Evaluation of Two- to Eight-element Antenna Array in Mobile Terminal

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***Abstract*—An extensive evaluation of practical 3400-3600 MHz multi-element mobile antennas (MAs) have been performed in indoor propagation environments. The overall performances are assessed by means of average efficiency and Multiple-Input Multiple-Output (MIMO) capacity. The study covers both uniform and actual multipath environments with consideration of user's interaction. The number of antenna elements is varied from two to eight to analyze the impact of the number of antenna elements on the foregoing performance metrics. While in an uniform environment the maximum MIMO channel capacity is obtained with the eight-element antenna array, measurements in real scenarios show that the maximum MIMO channel capacity is in practice obtained with a lower number of elements.**

***Index Terms*—Multi-element antenna, mobile terminal antennas, MIMO systems, user interaction.**

I. Introduction

The performance of multi-element mobile antennas (MAs) can be most accurately characterized by taking the actual propagation environment into account [1]–[5]. Interactions between the user's hands, MAs and propagation environments have been evaluated in different multipath scenarios, such as a uniformly distributed channel [6] and pre-defined statistically distributed channel which emulates site-specific propagation environment [7], [8]. More examples in this area comprise the combination of channel and antenna-user interactions by different methods [2], [9], [10] or throughout extensive outdoor [11], [12] and outdoor-to-indoor measurement campaigns [1], [2]. Fair performance evaluation of different MAs in the same propagation environment was the main concern in earlier assessments [3], [4], [13].

As two antennas can be separated easily by more than $\lambda/2$ at frequencies above 3000 MHz for spatial diversity, question arises for how many radiation elements should be used in a compact mobile terminal [5]. Furthermore, fabrication of an antenna becomes more challenging as the frequency increases. Hence, it is essential to improve the current understanding on the design of MA in mobile terminal especially for the 3400-3600 MHz Long Term Evolution (LTE) band. Therefore, MA structure incorporated with large amount of antennas is considered.

In this work, we investigate the feasibility of incorporating more antenna elements in compact MAs and evaluate the designs in the absence and presence of the user's hand in the same set of measurement-based indoor-to-indoor propagation environments. Our actual scenario measurements show that having more radiation elements does not necessarily yield better performance.

II. Antenna Designs Under Study

Planar inverted-F antenna (PIFA)-based MAs are used as exemplary structures when investigating the effect of more radiation elements on MIMO channel capacity. They represents a typical internal handset antennas. The radiating elements are distributed evenly while the size of the terminal chassis is kept to 100 $\times$ 40 mm^2.

The configurations and dimensions of the PIFAs are shown in Figs. 1(c) and 1(d), respectively. The height between the ground plane and the radiating plate is fixed to 5 mm and the separation between the shorting and feeding plates is 1 mm. The radiating plate dimensions are kept the same, i.e., W $\times$ L = 9.8 $\times$ 9.8 mm^2 for all structures under study, except for the reduced size of element 3 to element 6 in '8-PIFA' with W $\times$ L = 9.0 $\times$ 9.0 mm^2. Thickness of the radiating element is kept at 1 mm. The location of both shorting and feeding plates (with the same 1 mm separation) are positioned so that the PIFAs meet the matching criterion, i.e., input reflection coefficients $|S_{\rm jj}| \leq -6$ dB. The PIFAs are modeled as perfect electric conductor (PEC). Concerning antenna placement, a design proposed in [14] was chosen for the two-element structure. To maintain MAs aperture symmetricity, antenna elements were incorporated evenly from two receiving antennas, $n_{\rm R} = 2$ until the chassis is densely covered, i.e., $n_{\rm R} = 8$. The structures has been simulated by using full-wave electromagnetic simulator, SEMCAD-X from SPEAG [15].

III. Evaluation Metrics and Methodologies

A. Average Efficiency

Since the investigated structures are solely modelled as PEC, the losses over the structure are negligible. To further simplify

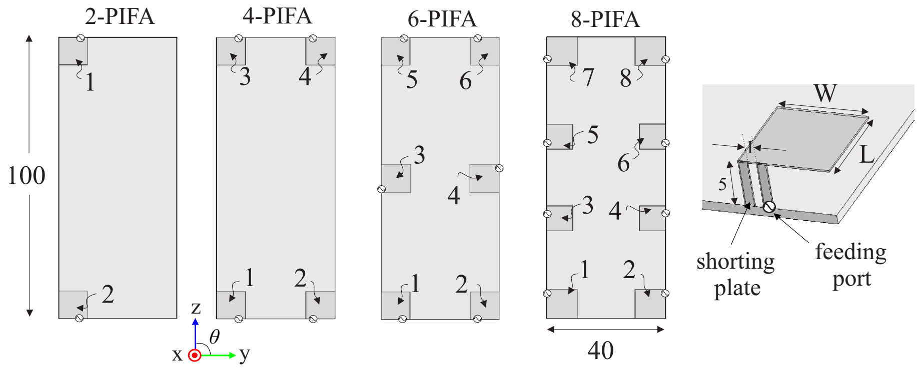

Fig. 1. PIFA-based MA configurations, namely as (a) 2-PIFA, (b) 4-PIFA, (c) 6-PIFA and (d) 8-PIFA. (e) Geometry of a single PIFA. All dimensions are in millimeter.

TABLE I
PARAMETERS OF THE MEASUREMENT ROUTES

Environments	**Mobile Locations, N_S**	**BS[1] Height**	**MS[2] Height**
Route A	1629	1.6 m	1.6 m
Route B	2028	1.6 m	1.6 m
Route C	2466	1.7 m	1.6 m

[1] BS = Base Station.
[2] MS = Mobile Station.

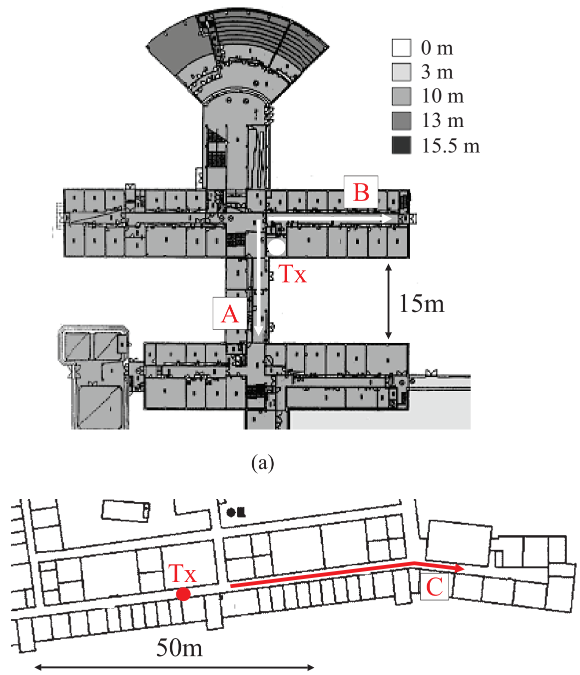

Fig. 2. Indoor mobile measurement routes: (a) obstructed Line-of-Sight (Route A) and non Line-of-Sight (Route B) scenarios, (c) Line-of-Sight (Route C) scenario. The circles represent base station locations while the arrows are mobile routes.

the evaluation; a single efficiency metric called average efficiency, e_av is used. This efficiency is obtained by taking the arithmetic average over all individual total embedded element efficiencies. That is,

$$e_\mathrm{av} = \frac{1}{N}\sum_{k=1}^{N}\frac{P_\mathrm{rad}^\mathrm{k}}{P_\mathrm{avs}^\mathrm{k}}, \tag{1}$$

where P_rad and P_avs denote radiated power and available power from the source, respectively.

B. Antenna Evaluation in Real Multipath Scenarios

Performance evaluation of the MAs is based on the principle of combining simulated radiation patterns with multiple plane waves from measured propagation channels. The tool is called Measurement-based Antenna TestBed (MEBAT) [3]. The radio channels used in this work were from an extensive double directional TKK Radio Channel Measurements database, previously measured at 5300 MHz frequency band.

The base station antenna and the arbitrary orientations of the antenna under test is based on the previous work in [5]. It is worthwhile mentioning that there were 24 antenna orientations for each MA and for each mobile location along the route. Channel matrices were computed for each orientation at all the mobile locations along the routes. Three scenarios in indoor measured propagation routes have been considered. For routes A and B, the transmitter was located in one room and for route C, the transmitter was located on a corridor. The maps of the measurement routes are shown in Fig. 2, and the parameters of the considered routes are given in Table I.

MIMO channel capacity for the i-th mobile location along the route, $C^{(i)}$ can be expressed as [3], [4], [13]:

$$C^{(i)} = \log_2\left[\det\left(\mathbf{I} + \frac{\rho}{n_\mathrm{T}}\frac{\mathbf{H}_\mathrm{AUT}^{(i)}(\mathbf{H}_\mathrm{AUT}^{(i)})^H}{\mathbf{P}_\mathrm{norm}^{(i)}}\right)\right], \tag{2}$$

where $\mathbf{I}$ is an identity matrix, ρ is the mean receiving Signal-to-Noise Ratio (*SNR*), n_T is the number of transmitting antennas and $()^H$ denotes the Hermitian transpose. MIMO channel matrix, $\mathbf{H}_\mathrm{AUT}$, includes the effect of the simulated antenna patterns at both base and mobile stations.

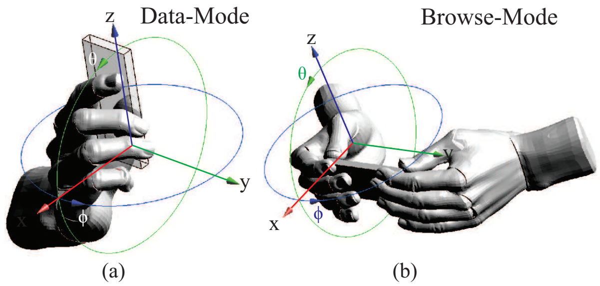

Fig. 3. Numerical model of hand grips in (a) 'Data-Mode' and (b) 'Browse-Mode', with 100 mm × 40 mm^2 mobile terminal chassis.

C. User's Hand Grips

In packet-based communications, the mobile terminals are likely in data transfer scenarios wherein a user holds the terminal with either one hand ('Data-Mode') or two hands ('Browse-Mode') [2], [8], [12]. The effects of hand grips on over-the-air performance were found to be very significant since a small shift or different positioning can lead to a substantial performance variation [16]. We presumably neglect the presence of other parts of the human body throughout our simulations. The relative permittivity of the hand and conductivity used at 3500 MHz were 24.2 and 1.90 S/m, respectively [17]. The two hand grips are illustrated in Fig. 3. In the case of MAs in the absence of hands, the scenario is referred to as 'No-Hand Mode'.

IV. Results and Discussions

A. Multi-element Antenna Characteristics

Scattering parameters of all studied MAs at 3400-3600 MHz is summarized in Table II. The maximum and minimum values of the impedance-matching and mutual coupling among all elements in the respective structure are listed. In the absence of the user's hand, all MAs have satisfied the impedance-matching criterion, $|S_{\mathrm{jj}}| \leq -6$ dB also with the worst-case mutual coupling of $|S_{\mathrm{jk}}| \leq -7.5$ dB.

In the presence of hands, detuning in resonance frequency (mismatch) and mutual coupling appeared. The mismatch was small for other studied MAs wherein the worst-case mismatch was $|S_{\mathrm{jj}}| \approx -4$ dB. In most investigated structures, the mutual coupling in the presence of hand was less compared to its absence. The average efficiencies for studied MAs also presented in Table II. In addition to acceptable multiport matching efficiency in the presence of hand, these results suggested that the absorption loss is the main effectual factor in decreasing the average efficiency.

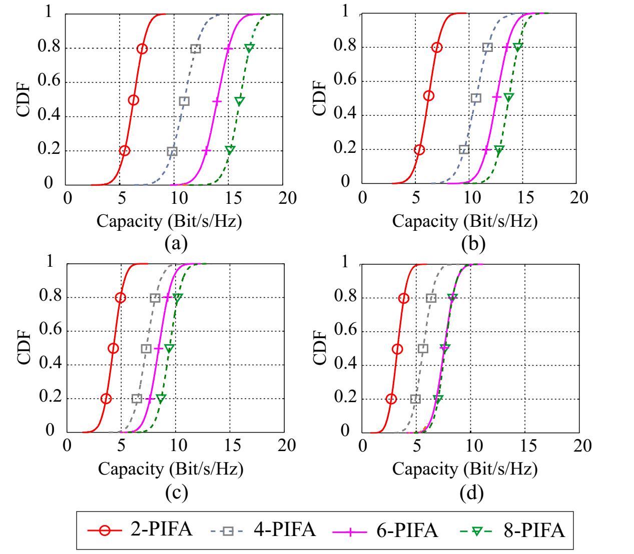

Fig. 4. CDFs of MIMO channel capacity ($\rho = 10$ dB) in uniform environment for (a) isotropic array, and PIFA-based MAs in (b) 'No-Hand Mode', (c) 'Data-Mode', and (d) 'Browse-Mode'.

B. Performance Comparisons in Multipath Scenarios

The performance of the studied MAs has been comprehensively evaluated for the combination of 24 antenna orientations per mobile location. The CDF at median level, i.e., CDF $= 0.5$ with the *SNR*, $\rho = 10$ dB, has been used for the evaluation of the MIMO channel capacity.

The CDFs of the MIMO channel capacities obtained for uncorrelated isotropic arrays and PIFA-based MAs in a uniform environment are shown in Fig. 4. The MIMO channel capacity was higher for the uncorrelated isotropic array (see Fig. 4(a)) compared to the deteriorated radiation performance of the PIFA-based MAs (see Figs. 4(b) to 4(d)). In the absence of hand, an improvement of 9.8 bits/s/Hz was obtained with the isotropic array compared to only 7.5 bits/s/Hz with the PIFA-based MAs.

In the presence of the user's hand, lower MIMO channel capacity of 5.1 and 4.3 bits/s/Hz were achieved in 'Data-Mode' and 'Browse-Mode', respectively. Overall, up to 43% reduction in MIMO channel capacity was mainly due to the power absorption by hands. The main mechanism was the reduced mean effective gain of the antenna system [1]. Figs. 4(c) and 4(d) show that the maximum number of antenna elements for achieving the best MIMO channel capacity in both hand grips is the '8-PIFA', as expected. The positions of the antennas and embedded element efficiencies are more

TABLE II
Minimum/Maximum Scattering Parameters and Average Efficiencies of Studied MAs at 3400-3600 MHz

MAs	No-Hand Mode			Data-Mode			Browse-Mode		
	Min/Max, $\|S_{\mathrm{jj}}\|$ (dB)	Min/Max, $\|S_{\mathrm{jk}}\|$ (dB)	e_{av}(dB)	Min/Max, $\|S_{\mathrm{jj}}\|$ (dB)	Min/Max, $\|S_{\mathrm{jk}}\|$ (dB)	e_{av}(dB)	Min/Max, $\|S_{\mathrm{jj}}\|$ (dB)	Min/Max, $\|S_{\mathrm{jk}}\|$ (dB)	e_{av}(dB)
2-PIFA	-12.4 / -10.7	-16.1 / -15.5	-0.14	-10.7 / -7.5	-20.5 / -19.6	-3.40	-4.4 / -4.0	-30.2 / -29.0	-5.95
4-PIFA	-12.2 / -10.4	-21.3 / -13.8	-0.30	-10.9 / -7.0	-26.4 / -18.3	-3.74	-4.5 / -4.3	-29.0 / -21.4	-6.18
6-PIFA	-24.3 / -10.8	-26.2 / -8.4	-1.08	-11.8 / -4.1	-47.3 / -12.8	-4.71	-36.5 / -4.7	-33.4 / -12.6	-5.98
8-PIFA	-16.5 / -11.2	-29.7 / -9.6	-1.84	-42.8 / -4.5	-50.1 / -9.7	-6.05	-9.5 / -4.6	-50.6 / -13.3	-7.56

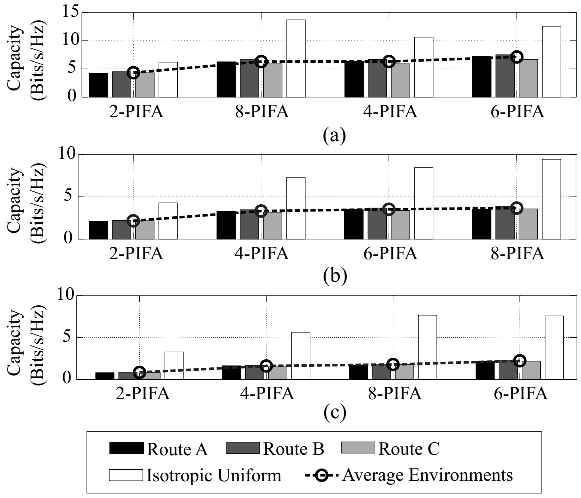

Fig. 5. Median CDFs of MIMO channel capacity ($\rho = 10$ dB) in uniform and nonuniform environments for PIFA-based MAs in (a) 'No-Hand Mode', (b) 'Data-Mode', and (c) 'Browse-Mode'. The structures are ranked according to the average of the three measured environments.

important for the maximization of MIMO capacity [1], [2], [5]. The reason is absorption losses associated with antenna elements is the dominant factor.

However, for the PIFA-based MAs with a nonuniform arrival of multipath signals, the number of antennas that achieves relatively the best MIMO channel capacity is bounded to fewer antenna elements compared to case wherein the antenna is evaluated in a uniform environment. Figs. 5(a) to 5(c) show the PIFA-based MAs that achieve the best MIMO channel capacity (at median CDF) in 'No-Hand Mode', 'Data-Mode' and 'Browse-Mode'; with '6-PIFA', '8-PIFA' and '6-PIFA' structure, respectively. It is shown that the performance of a multi-antenna system cannot be predicted reliably by the amount of incorporated antenna alone. Instead, MIMO channel capacity also depends on *SNR* level, the transferred signal power and the spread between the powers of the eigenvalues of the MIMO channel matrix [4].

V. Conclusion

In this work, four practical MAs have been extensively studied and evaluated in three indoor propagation environments. System level performance metric such as median MIMO channel capacity has been used. This metric comprises the effects of propagation environments and arbitrary mobile terminal orientations in both absence and presence of human hand. It is shown that having more radiation elements does not necessarily yield better performance. Based on the evaluated multipath propagation environments, multi-element antennas with less radiation elements is shown to perform better than in uniform environment. In order to reduce the complexity of the terminal design, having small amount of antennas and locating them at locations that are less obstructed by user's hand are of foremost important. It is worthwhile mentioning that these findings are limited to the antenna type-specific and specified operational frequency, i.e., at 3500 MHz. The conducted performance analysis will be an important finding in designing an MA system in a mobile terminal.

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