Optimal Antenna Location on Mobile Phones Chassis Based on the Numerical Analysis of Characteristic Modes

Celestin Tamgue Famdie*, Werner L. Schroeder† and Klaus Solbach*
*Universitaet Duisburg-Essen, 47057 Duisburg, Germany,
Email: celestin.tamgue@stud.uni-duisburg-essen.de, klaus.solbach@uni-duisburg-essen.de
†mimoOn GmbH, 47057 Duisburg, Germany
Email: werner.schroeder@mimoOn.de

Abstract—This paper contributes to the solution of the antenna-chassis coupling problem for handheld devices in mobile communication. That problem, up to now addressed in terms of equivalent circuits, is discussed here from a field theoretical point of view. A numerical analysis of characteristic modes on the chassis of the device provides a resonant mode which dominates the overall radiation properties. The modal excitation coefficient which relates the above mentioned chassis dominant wavemode to that of a given antenna element (exciter) should be maximized to achieve an optimal modal coupling. This paper establishes conditions to achieve maximum modal excitation coefficient which lead to an optimal placement of the antenna element on the chassis. A numerical approach for the evaluation of the optimal location of the exciter (electric and magnetic) on the chassis is performed. In this paper a theoretical approach based on some assumptions of the evaluation of the modal excitation coefficient is presented for the cases of an electric and a magnetic exciter. Numerical results are given for a bar-type and a folder-type phone chassis.

I. INTRODUCTION

Many investigations on antenna design for handheld devices deal with the interaction between the antenna element and the chassis on which it is mounted. They have revealed that the radiation properties, especially the bandwidth, largely depends on the coupling between both entities [1]. The influence of the chassis length on the bandwidth of bar-type phones at 900 MHz has been investigated in [2]. A further step was made in [3], [4] which for the first time addressed the analysis of the chassis itself in terms of its characteristic modes [5]. Characteristic mode theory for analysis of mobile phones chassis radiation properties has recently been subject of several publications. In [6] numerical characteristic mode analysis performed on the chassis of bar- and folder-type mobile handsets has not only revealed different resonant modes but has also allowed an evaluation of their modal radiation quality factors. In [7] this concept is applied to investigate the radiation properties of the slotted chassis of a folder-type phone for the design of its coupler and in [8] to determine the optimal antenna placement on the chassis of a bar-type mobile phone.

The theory of characteristic modes for conducting bodies [5] is in fact a powerful analytical concept for the design of small antennas, similar to what modal analysis means for the design of waveguide circuits. Knowledge of the (typically few) modes which can appreciably be excited at a given frequency gives valuable insight for the placement and design of antenna elements. Antenna–chassis coupling, which has so far mainly been discussed in terms of equivalent circuits [1] can be treated on a field theoretical level in terms of expansion into chassis modes. The chassis resonant mode obtained from the characteristic mode analysis must be efficiently excited since its contribution dominates in the global radiation properties. This work investigates through the knowledge of the chassis radiation properties, determined by that of its dominant mode, the optimal location of the antenna element seen in this context as an exciter. In order to achieve an optimal coupling between chassis and antenna element(exciter), the antenna element should be placed in such a way to excite at most the chassis dominant mode. In general, the method applied in the scope of this work can be extended to any other chassis mode of interest at a given frequency to achieve its effective excitation.

II. ANTENNA–CHASSIS COUPLING

Several papers [1], [2] dealing with mobile phones antennas have revealed that the antenna element contributes only moderately to radiation. It is rather the chassis which dominates overall radiation properties. Thus, the coupling between antenna element and chassis has gained great interest, since it has the potential to boost the overall performances of the mobile device.

To provide an insight into the coupling mechanism between antenna element and chassis, we separately consider chassis and antenna element as two distinct entities and investigate the radiation properties of the chassis on its own by making use of the theory of characteristic modes for conducting bodies. From this point of view, an optimal design and location of the antenna element can be obtained through the knowledge of the chassis radiation properties. In this case the antenna element is only used as exciter or coupler for the chassis.

The theory of characteristic modes for conducting bodies was introduced by [9] and further elaborated on in [5]. It is based on the properties of the operator \( \hat{Z} \) which maps a surface current density \( J_s \) on the surface \( S \) of a conducting body to...
the tangential components of the electric field
\[ \mathbf{E}_{\text{tan}} = \mathbf{\hat{Z}} \mathbf{J}_s = (\mathbf{\hat{R}} + j \mathbf{\hat{X}}) \mathbf{J}_s. \] (1)
on \mathbf{S}. The operators \( \mathbf{\hat{R}} \) and \( \mathbf{\hat{X}} \) represent the real and imaginary parts of \( \mathbf{\hat{Z}} \), respectively. \( \mathbf{\hat{Z}} \) is symmetric from the reciprocity theorem [10] but not Hermitian, whereas \( \mathbf{\hat{R}} \) and \( \mathbf{\hat{X}} \) are real and symmetric. The problem formulation chosen in [5] therefore leads via the generalized eigenvalue problem
\[ \mathbf{\hat{X}} \mathbf{J}_{s,n} = \lambda_n \mathbf{\hat{R}} \mathbf{J}_{s,n} \] (2)
to real eigenvalues \( \lambda_n \) and real eigenvectors \( \mathbf{J}_{s,n} \). Furthermore, the set of surface current densities \( \{ \mathbf{J}_{s,n} : n \in \mathbb{N} \} \) obeys the orthogonality relations
\[ \langle \mathbf{J}_{s,m}, \mathbf{\hat{R}} \mathbf{J}_{s,n} \rangle = 2 P_n \delta_{mn}, \] (3)
\[ \langle \mathbf{J}_{s,m}, \mathbf{\hat{X}} \mathbf{J}_{s,n} \rangle = 2 \lambda_n P_n \delta_{mn}, \] (4)
\[ \langle \mathbf{J}_{s,m}, \mathbf{\hat{Z}} \mathbf{J}_{s,n} \rangle = 2 P_n (1 + j \lambda_n) \delta_{mn} \] (5)
with respect to the inner product
\[ \langle \mathbf{f}, \mathbf{g} \rangle = \int \int \mathbf{f}^\ast \mathbf{g} \, dS. \] (6)
As outlined in the following section, \( P_n \) represents the radiated power due to \( \mathbf{J}_{s,n} \). The eigensolutions could be normalized so as to render \( P_n \) unity. In order to maintain physical units of current density for \( \mathbf{J}_{s,n} \), however, the quantity \( \lambda_n \) will be carried through explicitly in the following derivations in the sense of a normalization constant.
A conceptual analysis considers a current density \( \mathbf{J}_s \) induced on the chassis by an external electric field \( \mathbf{E}^\text{ex} \) as a superposition of characteristic modes in the form
\[ \mathbf{J}_s = \sum_n \frac{\langle \mathbf{J}_{s,n}, \mathbf{E}_{\text{tan}}^\text{ex} \rangle}{(1 + j \lambda_n) 2 P_n} \mathbf{J}_{s,n} \] (7)
where \( \mathbf{E}_{\text{tan}}^\text{ex} \) is the tangential component of \( \mathbf{E}^\text{ex} \) on the conducting body, \( \lambda_n \) and \( P_n \) are respectively the eigenvalue and radiated power associated to the \( n^{\text{th}} \) mode \( \mathbf{J}_{s,n} \).
For an effective excitation of the \( n^{\text{th}} \) mode, (7) suggests a maximization of the \( n^{\text{th}} \) modal expansion coefficient which logically implies the maximization of the excitation coefficient \( \langle \mathbf{J}_{s,n}, \mathbf{E}_{\text{tan}}^\text{ex} \rangle \) and the minimization of the denominator \( 1 + j \lambda_n \). The minimization of the denominator leads to \( \lambda_n(\omega) = 0 \), i.e. the most effective chassis excitation is achieved with resonant modes or modes next to the resonance. However, bringing a chassis mode to resonance at a given operating frequency may require a modification of the chassis geometry.
The reaction term in the nominator of (7) describes the coupling between an exciting field and the \( n^{\text{th}} \) characteristic mode. The goal is to maximize this term by optimum placement and design of the antenna element (coupler) under the usual restriction of limited antenna volume. Obviously from the nominator of (7), for an effective excitation of the \( n^{\text{th}} \) mode by means of an impressed electric field over a small region on the chassis, the exciting field must be located about the maximum of the modal surface current density and be aligned with it.

By making use of the reciprocity theorem, one obtains that the excitation coefficient is maximal if the current density on the exciter \( \mathbf{J}^\text{ex} \) (that generates \( \mathbf{E}_{\text{tan}}^\text{ex} \)) and the modal field \( \mathbf{E}_n \) (generated by \( \mathbf{J}_{s,n} \)) are maximum and furthermore in the same direction. In this case, the optimal placement for the antenna element is the location in the vicinity of the chassis where the modal field \( \mathbf{E}_n \) reaches its maximum. In this way an optimal capacitive coupling can be achieved.

III. APPLICATION EXAMPLES
A. Bar-Type Phones
A perfectly conductive metallic board is considered as model for simulation. The battery and other conductive parts of the housing are ignored. Dimensions are 100 mm × 40 mm.
Fig. 1 shows the frequency dependence of the eigenvalues \( \lambda_n \)

![Fig. 1. Frequency dependence of the first few eigenvalues for a 100 × 40 mm plate](image)

with magnitude less than 10. The graphs are constructed based on the correlation between eigenvectors at adjacent frequency samples. Four resonances \( \lambda_n(\omega) \approx 0 \) can be observed at frequencies 1.33 GHz, 3.02 GHz, 4.45 GHz and 4.78 GHz. Only the three first corresponding modes are shown and referred to as (a), (b) and (c) in the sequel. Fig. 2 shows the modes surface current densities representing the modes (a), (b) and (c). (a) and (b) represent respectively the \( \lambda/2 \) and the \( \lambda \) with respect to the major axis whereas (c) represents a resonance around the transverse axis. In the following, we investigate the optimum placement of the coupler for modes (a) and (b). Investigation of the optimal placement of a capacitive coupler directly on top of the chassis is the key to the volume problem for antenna development in handheld devices. Fig. 3 shows the electric field strength generated by the first (a) and second (b) resonant characteristic mode in Fig. 2 respectively, evaluated in a plane surface having the dimensions of the chassis extended by 10 mm at each side, parallel and 5 mm above the board. It clearly presents the potential optimal locations depicted in red for a capacitive coupler, corresponding to the maxima of the resonant characteristic fields. The field at that position is.
predominantly polarized vertically with respect to the chassis. Of course, the alignment of the orientation of the vectors $E_n$ and $J_{ex}$ must be taken into account.

**B. Folder-Type Phones**

For folder-type phones two cases are to be considered: the open and closed state of the device. As before a perfectly conducting chassis is assumed in the simulation. We first investigate the resonant characteristic modes in open state. The base part is modeled as a $70 \times 40$ mm and the flip part as a $50 \times 40$ mm plate at $15 \text{ mm}$ height. Fig. 4 presents the eigenvalues as a function of the frequency and exhibits 2 resonances. Fig. 5 shows the surface current densities for resonant modes at frequencies $1.05 \text{ GHz}$ (a) and $2.25 \text{ GHz}$ (b). This means for Fig. 5a a $\lambda/2$-resonant mode covering the whole chassis. Fig. 5b on the other hand presents a $\lambda$ resonant mode.

Fig. 6 represents the electric field strength of the first resonant characteristic mode (Fig. 5a) at $1.05 \text{ GHz}$ evaluated in a cross section along the major symmetry axis of the folder-type open phone. It can be clearly observed that the characteristic field reaches its maximum at the outer short edges (depicted in red) of the flip and base part. This reasonably leads to deduce that these edges of the base and flip part are optimal locations for the coupler. To expose more details, the modal electric field has been evaluated on segments next to the outer short edges and parallel to them, contained in planes $5 \text{ mm}$ above and parallel to the flip as well as to the base part, and shifted $2 \text{ mm}$ from the short edges inside the open phone. Fig. 7 shows that the optimal placement of the coupler above the chassis is situated in the corners.

**IV. CONCLUSION**

The theory of characteristic modes for conducting body was applied to investigate the optimal location of a capacitive coupler on the chassis of mobile phones. Numerical results
Fig. 5. Surface current density for characteristic mode resonances (a) at 1.05 GHz and (b) at 2.25 GHz of an open folder-type phone.

were provided for folder-type in open state and bar-type phones at some resonance frequencies. The same approach shall be used for investigation of the optimal location for a magnetic exciter on the chassis of mobile phones.

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REFERENCES


