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Research Article

An Optimal Design of Multiple Antenna Positions on Mobile Devices Based on Mutual Coupling Analysis

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The topic of practical implementation of multiple antenna systems for mobile communications has recently gained a lot of attention. Due to the area constraint on a mobile device, the problem of how to design such a system in order to achieve the best benefit is still a huge challenge. In this paper, genetic algorithm (GA) is used to find the optimal antenna positions on a mobile device. Two cases of 3×3 and 4×4 MIMO systems are undertaken. The effect of mutual coupling based on Z-parameter is the main factor to determine the MIMO capacity concerning the objective function of GA search. The results confirm the success of the proposed method to design MIMO antenna positions on a mobile device. Moreover, this paper introduces the method to design the antenna positions for the condition of nondeterministic channel. The concern of channel variation has been included in the process of finding optimal MIMO antenna positions. The results suggest that the averaging position from all GA solutions according to all channel conditions provides the most acceptable benefit.

1. Introduction

With the rapid growth of mobile communications, the new services are driven by users' demand requiring more and more data rate. In this light, the use of multiple input multiple output (MIMO) has promisingly supported such a requirement by providing enormous capacity as well as maintaining spectrum efficiency. The concept of MIMO systems is to apply multiple antennas on both transmitter and receiver in order to achieve diversity and beamforming gains [1, 2]. The greater number of antennas used, the more benefits are obtained. For mobile communications, the main concern of applying MIMO systems is on the size of mobile device. In general, a small size is needed for users' comfortable grip. Therefore, the limited area on a mobile device is a key constraint for designing multiple antennas. As a result, the challenge is how to arrange multiple antennas under such a condition in order to achieve the best MIMO performance.

In [3], the design of multiple antennas on mobile handset to devise small antenna for mobile handset was presented. The modified PIFA and PCE antennas reducing the influence of PCB on the antenna were also proposed in [3]. In [4], the modified PIFA antennas were applicable for MIMO systems on mobile handset. The results indicated the increase of channel capacity by using the modified PIFA while the antenna configuration provided a low mutual coupling and low correlation coefficient. A 2×2 MIMO antennas built for mobile device was proposed in [5] by using a folded loop antenna with balanced feed and a parallel plane antenna with unbalanced feed. However, the studies in the literature do not search all possible antenna positions to gain the best MIMO performance.

Genetic algorithms (GA) [6, 7] are a class of searching techniques that use the mechanics of natural selection and genetics to conduct a global search of a solution space. The goal of the search is to find a good solution to the given problem. In the design process, a synthesis of antenna positions on a mobile device for MIMO systems is one of the most important goals to find the optimal antenna placement. Different positions will affect the capacity due to different constructs of mutual couplings between antenna elements. For this complex problem, GA has become an attractive approach to conduct a global search for a solution that satisfies specified performance criteria. In this paper, the optimal antenna positions specified by a use of genetic algorithms are determined by considering mutual coupling effect based on Z-parameter matching on all possible positions of a mobile device. The 3×3 and 4×4 MIMO systems are considered on the rectangular size of a typical mobile handset. Monopole and bow tie antennas are both constructed and measured in order to confirm the success of GA algorithm.

Moreover, from all works in the literatures, they concern only the method to find the arrangement of antennas while assuming the static channels or deterministic channels. In fact, the mobile users usually roam from one place to the other.

Hence, the channels are changing with time, which abates the optimality of the antenna positions obtained from the previous channel. The time variability of channels is the main key factor that should be involved in the design of MIMO antenna positions. In this paper, the concern of various conditions of channels is included in the consideration of MIMO antenna positions. The study reveals that the averaging solution can offer the optimal benefits.

The remainder of this paper is organized as follows. The next section presents the analysis of mutual coupling in MIMO system. Then the configurations of monopole and bow tie antennas are given in Section 3. In Section 5, the MIMO channel model is explained in order to find the MIMO channel capacity which is the main target for optimization. Section 4 provides the details of GA algorithm, and Section 6 describes the results and discussion on all experiments. Finally, the conclusion of this paper is given in Section 7.

2. MIMO System Based on Mutual Coupling Analysis

Figure 1 shows the basic concept of using MIMO systems for mobile communications. There are two approaches, base station to mobile station and mobile to mobile communications. Both approaches are influenced by spatial fading correlation and mutual coupling effect. For this paper, the main concern is the mobile to mobile link. The basic expression of MIMO systems with n_t transmit antennas and n_r receive antennas can be represented by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \qquad (1)$$

where $\mathbf{y}$ is the complex receive array output, $\mathbf{H}$ is a $n_r \times n_t$ channel matrix, $\mathbf{x}$ is a transmit array vector, and $\mathbf{n}$ is an additive Gaussian noise with a unit covariance matrix. Now we can focus on the direct impact of mutual coupling (MC) of the compact receive end on the MIMO channel $\mathbf{H}$ excluding other possible factors which would affect the channel performance. Consider n-port theory, the channel transfer function between transmit and receive arrays can be represented as [8]

$$\begin{bmatrix} \mathbf{V}_T \\ \mathbf{V}_R \end{bmatrix} = \begin{bmatrix} \mathbf{Z}_{TT} & \mathbf{Z}_{TR} \\ \mathbf{Z}_{RT} & \mathbf{Z}_{RR} \end{bmatrix} \begin{bmatrix} \mathbf{I}_T \\ \mathbf{I}_R \end{bmatrix}, \qquad (2)$$

where $\mathbf{V}_T = [v_{T1}, v_{T2}, \ldots, v_{TN}]^T$, $\mathbf{I}_T = [i_{T1}, i_{T2}, \ldots, i_{TN}]^T$ are the voltage and current at the transmitter, respectively. Similarly, $\mathbf{V}_R = [v_{R1}, v_{R2}, \ldots, v_{RN}]^T$, $\mathbf{I}_R = [i_{R1}, i_{R2}, \ldots, i_{RN}]^T$ are the voltage and current at the receiver. The $N \times N$ matrices $\mathbf{Z}_{TT}$ and $\mathbf{Z}_{RR}$ are antenna impedance matrices containing the self and mutual impedances of the transmitter and receiver, respectively. The matrix $\mathbf{Z}_{RT}$ stands for the transmission impedance from the transmit array to receive array. Similarly, $\mathbf{Z}_{TR}$ stands for the transmission impedance from the receive array to the transmit array. We fix voltage $\mathbf{v}_T$ at the transmitter and at the receiver we put loads. We denote the diagonal matrix of loads at the receiver by $\mathbf{Z}_L = \text{diag}[Z_{L1}, Z_{L2}, \ldots, Z_{LN}]$. Under these situation the currents and voltages at the receiver are related through the loads $\mathbf{V}_R = -\mathbf{Z}_L \mathbf{i}_R$. Plugging this into (2),

$$\mathbf{V}_R = (\mathbf{I}_N - \mathbf{Z}_{RR}\mathbf{Z}_L^{-1} - \mathbf{Z}_{RT}\mathbf{Z}_{TT}^{-1}\mathbf{Z}_{TR}\mathbf{Z}_L^{-1})^{-1}\mathbf{Z}_{RT}\mathbf{Z}_{TT}^{-1}\mathbf{V}_T, \qquad (3)$$

where $\mathbf{I}_N$ denote the N-dimensional identify matrix. The entries of the matrix $\mathbf{Z}_T$, $\mathbf{Z}_{RT}$, $\mathbf{Z}_{TR}$, and $\mathbf{Z}_{RR}$ are related to the distance between the corresponding antennas. It assumes that the reflection power from receiver is negligible. Then the matrix $\mathbf{Z}_{TR}$ is reasonable to be neglected which can cause the last term in the bracket of (3) to be consequently neglected, thereby obtaining

$$\mathbf{V}_R = \mathbf{Z}_L(\mathbf{Z}_L + \mathbf{Z}_{RR})^{-1}\mathbf{Z}_{RT}\mathbf{I}_T. \qquad (4)$$

Thus, we obtain a very simple and intuitive channel model which agrees with the models considered by antenna array designers [9]

$$\mathbf{H}_{mc} = \mathbf{Z}_L(\mathbf{Z}_L + \mathbf{Z}_{RR})^{-1}\mathbf{H}\mathbf{Z}_{TT}^{-1}, \qquad (5)$$

where the channel $\mathbf{H}$ can be any physical or statistical propagation model which properly reflects the relation of transmitter and receiver defined by $\mathbf{Z}_{RT}$

$$\mathbf{Z}_{RR}, \mathbf{Z}_{TT} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots \\ Z_{12} & Z_{22} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}, \qquad (6)$$

where Z_{ii} is the self-impedance of ith element and Z_{ij} is the mutual impedance between the ith and jth elements. In this paper, Z_{ji} is assumed to be equal to Z_{ij} according to reciprocity theorem [10] where the matching-impedance matrix Z_L is given as

$$Z_L = \begin{bmatrix} Z_{L1} & 0 & \cdots \\ 0 & Z_{L2} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}. \qquad (7)$$

3. Antenna Configurations

It is obvious in (6) that the mutual impedance Z_{ij} is the key parameter to determine the property of channel matrix in (5). Hence, this section describes how to achieve mutual

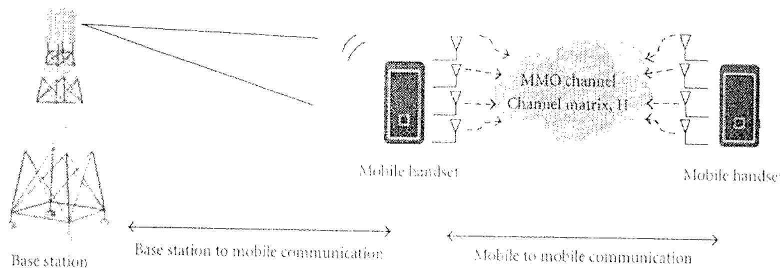

FIGURE 1: MIMO systems for mobile communications.

impedances for using in the GA algorithm. However, the mutual impedances mainly depend on the structure of antenna. In this paper, two types of antennas are employed as follows.

3.1. Monopole Antenna. Monopole antenna is one type of the wire antennas having the simplest structure for manufacturing. In addition, there is a close-form expression for calculating mutual impedances. The disadvantage of monopole antenna is on the space requirement of its structure. For mobile devices, it is impractical to install such a wire antenna. However, the mutual impedance expressions of monopole antenna are in the specific formulas which can help the optimization process much easier.

Consider an MIMO system with both ends being a self-conjugated matched system ($Z_L = Z_{11}^*$) in [11]. The real and imaginary parts of Z_{ij} [12] are given by

$$\begin{aligned} \mathrm{Re}\left(Z_{ij}\right) &= \frac{\eta}{4\pi}\left[2C_i(u_0) - Ci(u_1) - Ci(u_2)\right], \\ \mathrm{Im}\left(Z_{ij}\right) &= -\frac{\eta}{4\pi}\left[2S_i(u_0) - Si(u_1) - Si(u_2)\right], \\ u_0 &= kd_{ij}, \\ u_1 &= k\left(\sqrt{d_{ij}^2 + l^2} + l\right), \\ u_1 &= k\left(\sqrt{d_{ij}^2 + l^2} - l\right), \end{aligned} \tag{8}$$

where η is the intrinsic impedance of the medium, l is the length of the monopole, k is the circular wave number equal to $2\pi/\lambda$, d_{ij} is the distance in unit wavelength, and C_i and S_i are cosine and sine integrals.

3.2. Bow Tie Antenna. In order to confirm the proposed method of finding optimal MIMO antenna positions, the other antenna structure has to be undertaken. In this paper, the bow tie antenna is adopted because it is a microstrip antenna which can be easily implemented on the printed circuit board, and it requires a little space for installing. Although bow tie antenna seems more practical than monopole antenna, there is no close-form formula for calculating the mutual impedances. This causes the optimization process to be more difficult.

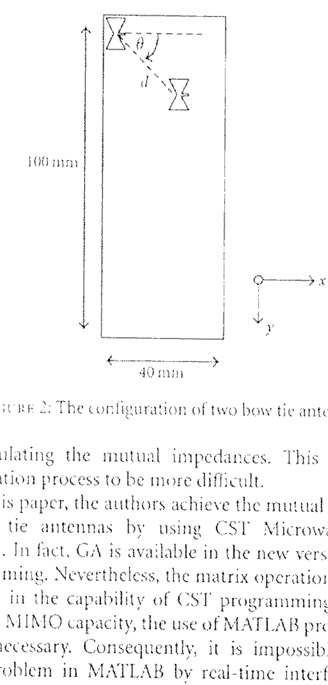

FIGURE 2: The configuration of two bow tie antennas.

In this paper, the authors achieve the mutual impedance of bow tie antennas by using CST Microwave Studio program. In fact, GA is available in the new version of CST programming. Nevertheless, the matrix operation is still not included in the capability of CST programming. Then, to calculate MIMO capacity, the use of MATLAB programming is still necessary. Consequently, it is impossible to solve a GA problem in MATLAB by real-time interfacing with CST programming. In order to response this constraint, all possible mutual impedances between two bow tie antennas are collected and stored in the specific file in which the MATLAB program can read those values for GA processing later. Figure 2 shows the configuration of two bow tie antennas which are designed and simulated by CST. The angle θ and distance d are varied to cover all possible positions of two antennas on the limited area of mobile devices.

3.3. Implementation of MIMO Antennas. The operating frequency band used in our experiments is in a 5.725–5.85 GHz range which supports the spectrum of IEEE 802.16e (mobile Wimax). For monopole antennas, the length of conductor is 53 mm and the size of a ground plane is 60 × 120 mm^2

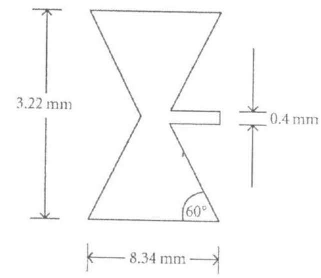

FIGURE 3: The dimension of bow tie antenna.

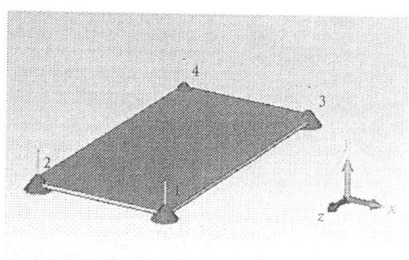

FIGURE 4: Example of antenna positions on a mobile device using CST for monopole antennas.

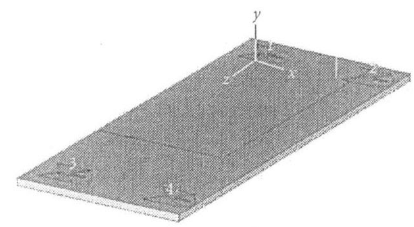

FIGURE 5: Example of antenna positions on a mobile device using CST for bow tie antennas.

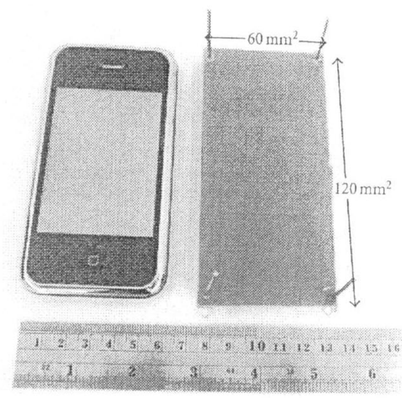

FIGURE 6: Example of monopole positions on a mobile device.

which is approximated as the size of iPhone device. For bow tie antennas, the dimension is shown in Figure 3 and the size of a ground plane is 40×100 mm^2 which is approximated as the size of Nokia device.

4. Genetic Algorithm

The examples of CST layouts for monopole and bow tie antennas are illustrated in Figures 4 and 5, respectively. Accordingly, the examples of four antennas mounted on PCB with dimension of mobile devices are shown in Figures 6 and 7. From measurements of both monopole and bow tie antennas, the return loss of expected frequency band is below -10 dB which is in an acceptable condition for implementation.

5. MIMO Channel Model

Since the channel capacity is determined by the radio propagation conditions of MIMO channel, characterization and modelling of MIMO radio channels for different environments are critical issues. Accuracy of the model used in design plays a vital role in the validity of predicted system performance. The channel H can be written as shown in Figure 1 [3]. There is an arbitrary number of physical paths between the transmitter and receiver [12]; the ith path having attenuation of a_i, makes an angle of departure Ω_{ti} with the transmit antenna array and an angle of arrival Ω_{ri} with the receive antenna array;

$$\mathrm{H} = \sum_i a_i^b \mathbf{e}_r(\Omega_{ri}) \mathbf{e}_t(\Omega_{ti})^*, \tag{9}$$

where

$$a_i^b := a_i \sqrt{N_t N_r} \exp\left(-\frac{j2\pi d_i}{\lambda_c}\right), \tag{10}$$

$$\mathbf{e}_r(\Omega) := \frac{1}{\sqrt{N_r}} \begin{bmatrix} 1 \\ \exp[-j(2\pi\Delta_r\Omega)] \\ \vdots \\ \exp[-j(N_r - 1)(2\pi\Delta_r\Omega)] \end{bmatrix}, \tag{11}$$

$$\mathbf{e}_t(\Omega) := \frac{1}{\sqrt{N_t}} \begin{bmatrix} 1 \\ \exp[-j(2\pi\Delta_t\Omega)] \\ \vdots \\ \exp[-j(N_t - 1)(2\pi\Delta_t\Omega)] \end{bmatrix}. \tag{12}$$

Also, d_i is the distance between transmit and receive antennas along path ith. The vector $\mathbf{e}_t(\Omega)$ and $\mathbf{e}_r(\Omega)$

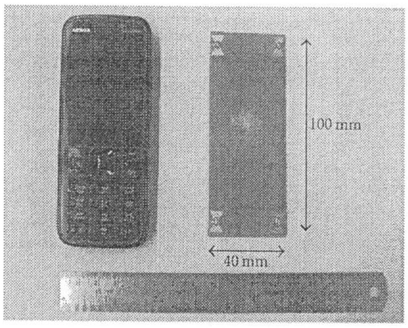

Figure 7: Example of bow tie positions on a mobile device.

are, respectively, the transmitted and received unit spatial signatures along the direction, λ_c is the wavelength of the center frequency in the whole signal bandwidth. Δ_t is the normalized transmit antenna separation, and Δ_r is the normalized receive antenna separation. Note that the authors use (9)–(11) as presented in [13].

Then, the MIMO capacity C using equal-power allocation can be expressed by [14]

$$C = \log_2 \det\left(\mathrm{I} + \frac{\rho \mathbf{H}_{\mathrm{mc}} \mathbf{H}_{\mathrm{mc}}^{H}}{N_t}\right), \qquad (13)$$

where ρ denotes the received signal-to-noise ratio (SNR) and $(\cdot)^H$ denotes the complex conjugate transpose.

There are many algorithms to find the best optimal solution for our problem. The exhaustive search is well known as the simplest algorithm. It verifies all possible combinations of optimized parameters and therefore can definitely find the best possible solution. But the time required for exhaustive search increases rapidly when the number of parameters increases. Instead, GA method is a search algorithm based on the mechanics of natural selection and natural genetics. They combine survival of the fittest among candidates with a structured yet randomized information exchange. This method uses genetics terms like fitness, population, generation, mutation, gene, and so forth. In contrast to random search methods, GA method is no simple random walk. It efficiently exploits historical information to speculate on new search points with expected improved performance. Its goal is to find a population of trading strategies with the best fitness (optimization criteria values). GA method combines the best characteristics of other optimization methods such as fast convergence that does not depend on properties of optimization criteria like smoothness and robustness. Figure 8 shows the flowchart of GA method and Figure 9 shows the example of GA fitness output versus iteration time (generation).

The objective function which determines the optimization goal is called the fitness function. The goal of this design in determining the design parameter is to solve for the optimal antennas positions. The design parameter is a distance (d_{ij}) between antenna elements. The maximum channel capacity can be achieved by considering the effect

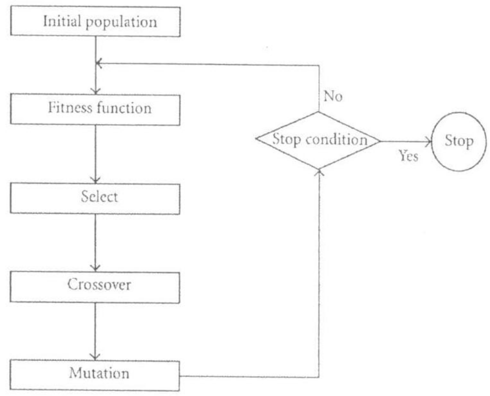

Figure 8: Flow chart of GA method.

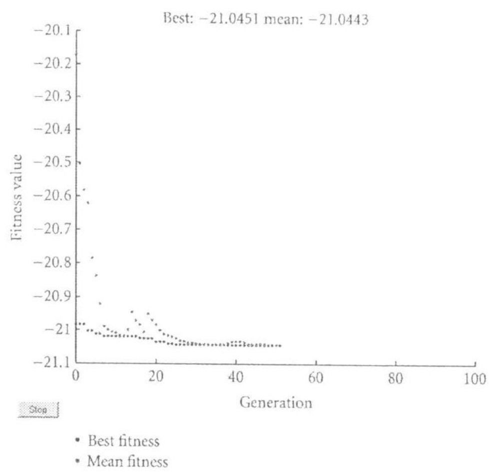

Figure 9: Example of GA simulations.

of mutual coupling between antenna elements. The fitness function can be determined by using MIMO capacity given in (13).

6. Results and Discussion

6.1. Deterministic Channel. The simulations of GA method to find the optimal antenna positions on a mobile device are undertaken by MATLAB programming. Basic parameters of evolving process are set as follows. The crossover and mutational probabilities are 0.8 and 0.2, respectively. The population includes 200 individuals. The number of generations is 150. Figure 9 shows an example of GA simulation. In this figure the optimal solution is achieved after 125 generations. This solution provides the coordination of either three or four antennas described as case (b) in Tables 1 and 2, respectively.

Table 1: Antenna positions of 3 × 3 MIMO system.

3 × 3 cases	Position of antenna coordinate (x,y): mm		
	Antenna (1)	Antenna (2)	Antenna (3)
(a) Corner			
:monopole	5, 5	55, 60	5, 115
:bow tie	6, 9	34, 50	6, 91
(b) GA			
:monopole	56, 8	19, 59	3, 117
:bow tie	33.5, 10.15	19.4, 50.25	7, 92.35
(c) Linear			
:monopole	30, 5	30, 31.2	30, 57.4
:bow tie	20, 9	20, 35.2	20, 61.4
(d) Random			
:monopole	17, 35	34, 48	15, 62
:bow tie	17, 35	34, 48	15, 62

Table 2: Antenna positions of 4 × 4 MIMO system.

4 × 4 Cases	Position of antenna coordinate (x,y): mm			
	Antenna (1)	Antenna (2)	Antenna (3)	Antenna (4)
(a) Corner				
:monopole	5, 5	55, 5	5, 115	55, 115
:bow tie	6, 9	34, 9	6, 91	34, 91
(b) GA				
:monopole	4, 7	48.25, 15	13, 97.75	45.5, 118.5
:bow tie	7.5, 11.25	31.15, 21	8.75, 82.5	30.5, 92.5
(c) Linear				
:monopole	30, 5	30, 31.2	30, 57.4	30, 83.6
:bow tie	20, 9	20, 35.2	20, 61.4	20, 87.6
(d) Random				
:monopole	17, 35	34, 48	15, 62	30, 76
:bow tie	17, 35	34, 48	15, 62	30, 76

The other cases detailed in Tables 1 and 2 are as follows: case (a) each antenna is located at the corners, case (c) a linear antenna array is spaced by a half wave length, and case (d) all antennas are randomly located. All cases are illustrated in Figures 10 and 11 for 3 × 3 and 4 × 4 MIMO systems, respectively.

For measurements, the antenna impedances are measured by Agilent *8722D Network Analyzer*. From Figure 12 to Figure 15, the results of case (b) provide the highest capacity than any other case. Both 3 × 3 and 4 × 4 results indicate a similar trend that antenna positions from GA optimization offer the best capacity performance.

For bow tie results, the antenna and mutual impedances are evaluated by using a CST Microwave Studio program. Then all impedances are collected into one file which MATLAB can read and use the data to find the optimal position. Both monopole and bow tie results reveal that case (b) provides the highest capacity in comparison with other cases. In turn, case (d) gives the lowest capacity. This confirms that the right antenna position is necessary to be designed in order to achieve a good MIMO capacity. The results in these figures are also point that the differences between corner and GA cases are not that much. This fact can be interpreted easily, since the larger the antennas' separation is, the more capacity we achieve [15].

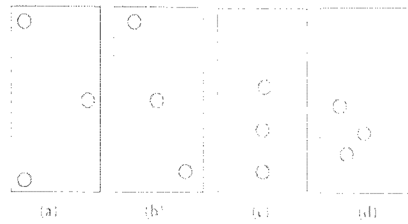

Figure 10: Four cases of three antenna arrangements on mobile device, for both monopole and bow tie antennas.

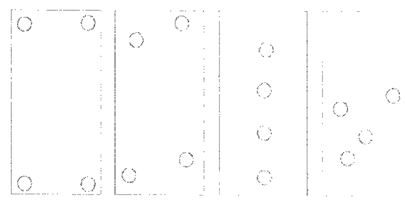

Figure 11: Four cases of four antenna arrangements on mobile device, for both monopole and bow tie antennas.

However, it is more difficult to locate the separation between antennas by eye decision for more complex areas or more number of antennas. Thus, the use of GA search method still provides the reliable solutions for those situations. Note that the results in this section are presented under the deterministic channel. Both monopole and bow tie antennas provide the similar trend within the same range of channel capacity. Hence, only monopole results are presented in the next section.

6.2. *Nondeterministic Channel.* The simulations of GA method to find the optimal antenna positions on a limited area are undertaken by MATLAB programming. The GA solution provides the coordination of four antennas which offers the best capacity under all possible positions on limited dimension. The channel fading environments are simulated by changing the conditions of angle spreads at transmitter and receiver. Figure 16 shows the amplitude of channel coefficients of four channel conditions as (i) 360° spread at transmitter, 360° spread at receiver, (ii) 360° spread at transmitter, and 60° spread at receiver, (iii) 60° spread at transmitter, 360° spread at receiver, (iv) 60° spread at transmitter, 60° spread at receiver. To confirm whether GA can find the best antenna positions, the authors compared the channel capacities between GA and other possible positions. The results in the previous section indicate that the solution from GA always offers the best capacity. However, 92

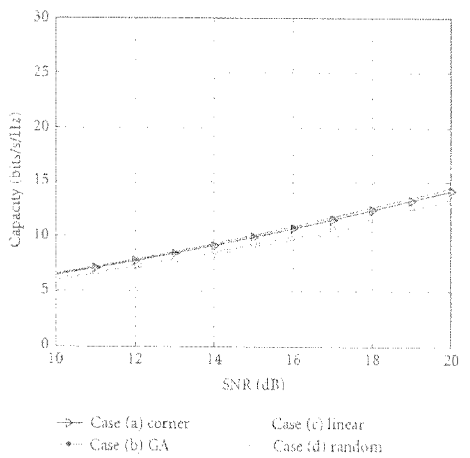

Figure 12: The monopole results of the average 3 × 3 MIMO capacity versus SNR in dB.

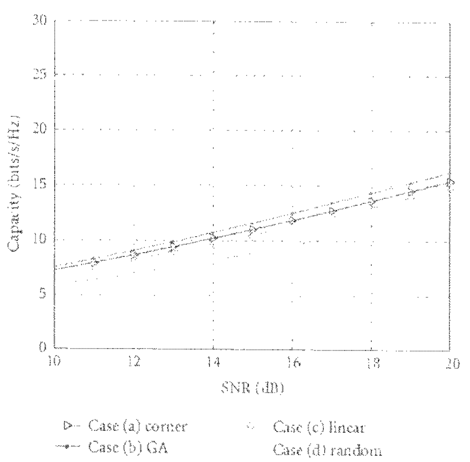

Figure 13: The bow tie results of the average 3 × 3 MIMO capacity versus SNR in dB.

this fact is based on the deterministic condition of channel which is the input of GA method.

The parameters used to simulate the channels are given as follows. The distance between transmit and receive antennas is 100 m. The operating frequency is set on 2.45 GHz and both Δ_t and Δ_r are equal to 0.5. There are 20 physical paths between the transmitter and receiver in which the scatters are surrounding within 10 meters of transmitter or receiver. Each path has a random attenuation a_i in a range of 0 to 1. Both arrival ($\Omega_{ri} := \cos\phi_{ri}$) and departure angles ($\Omega_{ti} := \cos\phi_{ti}$) are uniformly distributed within the range of angle spread.

In this section, the four channel conditions are considered and the optimal antenna positions obtained by GA are presented in Table 3. Please note that the positions in

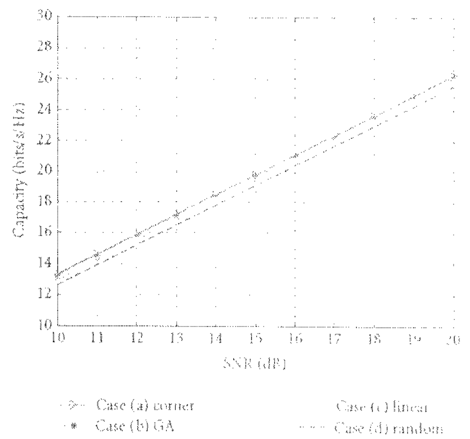

Figure 14: The monopole results of the average 4 × 4 MIMO capacity versus the SNR in dB.

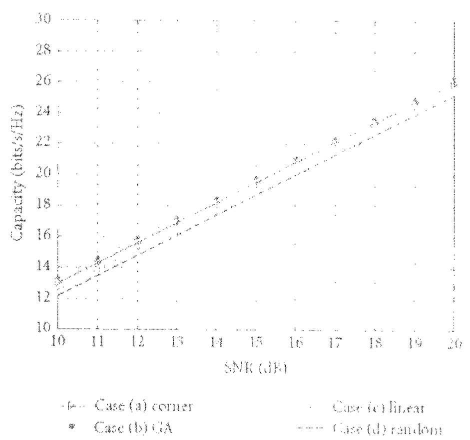

Figure 15: The bow tie results of the average 4 × 4 MIMO capacity versus SNR in dB.

Table 3: Antenna positions of 4 × 4 MIMO system obtained by GA in various channel conditions, for monopole antennas.

Channel condition	Positions of antennas, coordinate (x,y): mm			
	Antenna (1)	Antenna (2)	Antenna (3)	Antenna (4)
(i) 360-360	11.9, 14.1	59.9, 1.8	16.5, 97.1	46.8, 105.0
(ii) 360-60	16.5, 19.4	49.3, 12.5	19.9, 95.2	48.2, 97.8
(iii) 60-360	14.1, 16.7	52.5, 8.1	16.8, 99.4	44.2, 94.5
(iv) 60-60	16.4, 10.4	51.9, 12.4	15.6, 89.0	47.4, 87.6
Average	14.7, 15.1	53.4, 8.7	17.2, 95.2	46.7, 96.2

Tables 3 and 2 for GA are not the same. This is because the deterministic channel in the previous section is generated with the different random set of 360-360 fading channels. It

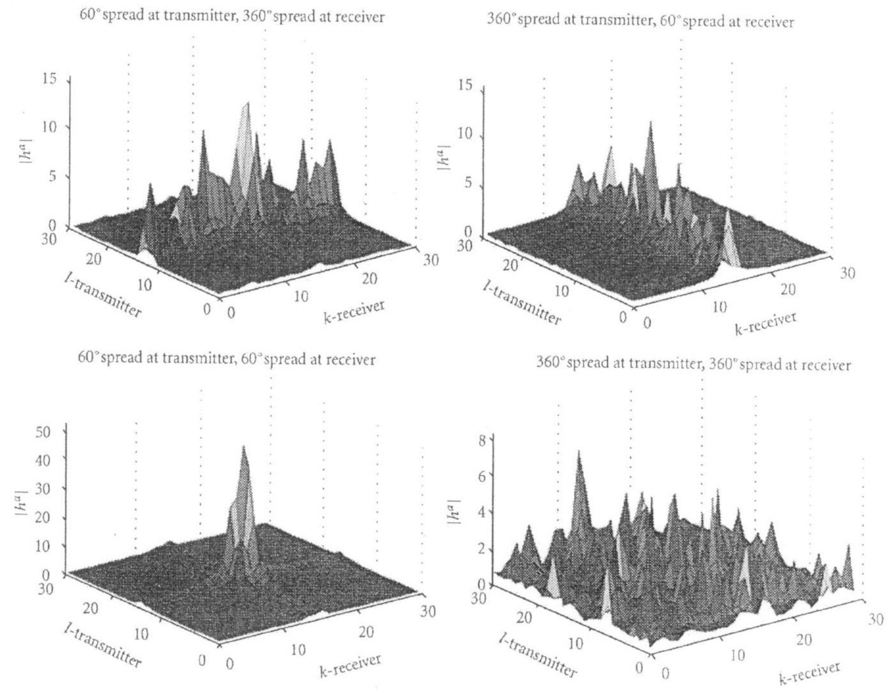

Figure 16: The amplitudes of fading channel coefficients.

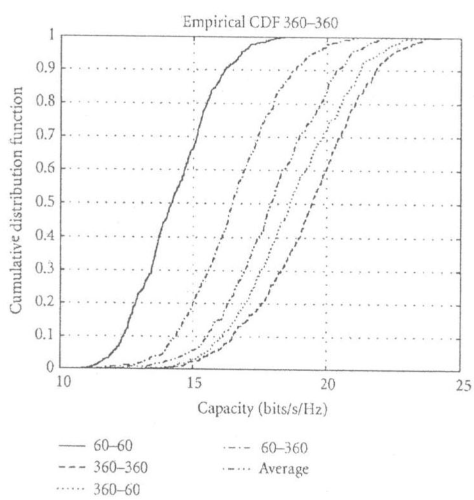

Figure 17: The cumulative distribution function of 4 × 4 MIMO capacity at channel condition (i).

is also noticed that the different channel conditions provide the different coordination of antennas. The results emphasize that to design the suitable antenna positions according to channel conditions is very important. However, the channels of mobile users are always changed by time and unpredictable. Hence, this paper proposes the averaging solutions to be used as the case of nondeterministic situation. By averaging all antenna positions from four channel conditions given in Table 3, the average solution is achieved. Next, the investigation on the average solution is undertaken.

Firstly, four antennas are manufactured according to all positions given in Table 3. Then, the antenna impedances including mutual impedances are measured by Agilent 8722D Network Analyzer. These impedances are the input parameters of MATLAB programming to calculate the channel capacity. Figures 17, 18, 19 and 20 show the cumulative distribution function of channel capacity when using all solutions given in Table 3 for channel condition (i), (ii), (iii), and (iv), respectively. The results indicate that the solution from the same condition of channels offer the best capacity in comparing with the others. However, the average solution still provides the high capacity with 0.2–1.7 bps/Hz less than the highest one and 0.8–5.1 bps/Hz more than the lowest one.

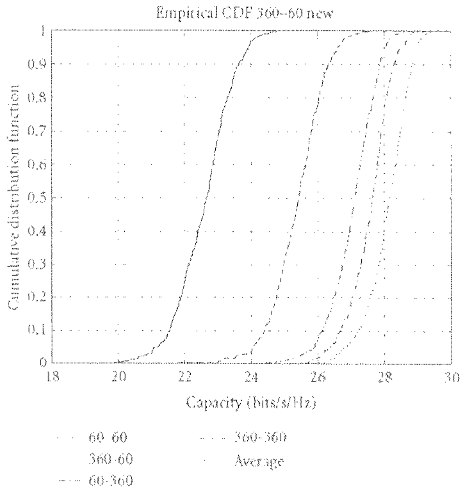

Figure 18: The cumulative distribution function of 4 × 4 MIMO capacity at channel condition (ii).

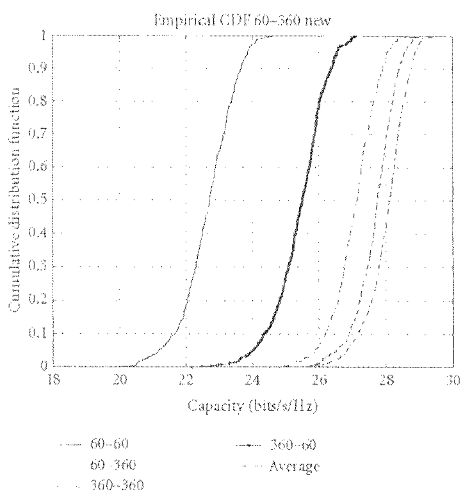

Figure 19: The cumulative distribution function of 4 × 4 MIMO capacity at channel condition (iii).

Therefore, the average solution should be appropriated to be practically used for implementing 4 × 4 MIMO system on mobile handset.

7. Conclusion

In this paper, the optimal antenna positions on a mobile device for MIMO systems are presented by using genetic algorithm. The success of proposed method is confirmed by both deterministic and nondeterministic channels. Also in the paper, two types of antennas are constructed and tested to

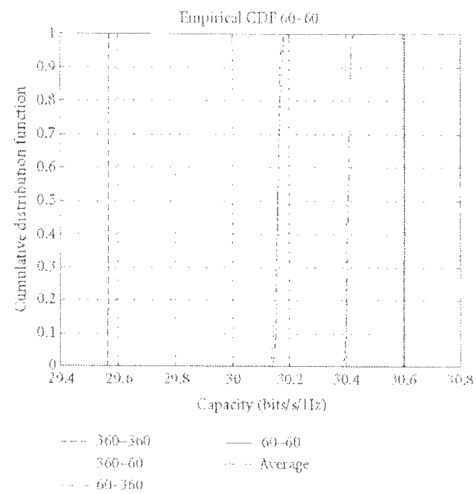

Figure 20: The cumulative distribution function of 4 × 4 MIMO capacity at channel condition (iv).

support the proposed concept for 3 × 3 and 4 × 4 MIMO systems. This investigation reveals an interesting antenna layout for implementing MIMO systems on a mobile device in practice. For nondeterministic channel, the experimental results indicate that the averaging approach of all solutions obtained from different channel conditions can provide the compromised benefits. Also, the paper suggests the MIMO designers to include the concern of channel conditions when MIMO antennas are practically manufactured for mobile handset.

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