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Optimal Multiple Antenna Design for Compact MIMO Terminals with Ground Plane Excitation

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ABSTRACT: The compactness of mobile terminals complicates the design of multiple antennas, since coupling among the antennas increases when they are placed in proximity of one another. While it is possible to mitigate coupling between closely spaced antennas, a tradeoff in bandwidth is required. In this paper, we highlight ground plane excitation as an additional dimension to consider in the design of multiple antenna terminals. This is because a compact ground plane, especially in mobile application, can interact with the antenna elements and contribute significantly to their radiation characteristics. Our results show that several design parameters, namely element locations, spacing between elements, and radiation characteristics of individual elements, must be jointly considered in order to achieve the optimal MIMO performance tradeoff for compact multiple antenna terminals.

INTRODUCTION

Implementing multiple-input multiple output (MIMO) technology with multiple antennas in both base stations and terminals is a key solution to increase the data rate of future wireless communication systems without sacrificing additional frequency spectrum and transmit power [1]. However, it also brings challenges for antenna design, especially in compact terminal devices such as mobile phones. For example, the performance of the multiple antenna systems as measured by metrics such as efficiency, bandwidth, diversity gain and capacity will generally deteriorate when the distance between the antennas becomes smaller [2].

Though a reduction in the coupling between the antennas can mitigate such performance deterioration, most of the existing decoupling techniques suitable for today's mobile terminals focus on relatively high frequency bands, including WLAN, DCS1800 and UMTS bands [2]. To our understanding, the main reason is that the mobile chassis (typically around 100 mm × 40 mm in size), which only functions as a ground plane for the antenna elements at high frequency bands, becomes the main radiator at the (low) frequency bands that are below 1 GHz [3]. This means that different antenna elements share the same radiator at the low bands, which increases mutual coupling (*e.g.*, as seen in the dual-antenna prototype in [4]) and further complicates any effort to decouple them. As a result, the influence of the mobile chassis is a critical design factor for multiple antenna systems at low frequency bands. However, nearly all existing studies of the impact of chassis on antenna design (*e.g.*, [5], [6]) focus their attention on single antenna design.

In this work, the theory of characteristic mode is used to analyze the interaction mechanism between the antenna elements and the mobile chassis. Useful insights are provided on how to achieve good isolation, efficiency, and capacity by varying the location of the antenna elements and taking advantage of the mobile chassis. The optimality of the compact multiple antenna design is also studied in terms of the performance tradeoff between bandwidth, efficiency and capacity with respect to the locations of the antenna elements, using a representative multiple antenna prototype.

CHARACTERISTIC MODE ANALYSIS

The characteristic (or eigen-) values (λ_n) and characteristic electric fields of a slot monopole on a chassis are obtained using the theory of characteristic mode [7] and illustrated in Fig. 1. The chassis, with the dimensions of a typical candybar-type mobile phone (100 mm × 40 mm), is modeled by a perfectly conducting board. Slots are etched in it to form a slot monopole antenna [8] (see Fig. 1(b)). The eigenvalues in Fig. 1(a) are numbered according to their resonances: The lower the resonant frequency, the smaller is the number. The zeroth eigenvalue (λ_0) denotes a non-resonance mode. It is observed that the first resonant frequency of the structure is 1.06 GHz, which is very close to the GSM900 band. Though not shown here, the corresponding eigenvalues are also obtained for the same chassis *without* the slot monopole, and they share similar trend as those in Fig. 1(a), though the case with the slot monopole has a lower first resonant frequency, due to the electrical length of the chassis being extended by the slot.

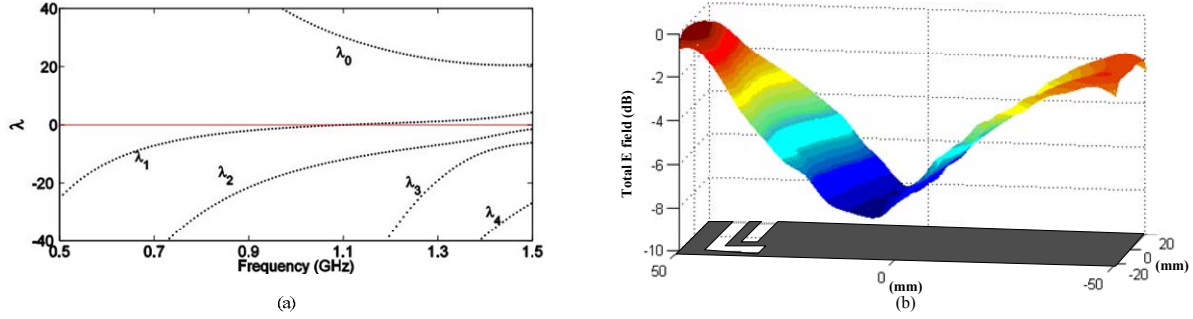


Fig. 1 (a) Eigenvalues against frequency for the chassis with a slot monopole. (b) Normalized magnitude of the total characteristic electric field 5 mm above the chassis with a slot monopole at 1.06 GHz. The chassis with the slot monopole is also shown.

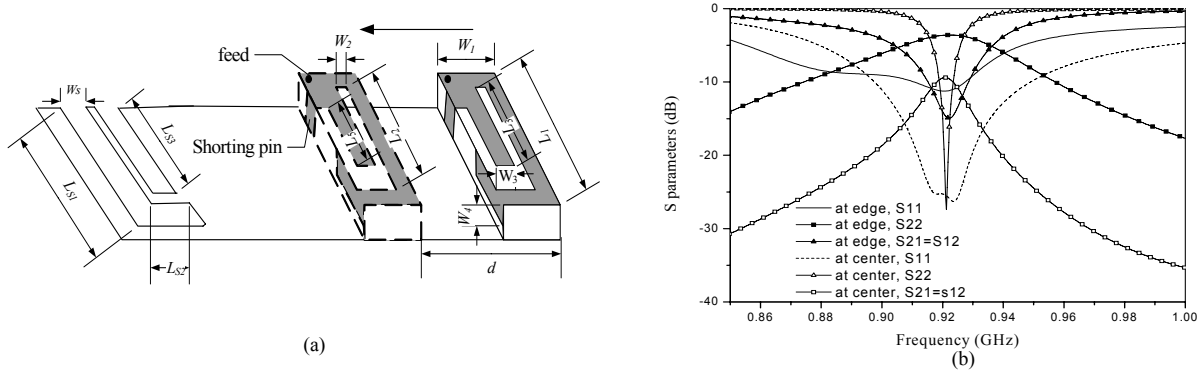


Fig. 2 (a) Geometries of the slot monopole and the PIFA. The dimensions are: $L_{S1} = 39$ mm, $L_{S2} = 6$ mm, $L_{S3} = 24$ mm, $W_S = 5$ mm, $L_1 = 40$ mm, $L_2 = 30.2$ mm, $L_3 = 26.2$ mm, $L_4 = 11$ mm, $L_5 = 22.8$ mm, $W_1 = 17$ mm, $W_2 = 4$ mm, $W_3 = 5$ mm, $W_4 = 4$ mm, $h = 6$ mm. (b) Simulated S-parameters for the monopole-PIFA case.

The magnitude of the characteristic total electric field corresponding to the first eigenvalue on a plane 5 mm above the chassis is evaluated at 1.06 GHz, and shown in Fig. 1(b). We only focus on the first eigenvalue in this work because the other eigenvalues contribute very slightly (less than 20%) to the current and the radiation characteristics of the structure. The field is normalized to the maximum value and presented in the dB scale. It can be observed that the position of maximum electric field is on the side of the slot monopole due to its strong resonance. The second maximum electric field is, however, on the opposite side of chassis, and the weakest electric field is almost in the center of the chassis. The trend of the total electric field is similar to that of a chassis without the slot monopole, which can be regarded as a flat half-wavelength dipole [3]. Thus, the chassis is efficiently excited. For the single antenna case, this insight reveals that the chassis is efficiently excited by an electric field near its shorter edges. For the two-antenna case, considering isolation, the best location for the other antenna should be in the region of the minimum electric field (the center of the chassis) so that the chassis radiation mode will not be simultaneously shared by both antenna elements. This principle will be further analyzed and verified by CST frequency domain simulations in the following section.

ANTENNA SIMULATIONS

The variation of the isolation level is studied here with respect to the locations of the antennas (*i.e.*, at the center or at the shorter edge) on the ground plane. The monopole-PIFA (M-P) case is chosen as an illustrative example. In the simulations, two antennas are integrated on the same chassis of dimensions $100 \text{ mm} \times 40 \text{ mm}$. The monopole antenna is fixed at the edge, and the PIFA is on the opposite edge *or* at the center, as shown in Fig. 2(a). The fixed planar slot monopole is the one used in the previous section. It is etched into the ground plane on a FR4 substrate (with permittivity of 4.7 and loss tangent of 0.015). The feed of the slot monopole is a microstrip line on the other side of FR4. The PIFA is slightly tuned for good impedance matching at each of its two locations.

The simulation results are shown in Fig. 2(b). It is interesting to note that, when the PIFA is moved to the center from the edge (*i.e.*, the two antennas become closer), the isolation is improved. This phenomenon contradicts the common knowledge on the relationship between antenna separation and port isolation. However, this situation can be explained

by the characteristic mode analysis in the previous section. When the two antenna elements are at the two edges of the chassis, they both excite the chassis efficiently. Thus, the mutual coupling not only comes from the field in free space and the conventional ground plane current, but mainly from the radiation of the shared chassis. One should also keep in mind that the chassis mode excitation modifies the radiation characteristics of the excited element. Thus, in this setup, angle and polarization diversities can hardly be achieved. When the PIFA is moved to the center, the chassis is not efficiently excited by the PIFA. The chassis is utilized as a radiator only by slot monopole. Consequently, angle and polarization diversities can be more easily achieved for the edge-and-center placement, which enhances the isolation. Isolation of over 10 dB is achieved for the edge-and-center placement, which is arguably low enough for practical low frequency band applications. In addition, the antennas are easy to design and tune, since neither decoupling circuit nor lumped elements are needed.

Rather than using only the slot monopole at the edge, different antenna types, including frequently used folded monopoles and PIFAs (such as those in [4]), are also simulated. The trend of isolation enhancement is the same when the PIFA is moved away from the edge to the center location, which further confirms the strong influence of the ground plane effect.

TRADEOFF ANALYSIS

In this section, the performance tradeoff of multiple antenna terminals is studied with respect to different PIFA locations on the chassis. The PIFA is moved gradually from the edge to the center in steps of 5 mm. d (see Fig. 2(a)) is the distance from PIFA's present location to the edge. When PIFA is at the edge, $d = 0$ mm.

The relative bandwidth of the two antennas is shown in Fig. 3(a). Here, the relative bandwidth is defined as the ratio of the 6 dB impedance bandwidth to the center frequency. It is obvious that the bandwidth of the monopole antenna is much wider than that of the PIFA, and it is almost independent of the PIFA's location. This is one reason that we can use the monopole antenna as the main radiator. The relative bandwidth of the PIFA drops quickly when it is moved away from the edge, since the chassis no longer contributes significantly to the radiation of the PIFA. Due to the narrow bandwidth, PIFA can be used as an additional (or diversity) antenna for downlink MIMO operation (as suggested in [4]), which requires a smaller bandwidth.

The efficiencies of both antennas, including radiation efficiency η_{rad} and total efficiency η_{total} at the center frequency and the average total efficiency over a given bandwidth, are presented in Fig. 3(b). Basically, efficiencies of both antennas increase when the PIFA is moved from the edge to the center. The total efficiency is given by

$$\eta_{total} = \eta_{rad} (1 - |S_{11}|^2 - |S_{21}|^2). \quad (1)$$

When the PIFA is at the edge, the total efficiencies are relatively low for both antennas, due to strong mutual coupling (*i.e.*, large S_{21}). As the PIFA is moved away from the edge, the total efficiency of the monopole increases greatly, regardless of the bandwidth within which it is calculated. The total efficiency of the PIFA increases as it is moved towards the center of the chassis, if it is only measured at the center frequency. However, the trend changes when it is measured within the 30 MHz bandwidth, because of its narrowing impedance bandwidth with d (see Fig. 3(a)). Therefore, the optimal position of the PIFA can be different, depending on the efficiency bandwidth requirements.

Channel capacity is an important metric for evaluating the overall performance of multiple antenna systems. The average channel capacity over different bandwidths calculated under the equal power (EP) and water-filling (WF) conditions for SNR = 20 dB is presented in Fig. 3(c). The WF procedure is performed over the antenna elements at each frequency. The Kronecker model and uniform 3D angular power spectrum (APS) are assumed. There is no correlation between the (base station) transmit antennas, whereas the (terminal) receive antennas are correlated according to their radiation patterns and the 3D APS. The capacity is averaged over 10,000 i.i.d. Rayleigh realizations at each frequency. The channels are normalized with respect to the i.i.d. Rayleigh case, *i.e.*, the correlation, total efficiency and power (or efficiency) imbalance are taken into account in the capacity evaluation. As reference cases, the average capacities for the 2×2 i.i.d. Rayleigh channel with the EP and WF schemes are 11.29 bits/s/Hz and 11.32 bits/s/Hz, respectively.

It is observed that the largest channel capacity is achieved when $d = 40$ mm, due to the high isolation level and high efficiency of the monopole when the PIFA is at the center. Because of the PIFA's narrow efficiency bandwidth, the power imbalance becomes serious at frequencies away from the center frequency. This means that one antenna (or spatial channel) is not efficiently used, and thus the average channel capacity decreases when a larger bandwidth is considered. In general, the average capacity increases when the PIFA is moved to the center, though the advantage is less obvious with an increase in bandwidth. For the WF case, the power imbalance is accounted for in the transmit power allocation, so the channel is more efficiently used than in the EP case.

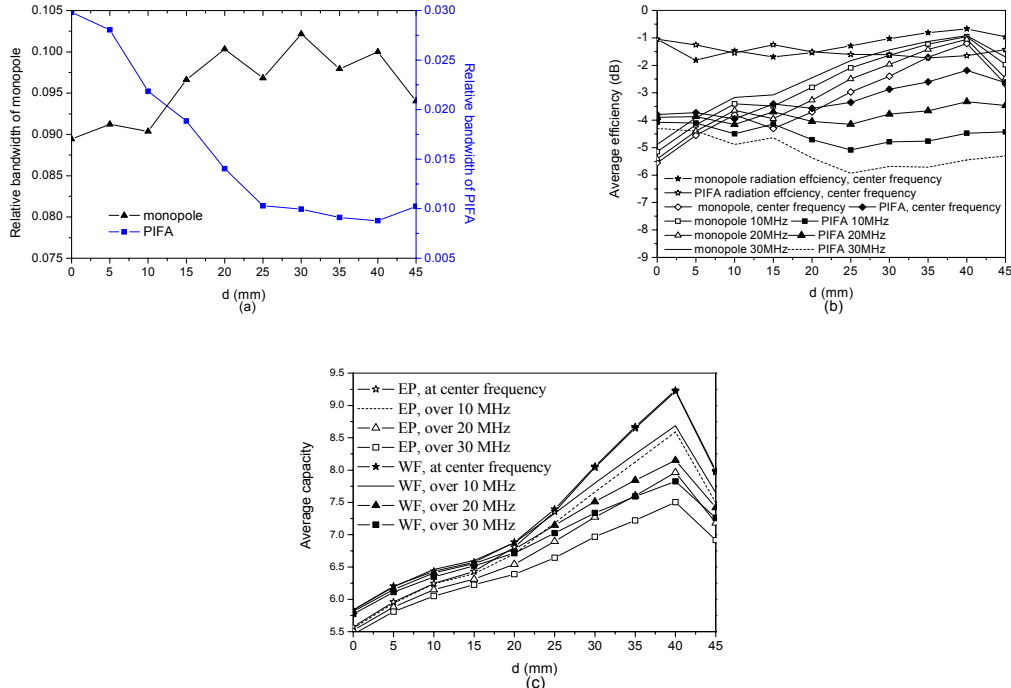


Fig. 3 Performance tradeoffs of the multiple antenna terminals in terms of (a) relative bandwidth, (b) average efficiency, (c) capacity.

CONCLUSIONS

In this work, multiple antennas on a compact mobile chassis working at 900 MHz are studied. The characteristic mode method is used to gain initial insights into proper locations of the multiple antennas on the chassis with respect to achieving good isolation. Isolation of above 10 dB is achieved in the monopole-PIFA combination by optimizing the location of the PIFA, without requiring any additional decoupling or matching network. A tradeoff study of antenna locations highlights that the element locations, spacing between elements and radiation characteristics of individual elements must be jointly considered in order to achieve the optimal performance for multiple antenna terminals. Experimental verifications have also been performed, but they are not included in this paper due to space constraint.

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