antennas and Propagation*, Vol. 56, 944–950, 2008.
8. Zheng, Y., A. Hristov, A. Giere, and R. Jakoby, "Suppression of harmonic radiation of tunable planar inverted-F antenna by ferroelectric varactor loading," *IEEE MTT-S Int. Microwave Symposium Digest*, 959–962, Jun. 15–20, 2008.
9. Chiu, C. Y., K. M. Shum, and C. H. Chan, "A tunable via-patch loaded PIFA with size reduction" *IEEE Trans. on Antennas and Propagation*, Vol. 55, No. 1, 65–71, 2007.
10. Myllymaki, S., A. Huttunen, M. Berg, M. Komulainen, and H. Jantunen, "Method for measuring user-induced load on mobile terminal antenna," *Electronics Letters*, Vol. 45, No. 21, 1065–1066, Oct. 2009.
11. Al-Mously, S. I. and M. M. Abousetta, "User's hand effect on TIS of different GSM900/1800 mobile phone models using FDTD method," *Proceedings of Worlf Academy of Science, Engineering and Technology*, Vol. 37, 878–883, Jan. 2009.
12. Kildal, P.-S., "Foundations of antennas — A unified approach," Studentlitteratur, Sweden, 2000.
13. Colas, O., A. Hadjem, C. Dale, and J. Wiart, "Influence of hand on the terminal total radiated power (TRP)," *European Cooperation Cost 273 TD(04)057 in the Field of Scientific and Technical Research*, 6–28, Athens, Greece, Jan. 2003.
14. Taoglas Guidelines for Achieving Highest RF Performance and Passing Select Regulatory Approvals for Cellular Devices with Internal Antennas, http://www.taoglas.com/, 2010.
15. Orlenius, C. and P.-S. Kildal, "Measurements of radiated power and radiated receiver sensitivity in reverberation chambers," *Proceedings from the Seventh Symposium GigaHertz 2003*,

Linköping University Electronic Press, 2003.

16. Myllymaki, S., A. Huttunen, V. K. Palukuru, H. Jantunen, M. Berg, and E. T. Salonen, "Capacitive recognition of the user's hand grip position in mobile handsets," *Progress In Electromagnetics Research B*, Vol. 22, 203–220, 2010.
17. Huttunen, A., S. Myllymaki, M. Komulainen, and H. Jantunen, "Capacitive sensor arrangement to detect external load on a mobile terminal antenna," *Progress In Electromagnetics Research Letters*, Vol. 15, 13–18, 2010.
18. Myllymaki, S., A. Huttunen, H. Jantunen, M. Berg, and E. T. Salonen, "Measurement method for sensitivity analysis of proximity sensor and sensor antenna integration in a handheld device," *Progress In Electromagnetics Research C*, Vol. 20, 255–268, 2011.
19. Anguera, J., A. Camps, A. Andújar, and C. Puente, "Enhancing the robustness of handset antennas to finger loading effects," *Electronics Letters*, Vol. 45, No. 15, 770–771, 2009.