Publication VI

J. Holopainen, R. Valkonen, O. Kivekäs, J. Ilvonen, L. Martínez, P. Vainikainen, J. R. Kelly, and P. S. Hall. 2010. Equivalent circuit model-based approach on the user body effect of a mobile terminal antenna. In: Proceedings of the 2010 Loughborough Antennas & Propagation Conference (LAPC 2010). Loughborough, UK. 8-9 November 2010. Loughborough University. Pages 217-220. ISBN 978-1-4244-7305-2.

Equivalent Circuit Model-Based Approach on the User Body Effect of a Mobile Terminal Antenna

J. Holopainen[#1], R. Valkonen[#], O. Kivekäs[#], J. Ilvonen[#], L. Martínez[#], P. Vainikainen[#], J. R. Kelly[*], P. S. Hall[*]

[#]*Aalto University School of Science and Technology*
P.O. Box 13000, FI-00076 AALTO, Finland
[1]`jari.holopainen@tkk.fi`
[*]*School of Electronic, Electrical & Computer Engineering, University of Birmingham,*
Edgbaston, Birmingham, B15 2TT, UK

***Abstract*—The user body effect on the operation of mobile terminal antennas is investigated based on equivalent circuit modelling. The purpose is to increase the understanding of the phenomenon, which is important, for example, when designing mobile terminal antennas with minimised user effect.**

I. INTRODUCTION

As is well known, the body of the user of a mobile terminal is effectively lossy dielectric material, which in the reactive near fields of the antennas shifts the resonant frequency, absorbs a part of the power and distorts the directional pattern. Fig. 1 shows a measured example which relates to the effect of a lossy dielectric cube on the input impedance of a matched capacitive coupling element (CCE) antenna. The cube is placed in three different positions with respect to the antenna, at a 3-mm distance from the structure; see Fig. 1a. It can be seen that the resonant frequency of the antenna can either increase, decrease or stay roughly the same depending on the location of the dielectric cube; see Fig. 1b.

There are several papers studying the impedance variations of mobile terminal antennas in the presence of the user. For example, in [1] it has been shown that lossy dielectric material close to the antenna element (PIFA) is a much bigger problem than the same material close to the terminal ground plane (or the chassis). The same conclusion can be drawn also from Fig. 1. In addition, it has been shown that the fundamental impedance of the antenna becomes more resistive and inductive due to the presence of lossy dielectric material [1],[2]. The impedance variations of the antennas have been well-described but the detailed explanations of the behaviour of the antenna impedance have not been given. A better qualitative understanding of the behaviour of the antenna impedance and efficiency can be obtained by using a coupled-resonator-based equivalent circuit model for a CCE-based mobile terminal antenna, with modelling the user effect separately for each wavemode of the circuit model [3]. Even though measurements and EM simulations have a great importance in the user body effect studies, the proposed circuit-theoretical study separates the analysis into smaller parts enabling profound understanding of the impedance and efficiency variations caused by the presence the user.

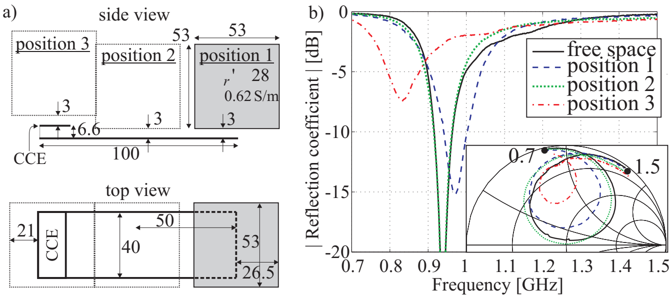

Fig. 1. a) Dielectric cube placed in three different locations around the prototype antenna of Fig. 2, and b) the measured reflection coefficient of the antenna matched in free space at 0.95 GHz when loaded by the dielectric cube. Dimensions are in mm.

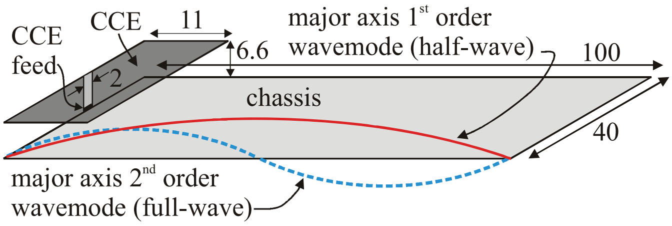

Fig. 2. Basic capacitive coupling element (CCE) mounted on a thin mobile terminal chassis, with principal current distributions of the two lowest order major axis wavemodes of the chassis. Dimensions are in mm.

II. CAPACITIVE COUPLING ELEMENT ANTENNA AND ITS CIRCUIT MODEL UNDER USER BODY EFFECT

A. *Capacitive coupling element antenna and its equivalent circuit model*

Capacitive coupling element (CCE) antennas are typically used as UHF band (0.3-3 GHz) digital television or cellular system antennas in mobile terminals [4]. Fig. 2 shows a typical geometry of a CCE on a mobile terminal chassis. The CCE-chassis antenna is just designed to optimise the coupling between the transceiver and free space electromagnetic waves at a wide frequency range. Consequently, the antenna does not have to be made self-resonant since it is matched with an external matching circuitry at any desired frequency band [4]. Hence, the CCE antennas are especially suitable for this kind of user effect studies as the variations of the fundamental impedance and radiation efficiency can be monitored at a wide frequency range without the matching circuit.

It has been shown in [3] that CCE antenna structures can be modelled at the UHF band with a wavemode-modelling-based

The work has been carried out in the AATE (Antennas Adaption to Usage Environments) project funded by TEKES and SMARAD Center of Excellence. The authors want to thank Professor Dr. Keijo Nikoskinen for discussions and comments.

978-1-4244-7307-6/10/$26.00 ©2010 IEEE

equivalent circuit; see Fig. 3. Each of the excited wavemodes of the antenna structure is modelled as an RLC resonant circuit, and the combination of the resonators as coupled resonators. Furthermore, each RLC resonator circuit is implemented based on the respective resonant frequency and Q value. The transformers (with scaling factors k_{c1} and k_{c2}) model the coupling between the resonators. The capacitor C_p is required to satisfy the zero impedance of the CCE feed at very high frequencies. Table 1 shows the component values derived for the CCE antenna structure shown in Fig. 2.

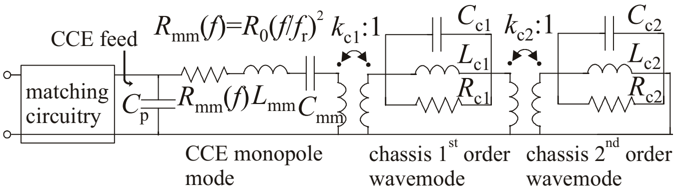

Fig. 3. Equivalent circuit for the CCE antenna of Fig. 2 in free space.

TABLE 1. COMPONENT VALUES OF THE EQUIVALENT CIRCUIT IN FIG. 3.

wavemode	***L* [nH]**	***C* [pF]**	***R* [Ω]**	**f_r [GHz]**	**Q_{rad}**	**other components**
monopole	5.80	1.39	1.46	1.77	44	$C_p = 0.18$ pF
chassis 1st	1.18	15.8	20.3	1.17	2.3	$k_{c1} = 1.0$
chassis 2nd	0.151	24.7	7.39	2.61	3.0	$k_{c2} = 1.0$

B. *Effect of lossy dielectric material on the behaviour of a resonant wavemode*

A user's head and hand introduce lossy dielectric material ($\varepsilon_{r2} = \varepsilon_{r2}' - j\sigma_{eff}/\omega\varepsilon_0$, $\varepsilon_{r2}' >> 1$) into the reactive near fields of a mobile terminal antenna. Since the operation of mobile terminal antennas is based on resonant wavemodes, the effect of such material on each wavemode can be analysed using the perturbation theory. The general formula for the shift of the angular frequency of the resonator is [5]

$$\frac{\omega_2 - \omega_1}{\omega_2} = -\frac{\int\left((\varepsilon_{r2} - \varepsilon_{r1})\varepsilon_0 \vec{E}_2 \cdot \vec{E}_1^* + (\mu_{r2} - \mu_{r1})\mu_0 \vec{H}_2 \cdot \vec{H}_1^*\right)dV}{\int\left(\varepsilon_{r1}\varepsilon_0 \vec{E}_2 \cdot \vec{E}_1^* + \mu_{r1}\mu_0 \vec{H}_2 \cdot \vec{H}_1^*\right)dV}, \qquad (1)$$

where subscripts 1 and 2 refer to the original (here free space $\varepsilon_{r1} = 1$) and the perturbed (ε_{r2}) situations, respectively. In a case of non-magnetic material ($\mu_{r2} = \mu_{r1} = 1$), such as the user, the H-field term disappears in the numerator. The denominator corresponds to the energy stored in the wavemode. At resonance, the energy stored is twice the energy stored in the E fields and thus, it can be concluded that the effect of the dielectric material on the resonance of a wavemode can be analysed through the electric fields only. In addition, (1) can be used to show that the resonant frequency of a wavemode can only decrease due to dielectric material since $\varepsilon_{r2}' > \varepsilon_{r1}'$ [5].

C. *Equivalent circuit model for the combination of CCE antenna and lossy dielectric material*

The user effect is modelled here by introducing additional parasitic components to each RLC resonator of the circuit model shown in Fig. 3 in such a way that certain change of the resonant frequency and quality factor are implemented. As discussed above, the dielectric material affects primarily through the electric fields and the resonant frequency of the wavemodes decreases. This can be associated with an increased total capacitance of the RLC resonator. The increase of the total capacitance is implemented with a parasitic capacitor C_u placed parallel to the free space capacitor of the RLC resonator circuit; see Fig 4. The decrease of the resonant frequency of the respective wavemode determines the value of C_u.

The resistive losses of the dielectric material decrease the Q value of each wavemode. However, modelling of the resistive losses at a wide frequency range is not as straightforward as the modelling of the resonant frequency shift. The Q value of each resonator circuit at the resonant frequency can be controlled by introducing a parasitic resistor R_u. Fig. 4 shows the modification of each resonator circuit. The placing of R_u is chosen so that it gives the best possible agreement with the actual resistance behaviour while keeping the model as simple as possible. Accurate broadband modelling of the resistive losses would require a much more complex model. However, in this paper, the main trends of the impedance and efficiency behaviour of the CCE antenna can be described accurately enough by using this simple one-resistor model.

The other component values in the free space model, such as the transformer scaling factors (k_{c1} and k_{c2}) modelling the coupling between the wavemodes, are not changed. This is stated due to the fact that the coupling between the CCE and chassis takes place mainly through the electric fields located in the empty space between the CCE and chassis (see Fig. 2) and thus, it is expected that the coupling does not change very significantly due to the lossy dielectric material. However, this issue requires also further research and validation in the future.

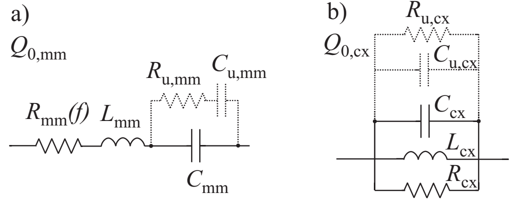

Fig. 4. Modification of a) CCE monopole mode, and b) chassis wavemode RLC resonator circuits due to lossy dielectric material placed into the near fields of the respective wavemode. Subscript x refers to the order of chassis wavemode. Q_0 is the unloaded quality factor of the respective wavemode.

III. THEORETICAL RESULTS WITH CIRCUIT MODEL

A. *Effect of lossless dielectric material close to chassis*

In this section, the effect of lossless dielectric material on the impedance variations of the CCE antenna is studied with the help of the equivalent circuit model consisting of the circuit in Fig. 3 and the modifications introduced in Fig. 4 on each resonator. The free space impedance of the antenna is compared with the "perturbed" impedances. Firstly, we focus on the case where only the chassis wavemodes are affected.

Based on (1) [5], the largest decrease in the resonant frequency of the chassis wavemodes takes place when the dielectric material is located in the maximum of the electric field distribution of the respective wavemode. As is typical for standing waves, the electric field maxima coincide with the current distribution zeros; see Fig. 1. Thus, the ends of the chassis are the locations where the dielectric material affects the most. This explains why in the example of Fig. 1 the dielectric block affects the resonant frequency more in "position 1" than in "position 2". However, dielectric material close to the midpoint of the long axis of the chassis would affect significantly the second order wavemode.

In this paper, a parametric approach is applied for the magnitude of the shift of the resonant frequencies. However, it has been studied with EM simulations that the used magnitude of the frequency shift is typical for the case where the user's hand loads the chassis wavemodes. The resistance and reactance derived from the equivalent circuit model (without the matching circuit) are shown in Fig. 5. The resistive losses are not modelled–i.e., $R_{u,cx} = \infty\ \Omega$–and thus, the resistance can be considered to represent only the "losses" due to radiation.

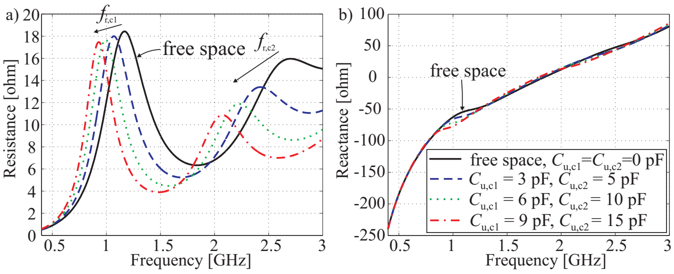

Fig. 5. Effect of the shift of the resonant frequencies of the chassis wavemodes on the a) resistance and b) reactance of the circuit model.

Firstly, it can be seen that the decrease of each resonant frequency of the chassis wavemodes has a relatively big influence on the resistance behaviour. This happens because the resistance of the CCE-chassis antenna is mainly dictated by the chassis wavemodes [3]. The shift of the radiation resistance maximum downwards in frequency is useful for systems operating at frequencies below the resonant frequencies of the chassis wavemodes (below 1 GHz and around 2 GHz) since the higher radiation resistance at those frequencies improves the efficiency. In practice, the resistive losses of a realistic lossy dielectric material, such as human tissue, reduce the benefit gained from the higher radiation resistance. Nevertheless, in certain specific cases the total effect can even be positive and the efficiency of the antenna increases due to the user interaction. For example in [6] this "positive hand effect" is demonstrated. Secondly, the reactance is significantly affected only around the resonant frequency of the first order chassis wavemode (at 1-GHz range). This happens because the reactance of the CCE mainly determines the reactance behaviour of the antenna, and the chassis wavemodes can affect the reactance only around the chassis resonances [3].

B. Effect of lossless dielectric material close to CCE

Next, the effect of the lossless dielectric material loading the CCE monopole mode is investigated. The fundamental frequency $f_{r,mm}$ of the monopole mode is decreased by introducing the parasitic capacitor $C_{u,mm}$; see Fig. 4a. Again, the magnitudes of the change of the fundamental frequency are typical for the effect caused by the palm or fingers of the user's hand. The resistance and reactance of the circuit model of Fig. 3 after applying $C_{u,mm}$ are shown in Fig. 6.

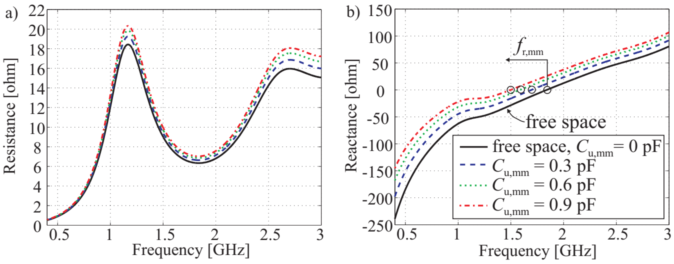

Fig. 6. Effect of the shift of the fundamental frequency of the CCE monopole mode on the a) resistance and b) reactance of the circuit model.

As can be seen, the decrease of the fundamental frequency of the CCE monopole mode has a relatively big influence on the reactance behaviour. The explanation is that the CCE reactance dictates the reactance of the whole antenna [3]. It can be seen that the impedance always changes to the inductive direction, as described also in [1]. Since the reactance increases significantly at all the UHF frequencies, it can be expected that the resonant frequency of a matched antenna would decrease correspondingly. The relative change of the radiation resistance is not very significant.

C. Effect of lossless dielectric material on matching

The effect of the shift of the resonant frequencies of the wavemodes on a matched antenna is studied in this section. As an example, the free space impedance in Fig. 5 is matched separately at 0.95 and 2 GHz with ideal lumped-element L-section matching circuits; see Fig. 7.

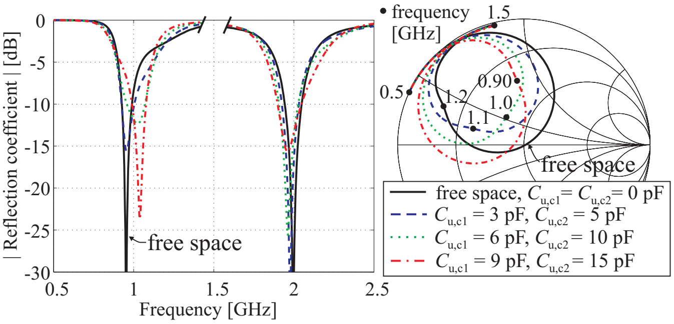

Fig. 7. Effect of the shifting of the resonant frequencies of the chassis wavemodes on the matching at 0.95 and 2 GHz of the circuit model.

It can be seen that the resonant frequency can even increase at the 1-GHz band due to dielectric loading. This result is similar to the measured example with the dielectric block in "position 1" in Fig. 1. This happens because the change of the chassis resonant frequency decreases the antenna reactance around 1 GHz; see Fig. 5b, and thus the resonance is shifted upwards in frequency. This does not, however, conflict with the perturbation theory, which claims that the resonant frequency can only decrease. This is because the perturbation theory applies directly only to a single wavemode case, whereas the circuit model (as well as the CCE-chassis antenna) consists of several coupled wavemodes. In addition, based on the circuit model, it can be shown that the stronger the coupling between the CCE and chassis wavemodes (larger k_{c1} and k_{c2}) is, the larger is also the increase of the resonant frequency. From the Smith chart in

Fig. 7 (only 1-GHz case shown) it can be seen that the impedance loop gets somewhat smaller. This can be understood with basic resonator theory: a critically-coupled resonator becomes undercoupled when the internal losses increase. It can be seen in Fig. 5a that the radiation resistance really increases at the resonant frequency of the matched antenna, and that causes the decrease in the size of the impedance loop. So, in the case of lossless dielectric material, the increased "losses" are radiation. At the 2-GHz band, the antenna reactance is essentially unchanged (see Fig. 5b), and so is also the resonant frequency of the matched antenna.

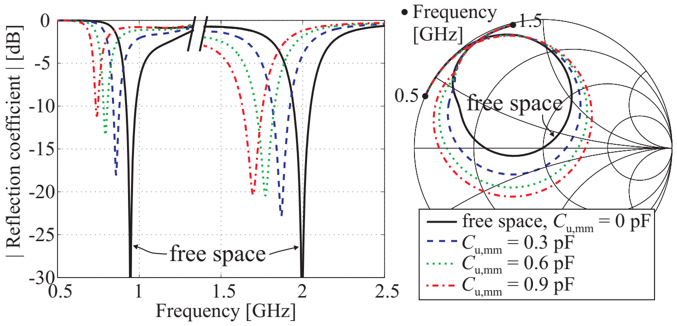

Fig. 8. Effect of the shifting of the fundamental frequency of the CCE monopole mode on the matching at 0.95 and 2 GHz of the circuit model.

Fig. 8 shows the effect of the change of the resonant frequency of the CCE monopole mode on the matched antenna impedance. As it was expected based on the reactance change in Fig. 6b, a significant decrease in the resonant frequency of the matched case can be noticed at both frequency bands. A similar effect can also be seen in the measured example; see "position 3" in Fig 1. One should however note that in the measured example the dielectric cube in "position 3" affects also the chassis wavemodes which is not the case in Fig 8. From the Smith chart (only 1-GHz case shown) it can be seen that the impedance loop gets larger (overcoupled) due to decreased radiation resistance at the tuned resonant frequency; see Fig. 6a. The measured "position 3" case in Fig. 1 gives an opposite result, a clearly smaller (undercoupled) impedance loop. The difference is due to the effect of the resistive losses which exist in the measured case. Thus, the resistive losses in the CCE monopole mode have a "drastic" contribution to the overall resistive losses of the whole structure. This is typical for resonators having a relatively high radiation Q value, which is also the case with the CCE monopole mode; see Table 1.

C. *Effect of simultaneous loading of wavemodes on matching*

Finally, simultaneous loading of the first chassis wavemode and the CCE monopole mode with lossy dielectric is studied with an example shown in Fig. 9. If only the chassis wavemode is loaded, the resonant frequency of the matched antenna is tuned upwards. Increasing the resistive losses $R_{u,c1}$ on the chassis wavemode partly compensates the frequency shift caused by the effect of the capacitance $C_{u,c1}$. The case of only loading the chassis wavemode can be associated with the "position 1" of the measured example in Fig. 1.

Then, if dielectric loading on the monopole mode is added, the resonant frequency quickly decreases. Adding resistive losses on the monopole mode does not change the frequency anymore, but it makes the matching level worse by shrinking the matching loop on the Smith chart. This behaviour is very similar to the "position 3" case in the measured example.

Also rough radiation efficiency estimations can be made based on the circuit model, indicating how much losses are generated in each wavemode. The results indicate that the resistive losses in the CCE wavemode have much larger effect on the efficiency than those in the chassis wavemodes.

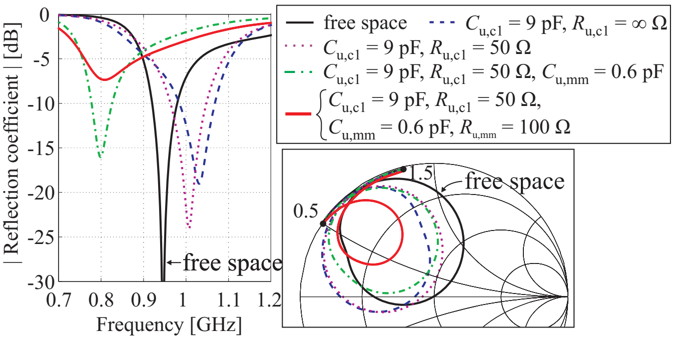

Fig. 9. Effect of the simultaneous loading of the wavemodes on the matching.

IV. CONCLUSIONS

The proposed equivalent circuit model can be used at a qualitative level to explain and predict the impedance and efficiency behaviour of a capacitive coupling element antenna under the user body effect. The model gives also insight that shows how to relieve the problem. Possible ways would be 1) to try to place the antenna element in such a location that the user's body does not cause too heavy loading, 2) to match the antenna over a wide enough impedance bandwidth so that the detuning does not result in significant degradation of matching efficiency, or 3) to use adaptive matching. The main results can be generalised also for other antenna structures, such as PIFAs, since the radiation characteristics–i.e., the radiation of the chassis–are similar. The future work in this area includes further development of the circuit model and better quantitative validation of the model by comparing the results to measured and/or simulated data.

REFERENCES

[1] K. R. Boyle, Y. Yuan, L. P. Ligthart, "Analysis of Mobile Phone Antenna Impedance Variations with User Proximity," *IEEE Trans. Antennas and Propag.*, vol. 55, issue 2, February 2007, pp. 364-372.

[2] T. Huang, K. R. Boyle, "User Interaction Studies on Handset Antennas," *EuCAP 2007, The Second European Conference on Antennas and Propagation*, 11-16 November 2007, Edinburg, UK.

[3] J. Holopainen, R. Valkonen, O. Kivekäs, J. Ilvonen, and P. Vainikainen, "Broadband Equivalent Circuit Model for Capacitive Coupling Element –Based Mobile Terminal Antenna," *IEEE Antennas and Wireless Propagation Letters,* vol. 9, 2010, pp. 716-719.

[4] J. Villanen, J. Ollikainen, O. Kivekäs, P. Vainikainen, "Coupling Element Based Mobile Terminal Antenna Structures", *IEEE Trans. Antennas and Propag.*, Vol. 54, No. 7, July 2007, pp. 2142-2153.

[5] R. F. Harrington, *Time-Harmonic Electromagnetic Fields*, New York: McGraw-Hill, 1961, 480 p.

[6] P. Hui, "Positive Hand Effects on Mobile Handset Antennas," *Asia-Pacific Microwave Conference 2008*, Macau, 16-20 December, 2008.