Study of Mutual Coupling and Chassis Modes Coupling through the Equivalent Circuit Model of Two Monopoles on a Small Platform

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***Abstract*— In addition to the mutual coupling between array elements, the coupling to the characteristic current modes of the chassis has to be considered. In this paper, the performance of a two-element monopole antenna on a small rectangular ground plane is analyzed based on a decomposition of the contributions from the elements and the coupled chassis modes. A resonator-based equivalent circuit is proposed to model closely the full-wave simulation which allows the calculation of radiation and impedance contributions from the elements and the chassis modes.**

Keywords—equivalent circuit model; chassismodes; mutual coupling; resonators;

I. INTRODUCTION

Several published studies on radiation from antennas on small chassis (ground plane) show that the dominant characteristic current modes of the chassis can contribute significantly to the radiation behavior of the chassis and the antenna element. In [1], it was noticed that tradition self-resonant antenna elements of mobile terminals especially at 1 GHz work mainly as matching circuit and coupling elements to the chassis characteristic current modes and may radiate as low as only 10% of the total radiated power. A similar result was found in [2] through the equivalent circuit modeling of a single monopole on a small platform.

The bandwidth of an antenna-chassis combination can be improved by enhancing the coupling to the dominant characteristic current modes of the chassis [3]. For efficient coupling to the chassis modes, the location and shape of the coupling element have to be chosen suitably. In [4], [5], optimal antenna placement on a rectangular ground plane has been studied using a small probe antenna element that was moved over the ground plane and computing the radiation quality factor of the antenna as the ratio of the susceptance to the conductance. The optimal location was found to be at the corner and short ends of the ground plane, where also the electric field of the chassis resonant mode has its maximum. In [6], [7], the theory of characteristic modes for conducting bodies was applied to get the optimal location of a coupling element on the chassis of a mobile phone. In [8], mutual coupling of two monopoles on a small ground plane was experimentally found to depend critically on the ground plane size.

In this paper, in addition to coupling to the chassis modes, mutual coupling between two monopoles on a rectangular ground plane will be analyzed by the help of the equivalent circuit model. The equivalent circuit modeling will be presented for deeper understanding of the element-to-chassis and element-to-element interactions and their contribution to the element impedance and radiation characteristics required for phased array, diversity and MIMO concepts.

II. CHASSIS MODE EXCITAION BY TWO MONOPOLES

Fig.1 shows the geometry of two quarter-wavelength monopoles for 2.45 GHz mounted on a 100 mm x 40 mm ground plane and placed at distance *d* from the middle of the chassis short ends. To study the effect of chassis modes on impedance and radiation of two monopoles on a small platform, the characteristic modes theory allows calculating the resonant frequencies and corresponding quality factors of the chassis modes. In [9], the characteristic mode theory was applied to analyze a wire grid model of a 100 mm x 40 mm conducting plate. The half- and full-wavelength resonant frequencies of the chassis major axis were found as 1.26, and 2.68, and their respective radiation quality factors values are 2.3, and 3.0. In order to selectively excite the chassis modes, suitable couplers positions and their excitation phases can be found. In [10], for a selective excitation of the characteristic modes of the chassis near to their resonant frequencies, an arrangement of four capacitive coupling elements and a feed network has been proposed.

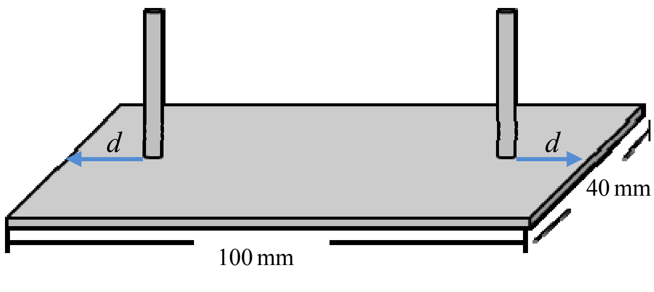


Fig. 1. Two quarter-wavelength monopoles mounted on 100 mm×40 mm ground plane.

A 180° hybrid based feed network was used to feed the structure by the eigenvector of the selected chassis mode excitation. In Fig.1, to excite the half- wavelength and full-wavelength modes of the major axis of the chassis, odd and even excitation, respectively, of the two monopoles placed on the middle of the chassis short ends *d* = 4 mm is required. For the two port network created by the two monopoles, the off-diagonal elements of the scattering matrix represent the mutual coupling between ports. Due to symmetry of geometry in Fig.1, the S-matrix can be transformed via

$$U^{t}SU = \Gamma \tag{1}$$

into a diagonal matrix $\Gamma = \mathrm{diag}\,[\Gamma_h, \Gamma_f]$ while the unitary matrix is given by

$$U = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{2}$$

The two-column vectors of U represent the excitation vectors for the half- and full-wavelength characteristic current modes of the chassis with related excitation eigenvalues denoted by Γ_h, Γ_f respectively. The surface current distributions Fig.2 of the odd and even excitation of the two monopoles placed at the middle of the chassis short ends with *d* = 4 mm exhibit close similarity with the 1st (odd) and 2nd (even) characteristic current modes of the chassis. The effect of the monopole-to-chassis coupling on the monopole input impedances is shown in Fig.3. The reactance behavior of the impedance below the quarter-wave resonance is mainly determined by the monopole self-impedance, while the effect of the chassis modes is dominant in the resistance part of the impedance. This can be explained by the high Q-factor of the monopole compared to the chassis modes and the low radiation resistance of the monopole (at least below quarter-wavelength resonance).

III. Equivalent Circuit Modeling of Two Monopoles on a Small Chassis

To improve an overall understanding of the effect of coupling to the chassis modes, an equivalent circuit model is proposed. Each of the monopoles and the first two chassis modes are modeled using RLC-resonator circuits. Based on [11], a series RLC resonator is used to model the monopole impedance. Consequently, a parallel RLC-resonator is used to model each chassis mode [1, 12]. Two cascaded T-section networks are used to model the mutual coupling between the monopoles, while L-section networks are used to model the coupling to the chassis modes Fig.4. The resonant frequencies and corresponding quality factors calculated in [9] are used as initial values for the resonator equivalent circuits.

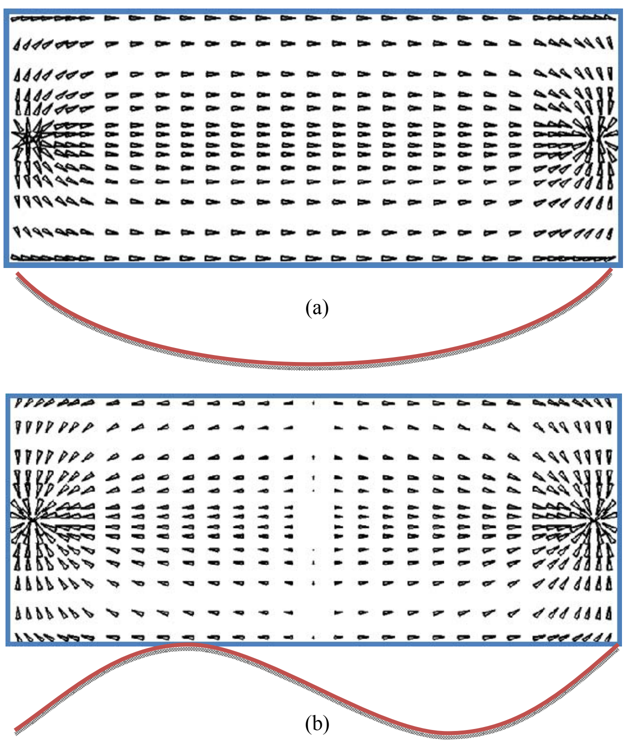


Fig. 2. Current distribution of two monopoles at the middle of the chassis short ends.(a) odd excitation at 1.14 GHz, and (b) even excitation at2.45 GHz.

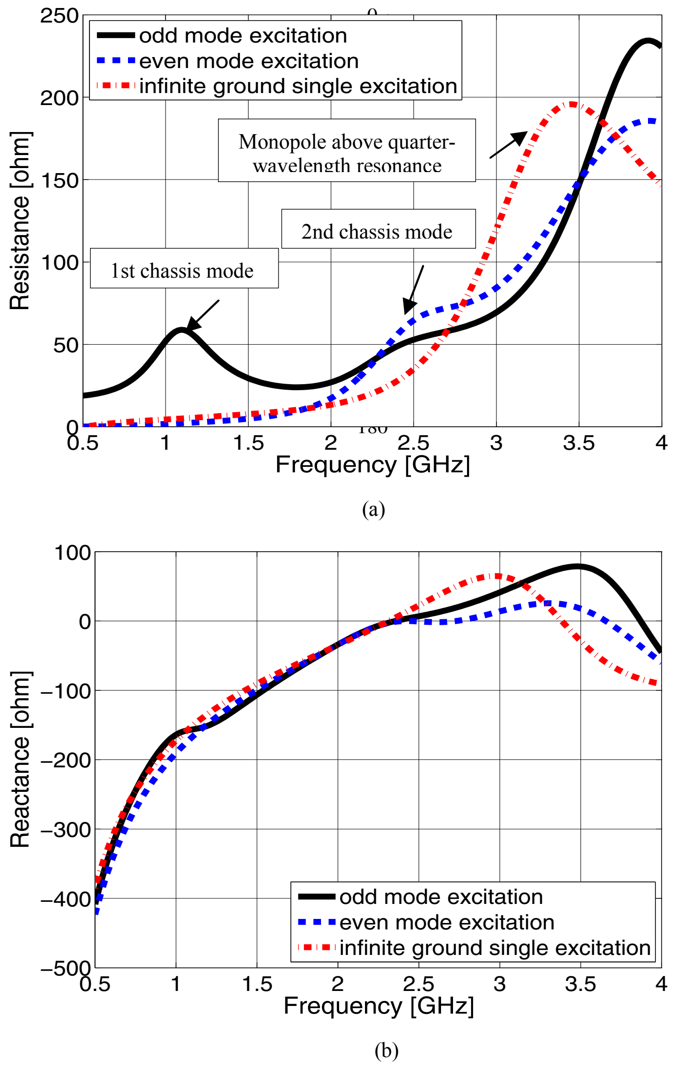


Fig. 3. Active input impedance of the simulated monopoles at *d* = 4 mm for odd and even excitation compared to single excitation for infinite ground case.

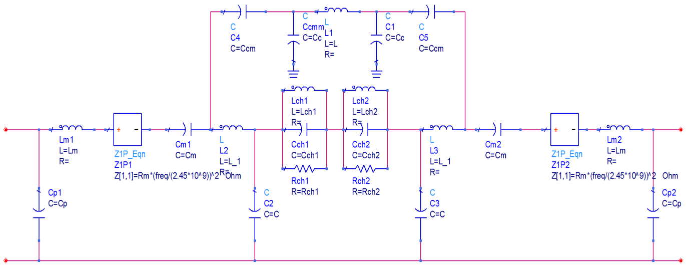
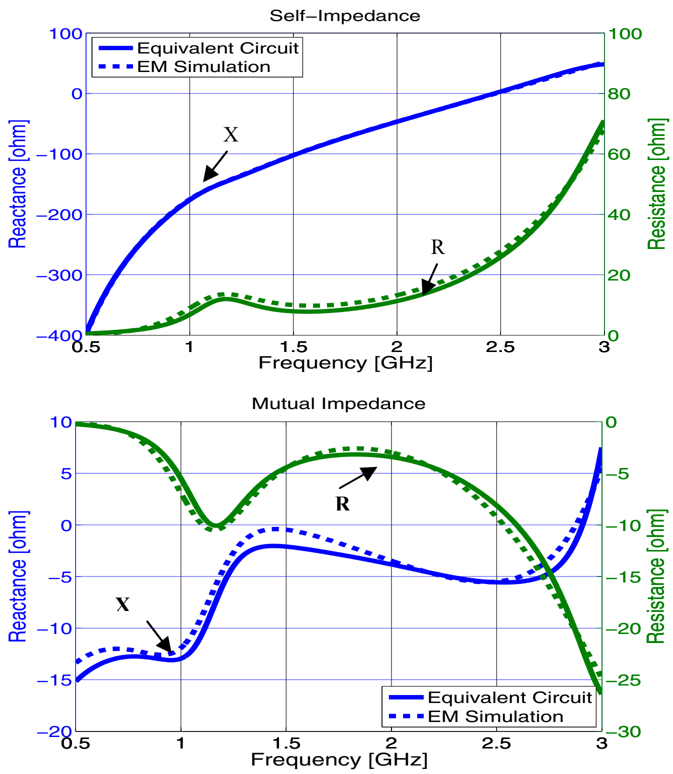
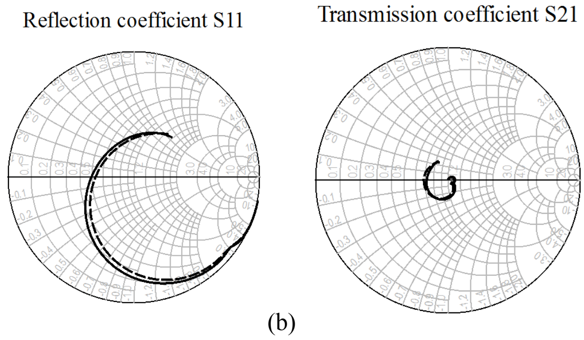


Fig. 4. Equivalent circuit model of two monopoles placed at the middle of the chassis short ends including two chassis mode resonators.

The resonant frequencies and corresponding quality factors calculated in [9] are used as initial values for the resonator equivalent circuits. Using the Advanced Design System (ADS) simulator, the susceptance or reactance slope parameters, the resonant frequencies and Q-factors of the monopole elements and chassis modes were optimized aiming to achieve best agreement between EM-simulation and circuit simulation. Good agreement between results for the monopole self and mutual impedances and refection and transmission coefficients from EM and circuit simulation has been achieved as shown in Fig.5 for the antenna structure in Fig.1 with *d* = 19.5 mm. For this element position, only the 1st chassis mode will be excited because the monopoles are placed where the current distributions for the 2nd and 3rd chassis modes are at their maximum. Consequently, the equivalent circuit for this situation emphasizes the 1st chassis mode resonator (high susceptance slope) in order to correctly model the impedance variation, as seen in Fig.5. For other element positions, e.g., *d* = 4 mm, as used in Fig. 1 and 3, both resonators may appear similar in admittance level.



(a)



(b)

Fig. 5. Equivalent circuit (solid) and EM simulation (dash) (a) self- and mutual impedance, and (b) reflection coefficient S11 and transmission coefficient S21 in Smith chart for two monopoles placed at *d* = 19.5 mm.

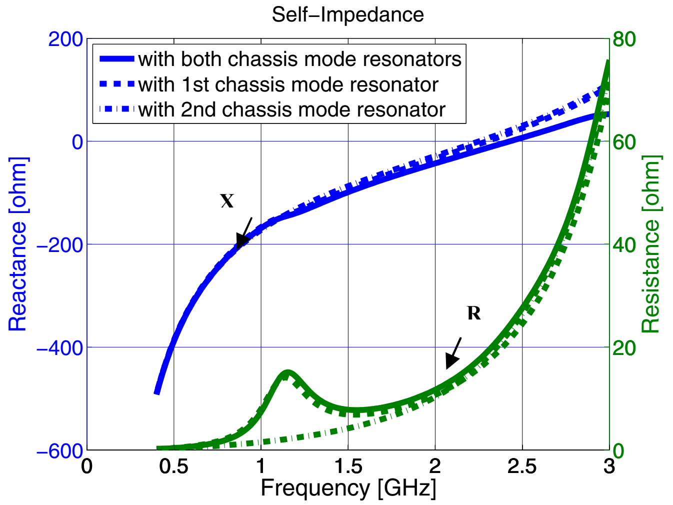
The resonator properties for the equivalent circuit model obtained from the optimization process are summarized in Table I. As the electrical length of the chassis increases due to implementation of the monopole elements on the chassis, its resonant frequencies decrease compared to the unloaded case [13].

The equivalent circuit model can be used to separate the effect of chassis modes on the self- and mutual impedances and their contribution to the total radiation. Fig.6 shows the effect of the chassis modes on the self- and mutual impedances with calculations performed by the circuit model with either both chassis mode resonators effective or one of the chassis mode resonators short-circuited. Below the monopole quarter-wave resonance, the self-impedance for the case of both chassis mode resonators effective is nearly the same as with the 1st chassis mode only (peak only seen at the chassis 1st mode resonance); this verifies the excitation of the 1st chassis mode, while the 2nd chassis mode approximately is not excited, but without the 1st chassis mode resonator, the peak in the self-impedance real part cannot be modeled properly. On the other hand, the mutual impedance real part dips and the reactive part steeply slopes at the resonance of the 1st chassis mode. At frequencies above the quarter-wave resonance of the monopoles we observe that both resonators are required to model the impedance behavior correctly.

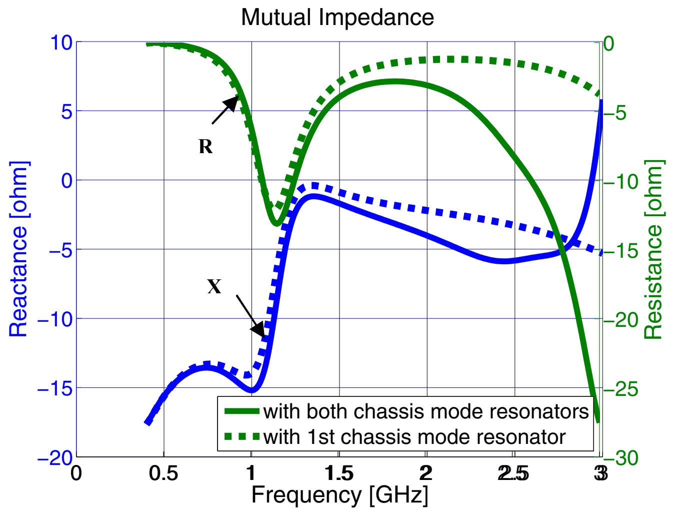
The percentage contribution of each chassis mode and monopole to the total radiation calculated by the equivalent circuit are shown in Fig.7.

TABLE I. RESONANT FREQUENCIES AND Q-FACTORS FOR LOADED AND UNLOADED CHASSIS

Chassis Modes	Loaded Chassis		Unloaded Chassis	
	Resonant frequency GHz	***Q-factor***	***Resonant frequency GHz***	***Q-factor***
1st chassis mode	1.21	1.8	1.26	2.3
2nd chassis mode	2.62	3.38	2.68	3



(a)



(b)

Fig. 6. Effect of chassis modes on the (a) self-impedance and (b) mutual impedance of two monopoles placed at d = 19.5 mm.

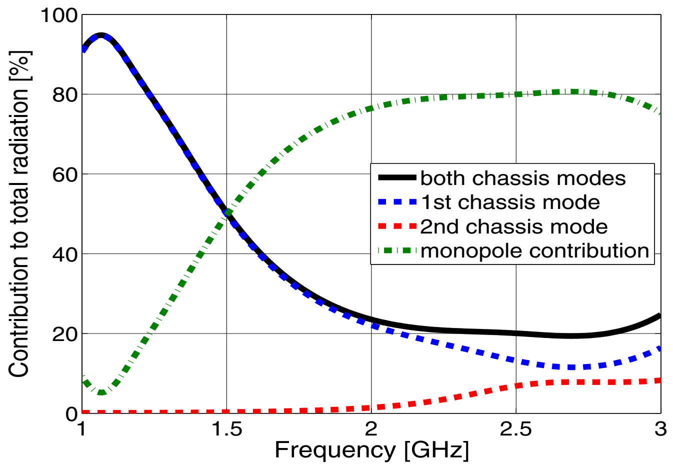


Fig. 7. Contribution of chassis modes to the total radiated power for two monopoles placed at d = 19.5 mm.

It can be seen that at the 1 GHz frequency range, 95% of the power is radiated by the chassis modes (mainly the 1st chassis mode); this is fully in agreement with the results obtained in [5], while at the 2.5 GHz frequency range, the 2nd chassis mode is less excited to contribute only about 10% of radiation power, same as the 1st mode. Thus, the contribution of the chassis modes to the total radiation doesn't exceed 20%, while the quarter wavelength monopole is the main radiator at the 2.5 GHz frequency range.

IV. Conclusion

In this paper, two monopoles placed on a rectangular ground plane were analyzed as couplers to excite the current distributions of the chassis modes and their simulated effect on monopole self- and mutual impedances were presented. An equivalent circuit model of two monopoles at the middle of the chassis short ends is proposed. Good agreement of the self- and mutual impedances and scattering parameters between EM simulation and equivalent circuit model was achieved. By the help of the circuit model, the mutual coupling and chassis modes coupling were analyzed. The effect of chassis mode excitation is seen as a peak in the self-resistance and as a dip in the mutual resistance variation. Through the equivalent circuit model it will be possible to separate between the effect of each chassis modes and the monopole mode. Contributions of chassis modes to the total radiation were calculated. The chassis is the main radiator at the 1 GHz frequency range, while at the 2.5 GHz frequency range, the contribution of chassis modes does not exceed one quarter of the total radiated power.

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