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Fundamentals for a Pragmatic MIMO Performance Evaluation

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1. Introduction

The user's experience of a mobile communication system entirely depends on the performance of the bidirectional radio link between the base station (BS) and the handset. Each mobile network operator creates a system of linked BSs located to provide coverage of as large a physical area as possible. While the BS will typically be equipped with a relatively large high-gain antenna and a transmitter cable for delivering some tens of watts of radio frequency (RF) power, the handset relies on an antenna whose dimensions are severely constrained by those of the handset in which it is fitted, with typical maximum effective radiated power of 1 watt. With this said, the communication link quality, and hence the user's experience, can mainly get as good as the handset antenna performance.

Multiple Input Multiple Output (MIMO) has promised the potential for improved data rates and signal quality (Foschini, 1998). The promised improvement in the system's performance comes at the expense of added challenges, especially from the perspective of handset antenna design. An important aspect in the process of designing a multi-antenna handset is the proper evaluation of its performance. Although the antenna itself can be seen as a deterministic element, its performance becomes random once operated in a realistic, random, environment and in the presence of the operating user. The key questions in ensuring performance are: What are the parameters that need attention when designing the multi-antenna system and how should the evaluation of this system be done?

In this chapter the author discusses some aspects that are fundamental for a pragmatic evaluation of multi-antenna system. This becomes especially important to realize at the early stages of a design process when the multi-antenna system is evaluated entirely or partially through simulations.

2. The antenna as part of the propagation environment and of the handset

Let's start our discussion by defining the antenna element as the transducer element that is designed to transmit or receive electromagnetic waves. In other words, an antenna converts electromagnetic waves into electrical currents and vice-versa. The interaction of the propagation channel environment with the antenna is through the antenna complex field radiation pattern, which in turn is scaled by the antenna efficiency. On the other hand, the interaction of the RF front-end in the handset with the antenna comes down to the amount of signal that goes through the antenna and the amount of signal that reflects back from it

into the RF front-end. Therefore, when designing a system, it is necessary to consider the antenna as an integrated part of both the propagation channel environment and of the handset RF front end. Consequently, its evaluation should be as such.

Fig. 1 shows an illustration of this intergation. The blue parts show the handset elements while the yellow part shows the propagation channel environement. The antenna part of the diagram is shaded to reflect its integration into both the channel and into the handset. The evaluation of the multi-antenna system throughout this chapter will be based on the assumption illustrated in this figure.
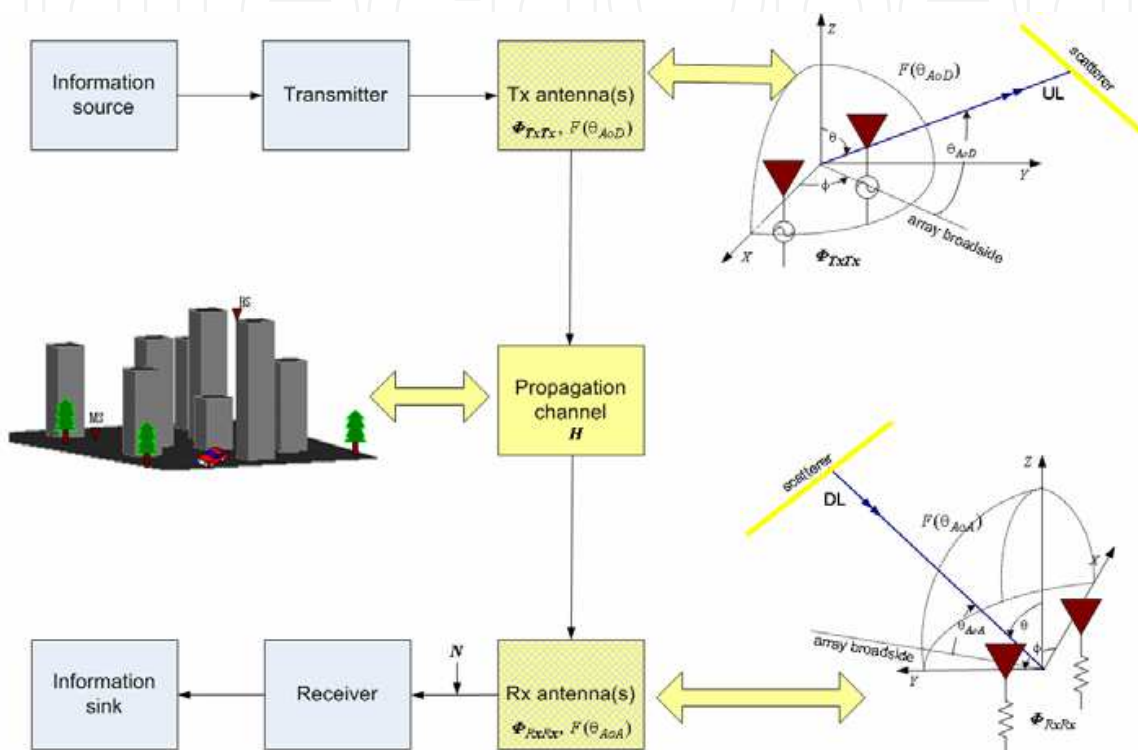

Fig. 1. Illustration of the antenna as a common element of the handset and of the propagation channel. The antenna can be tied to the channel through its coupling matrix $\boldsymbol{\Phi}$ and the field pattern F.

3. Evaluating the performance with partial Information

An advantages of evaluating an antenna system within a statistical channel model rather than a deterministic channel model is it allows for the incorporation of the random aspects that are likely to happen in a realistic communications situation (Ali,[1] 2008), (Ali[2], 2008), (Ali[1], 2009), (Kanj, 2008), (Kanj[1], 2008), (Lusina, 2008), (Lusina, 2009). As discussed later in the chapter, these random elements of the environment could facilitate knowledge of the parameter(s) that need attention during the design. In many evaluation scenarios reported in the literature, however, only part of the antenna information – the antenna information refers to the radiation patterns when discussing the interaction between the channel and the antenna – is included into the statistical channel model. The incorporation of partial information could very much lead to an inaccurate evaluation, as is illustrated below.

Fig. 2 shows the performance of a 2X2 PIFA-based antenna design when integrated into the spatial channel model (SCM), (Technical specifications group radio access network, 2006).

The channel settings are chosen as described in Table I. The effective radiation pattern of each PIFA is uploaded into the channel code in four different test scenarios: (i) using the default setting in the SCM, which assumes the upload of only one cut plane of the radiation pattern in the 0 deg evaluation; (ii) uploading five equally-spaced cut planes in the elevation; (iii) including eighteen equally-spaced in elevation cut planes; and (iv) uploading the whole 3D pattern, i.e., taking all 180 elevation cut planes. In the fourth test scenario (iv), a 3D-to-2D equivalent transformation is used (Kanj, 2009). The four test scenarios are simulated in five different orientations of the handset with respect to the servicing BS. The performance metrics are the correlation given in Fig. 2(a), the power transfer factor (Kanj, 2008) given in Fig. 2 (b), and the channel capacity given in Fig. 2(c).

Notice that the worst performance, i.e., higher correlation and lower power transfer and channel capacity, is seen when including the minimum antenna information with the single cut plane. The most optimistic performance is seen when more information is included with the five cut planes uploaded. After a convergence test, it is found that at least eighteen cut planes in the elevation plane are required to capture the majority of the antenna properties and have a performance equivalent to that when the whole 3D pattern is included. Although it may be argued that this performance is dependent on the particular antenna and scenario being examined, we would most likely come to the same conclusion that partial information would result in either a conservative or in an optimistic performance prediction. Therefore, the 3D antenna properties need to be included in its evaluation and not parts of it aforementioned.

Amongst the three performance metrics, the correlation metric seems to be the one that is the least affected by the partial antenna information. Therefore, at this point in our discussion, the channel power factor and the capacity seem to better reflect the antenna properties within the channel than the correlation values. The author will continue to examine the parameters that better describe the antenna performance as the chapter progresses; in an effort to answer the question: What parameters should be considered when designing a multi-antenna system?

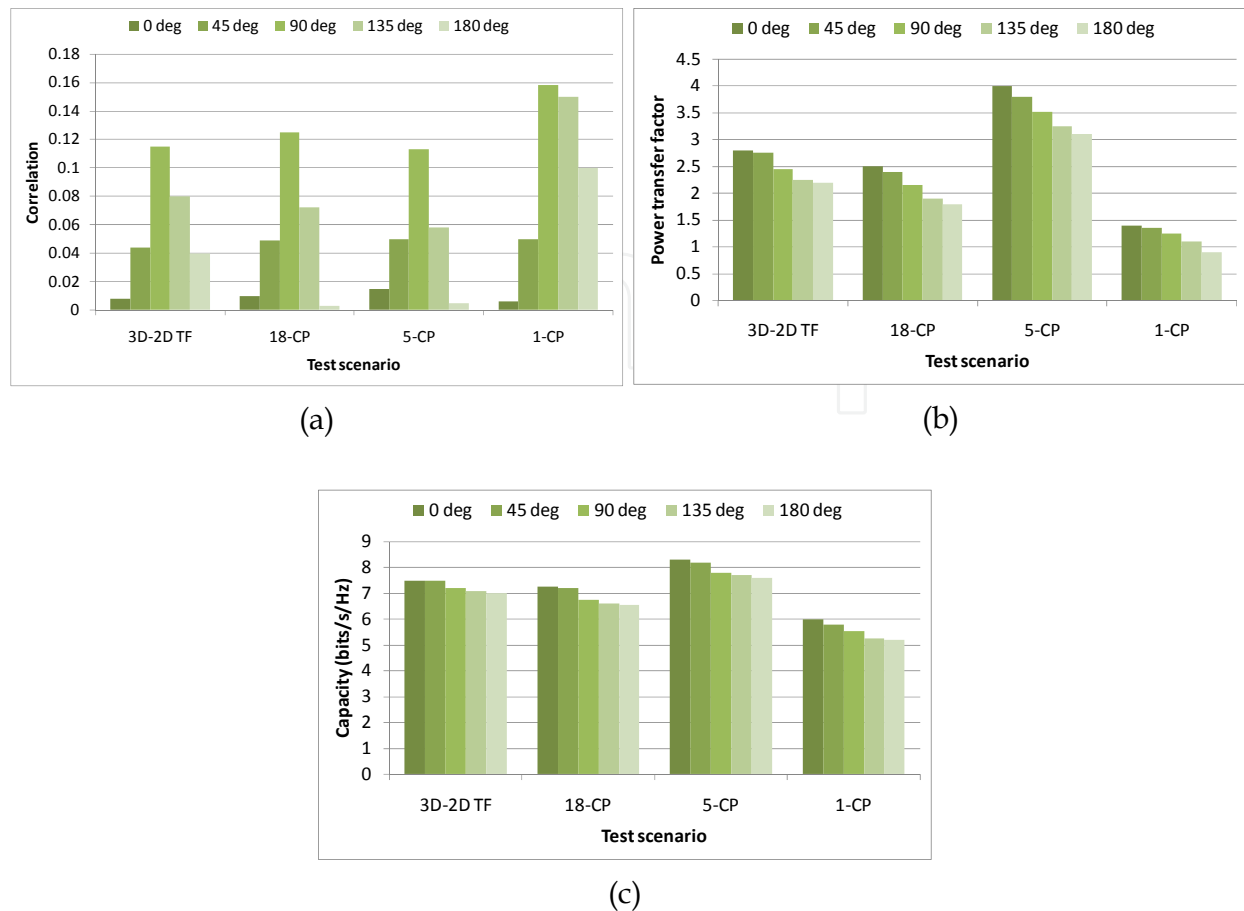| Parameter	Setting
• Carrier frequency	2 GHz
• MS height	1.5 m
• BS height	32 m
• BS to MS distance	100 m
• Realizations	10,000
• Antennas characteristics	Equivalent 2D of the embedded patterns, effective gain
• Scenario	Urban macro-cell
• Usage scenarios	Free space (FS), Voice (HH), Data (D), Head (H)

Table I. Channel simulation parameters

(a)

(b)

(c)

Fig. 2. Performance of a 2X2 antenna system when different percentage of the antenna information is incroporated into the channel: (a) correlation values, (b) power transfer factor, and (c) channel capacity

4. Propagation environment domination

As discussed in Section 2, the antenna is part of the communication channel and therefore the channel characteristics would significantly affect the overall multi-antenna performance. Even though the antenna itself is a deterministic element, its performance cannot be predicted in a generalized manner and any predictions would have to be made under certain assumptions of the propagation channel environment.

Let's investigate the propagation environment looking at the parameters that mainly affect the channel behavior, from an antenna stand point. These are the frequency, the scattering richness of the environment, the antenna polarization, and the presence of the user. For this, dipole antennas can be used where the channel matrix H, see Fig. 1, is constructed at three frequencies, 700 MHz, 950 MHz, and 1880 MHz, for the four investigated scenarios shown in Fig. 3. These are investigated in two cases. The first assumes a poor scattering environment and the second assumes a rich scattering environment, as shown in Fig. 3. The presence of the user's head is also noted in each of the described test scenarios. As the discussion is from the antenna view point, the un-normalized channel matrix is used in the analyses (Kanj, 2008), (Suvikunnas, 2007), (Pérez, 2003).

4.1 Channel capacity and power transfer

Channel capacity results for the described scenarios are given in Figs. 4-6, for both scattering environment assumptions. The first observation that can be made is that the channel capacities indicate a decline in the capacity as the operating frequency becomes higher when operating in a poor scattering environment. This is true whether the user is present or not. However, the same cannot be said for capacities in rich scattering environment scenarios, where a fluctuating channel capacity is measured. This can also be seen when considering the power transfer factor shown in Fig. 7. The highest power transfer is noticed at 700 MHz in Fig. 7(a) with the poor scattering environment while a fluctuating channel power is measured with the rich scattered environment; see Fig. 7(b).

Without loss of generality, with the channel being frequency-dependant one can expect that the performance of a system would vary with frequency. Therefore, there would be a frequency at which the performance trend of the multi-antenna system would go through a turning point. Let's try to apply this general statement on our defined test scenarios. Notice that the capacity at frequency 700 MHz shows that the performance is comparable whether the environment is a rich or a poor scattering one, and whether or not the user is present. The capacity is slightly higher with the rich scattering environment but the system performance is comparable. Also, the power transfer factor appears to be linearly associated with the channel capacity in the poor scattering environment. Therefore, at this frequency we can assume that the system performance is relatively independent of the scattering environment; i.e., the antenna system properties are dominant in the performance equation. On the other hand, as we go to higher frequencies, the channel power becomes less associated with the channel capacity in the rich scattering environment; therefore, the propagation environment characteristics are dominating the system performance. The turning frequency in the performance occurs at 1800 MHz in the poor scattering environment case, but occurs at a lower frequency (950 MHz) in the rich scattering case.

When the discussion comes to which polarization improves the multi-antenna system capacity for a spatial multiplexing MIMO system, by intuition, one might think of the cross-polarization choice. This has been indeed discussed widely in the literature (Chuang, 1994), (Ogawa, 2001), (Valenzuela, 2007). However, in many of these research investigations the user's presence, the environment scattering richness, and the operating frequency are not fully considered leading to conclusions that are based on partial information. From the defined experiments shown in Fig. 3 and the related discussion, it can be stated that a generalized statement on the best polarization choice cannot be made. At 700 MHz, the user appears as a smaller object to the propagating wave. Therefore, its effects are mainly shown in the power loss and do not disturb the propagating wave's characteristics much. Therefore, as the intuitive designer might plan, the x-polarized multi-antenna design is the better choice. This, on the other hand, becomes less true as the frequency of operation increases and as the channel scattering richness changes. As a matter of fact, the user presence becomes more effective as we operate higher in frequency where the channel properties become increasingly dominant. Therefore, a vertically polarization choice could yield higher channel capacity in the presence of the user when operating in a rich scattering environment. This effect could change significantly in a poorly scattered environment, as shown in Figs. 4-6 (a) and (b), respectively (Ali[2], 2009).
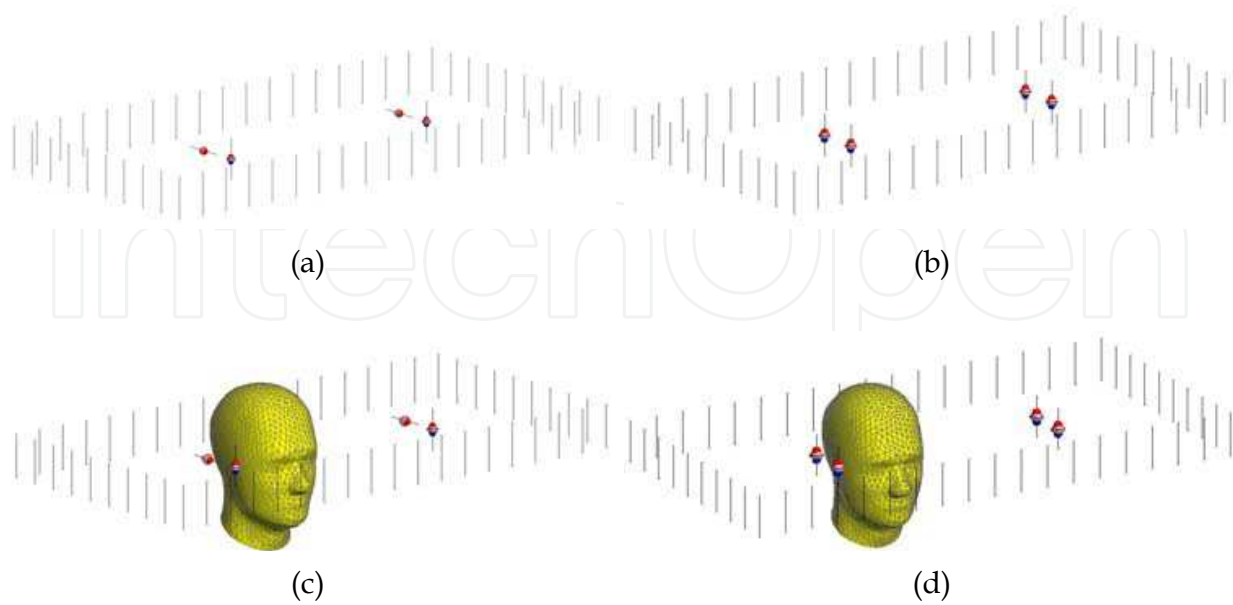
Fig. 3. Test scenarios for a 2×2 MIMO configuration: (a) vertically cross-polarized dipoles without the user head, (b) vertically co-polarized dipoles without the user head, (c) cross-polarized dipoles with the user head, and (d) co-polarized dipoles with the user head. Illustration not to scale.
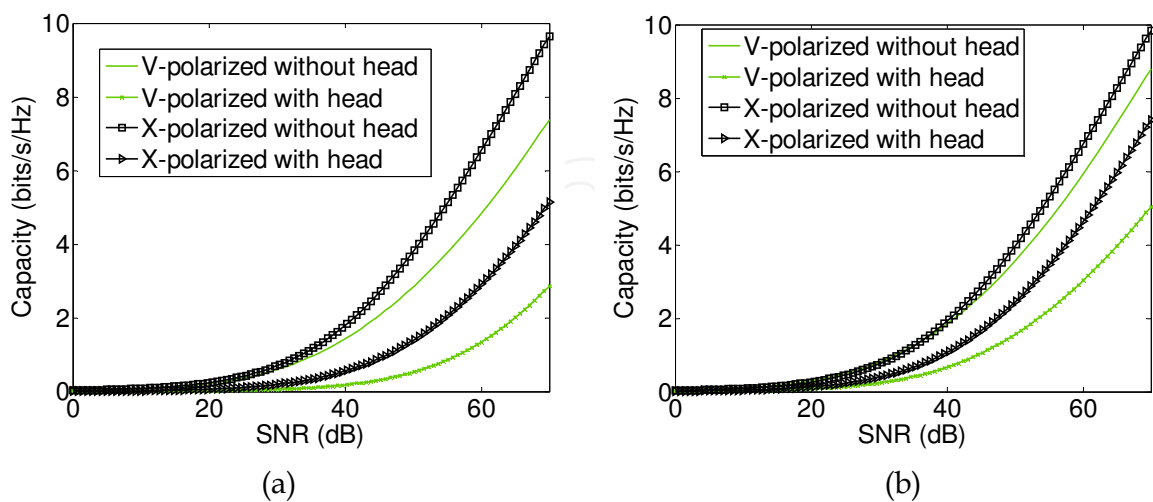

Fig. 4. Capacity for the different tested scenarios at 700 MHz: (a) poor scattering environment, and (b) rich scaterring environment
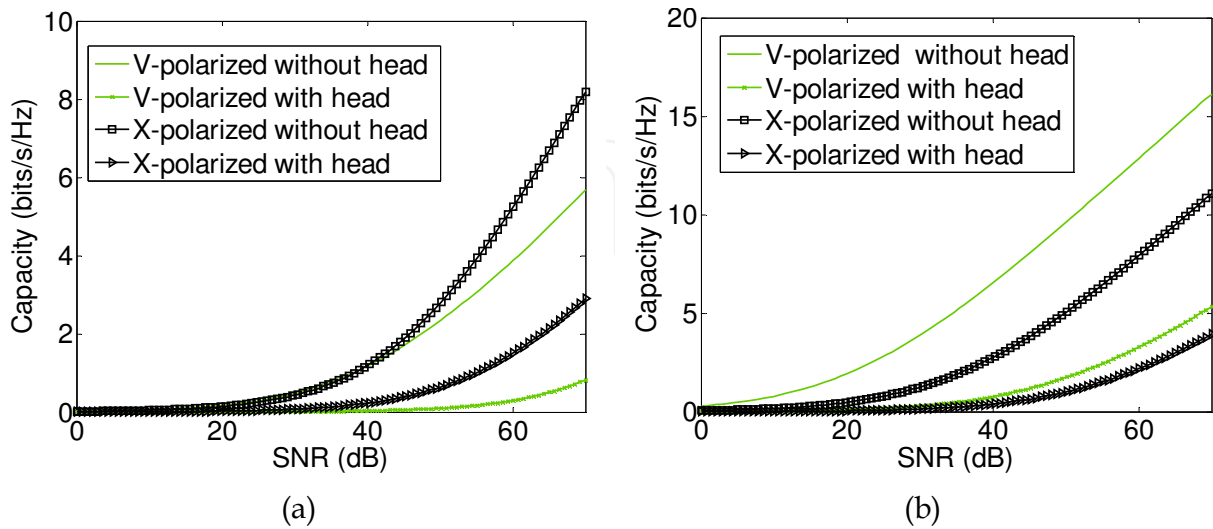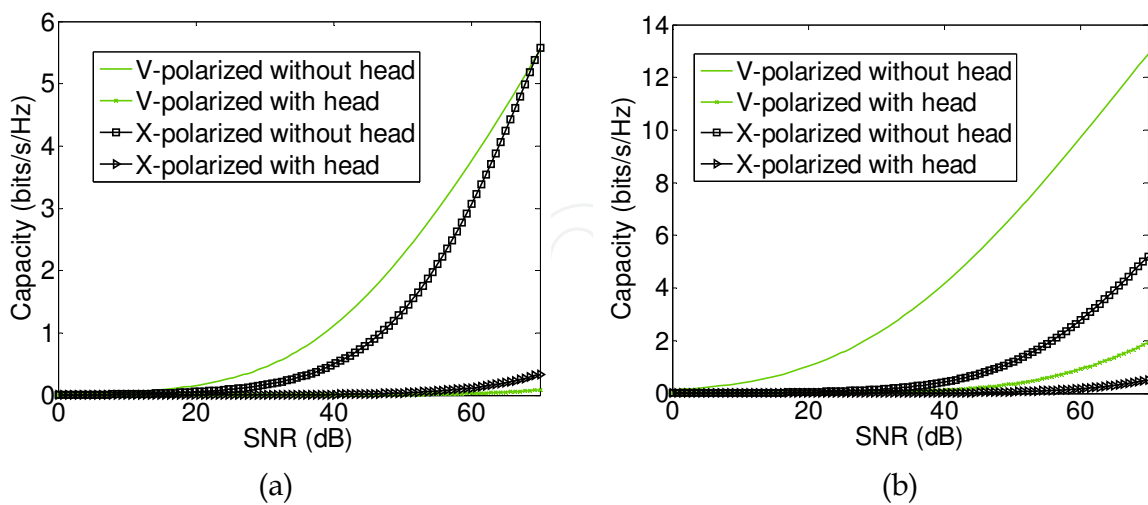
Fig. 5. Capacity for the different tested scenarios at 950 MHz: (a) poor scattering environment, and (b) rich scaterring environment

Fig. 6. Capacity for the different tested scenarios at 1880 MHz: (a) poor scattering environment, and (b) rich scaterring environment
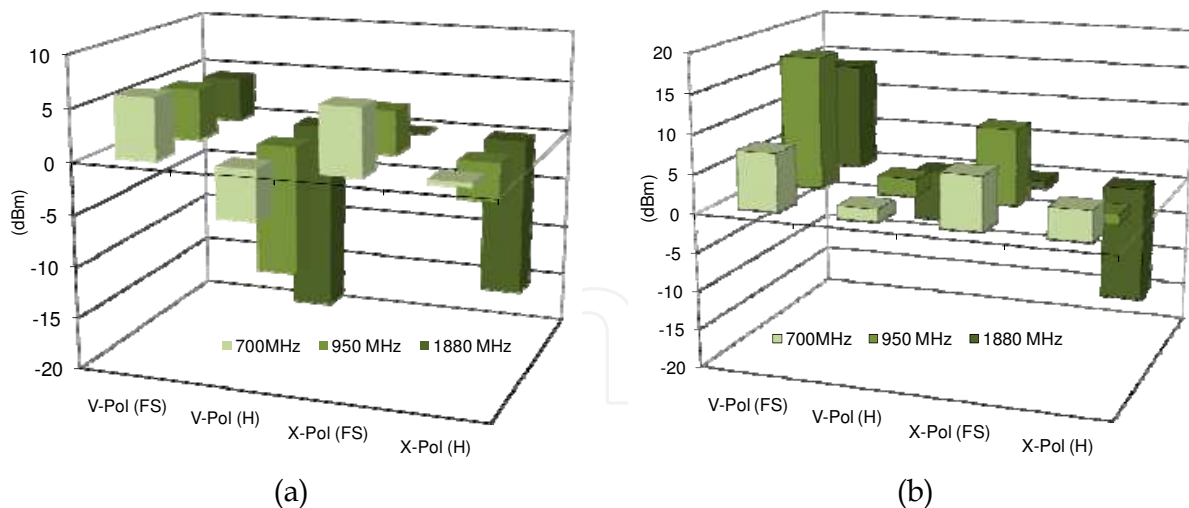
Fig. 7. Channel average power factor (dBm) at the three frequencies of operation for the four investigated scenarios in free space (FS) and with the user head (H) : (a) poor scattering environment, and (b) rich scaterring environment

4.2 Correlation

Since the environment is already included in the defined setting of Fig. 3, the correlation values computed here will be based on S-parameters measured at the terminals of each antenna (Blanch, 2003). Therefore, their values are expected to be, in general, low and reflect a deterministic evaluation. The involvement of the environment on the correlation would be included through the amount of signal reflected back into the system and the amount of signal leaked from one antenna terminal into the other antenna in a given handset configuration. These correlation values are shown in Fig. 8.

Examining the correlation values with the defined test scenarios comes with a general interesting observation. That is, regardless of the test scenario, the correlation values measure the highest at the lowest frequency of operation, 700 MHz. This can be expected due to the Omni-directional pattern type of the antennas at this frequency. The observation agrees well with the observation made before in Section 4.1 where the antenna properties were found to be dominating on the performance at this low frequency of operation and not the propagation environment.

Other observations can be made based on our defined test experiment but they cannot be said to be general. Looking at Figs. 8 (a) and (b), as the environment scattering richness changes from a poor scattering environment to a richer one, higher correlation values vary from the vertically polarized test scenario to the cross-polarized scenario in the absence of the user. The correlation values follow the same trend and alternate with frequency, as observed with the channel power values and capacity measurements from Section 4.1.

In the presence of the user, the lowest correlation values are seen in test scenario (c) where the antennas are cross polarized to each other, for both poor and rich scattering environments. This agrees well with the intuitive choice of choosing a cross polarization antenna configuration for improved system performance, which in this case is defined by the performance metric of the correlation values. However, the channel power factor and the capacity measurements given in Figs. 4-7 showed that this scenario performance is not necessarily the best. Hence, once again, evaluating the system performance having the correlation values as a main performance metric can lead to inconsistencies.
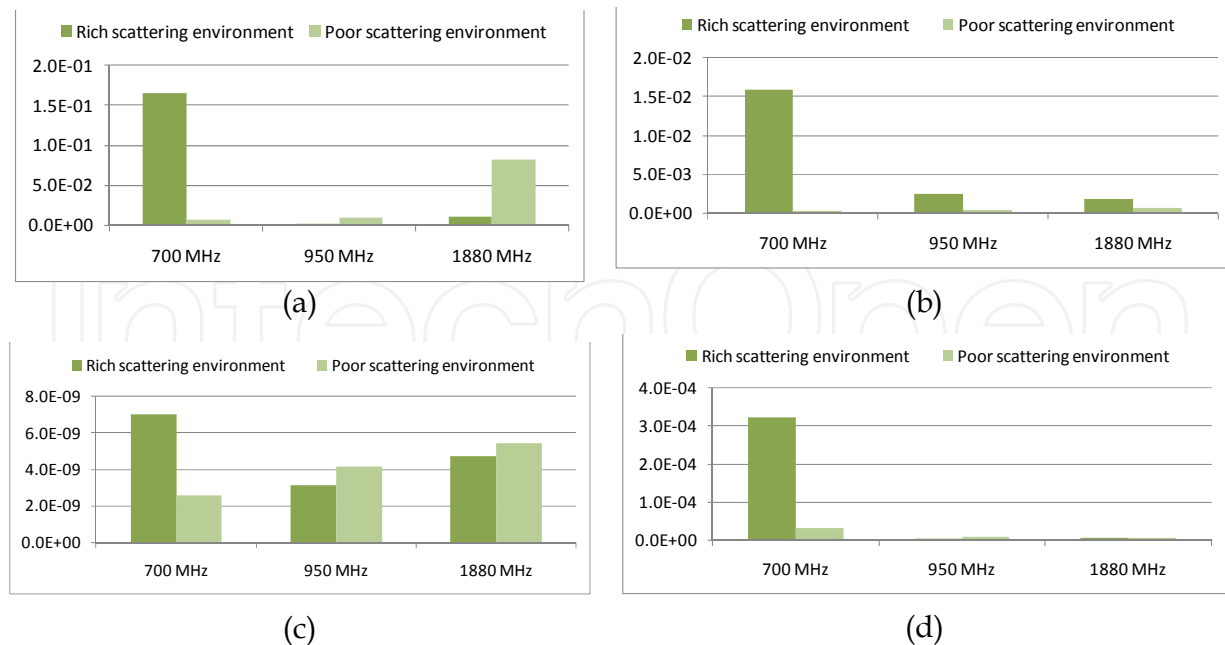
Fig. 8. Correlation values at different frequencies: (a) vertically co-polarized dipoles without the user head, (b) vertically co-polarized dipoles without the user head, (c) cross-polarized dipoles with the user head, and (d) cross-polarized dipoles with the user head. Calculations are based on (Blanch, 2003)

5. Handling of the antenna efficiency

A vital parameter in the communication system design is the antenna efficiency as this directly plays into the antenna link budget (Ali[3], 2008) (Aulraj, 2004), (3G Americas, 2010). The antenna efficiency describes how much of the signal provided to the antenna terminal is in fact being radiated to the destination. Of course, there is the orientation dependence factor that is described by the antenna directivity, but this quantity is tied to the efficiency and is scaled by it. The higher the antenna efficiency, the better the link margin, and the more tolerant the handset antenna is to changes in the environment. Additionally, there are other benefits from designing a high efficiency antenna as it would have a lower quality (Q-factor) value (Balanis, 1005) and hence can be expected to have less specific absorption rate (SAR) readings. This leads to the following question: How should the antenna efficiency be accounted for in the multi-antenna evaluation?

5.1 Evaluation setup

To investigate the proper handling of the antenna efficiency in multi-antenna system, the PIFA based antennas discribed in Section 3 are used agian here. The effects of the change in the efficiencies of these antennas on the link performance are emphasized through the presence of a user and in different usage scenarios. The main usage scenarios considered are: (i) Head only H; (ii) voice scenario with the user head and hand HH; and (iii) data scenario D with the user's two hands. The scenarios are shown in Fig. 9 where the phantom head and the hand models are used to simulate the user.

To reflect realistic usage, the handset and the user are factored into the propagation channel matrix, **H** as discribed in Section 2, see Fig. 1. The simulations are carried out having the

discussion of Section 2 in mind where the channel matrix *H* is computed statistically and is modeled with the SCM for an urban macro-cell environment but with specific antenna properties at the handset. The antennas and the user are simulated through full-wave EM simulations that are performed with a 3D solver, FEKO (FEKO, 2006).
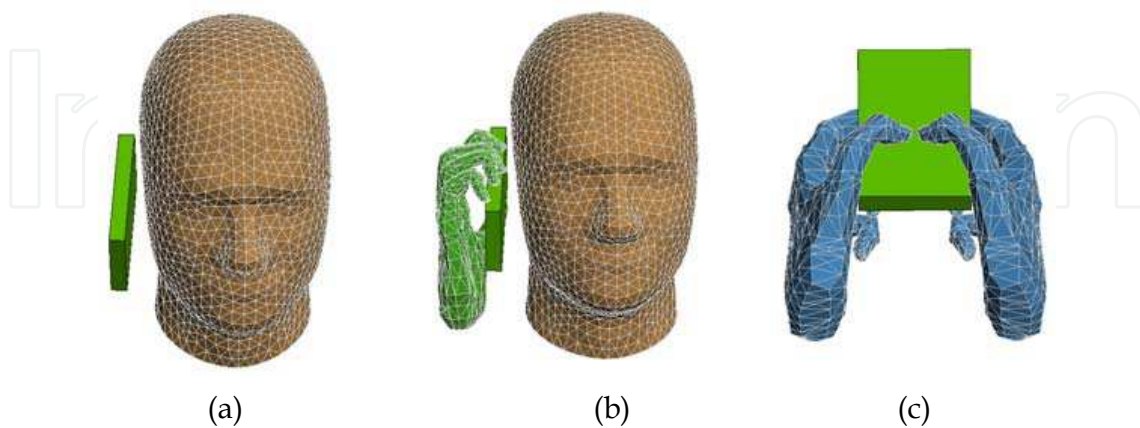

| (a) | (b) | (c) |

Fig. 9. Different usage scenarios: (a) Head only - H, (b) Voice with head and hand - HH, and (c) data with two hands – D

5.2 Antenna efficiency in the presence of the user

The antenna patterns and efficiency definitions are not simple enough so as to be derived directly from conventional pattern descriptions when the antenna is placed in the vicinity of or on a lossy medium. This is due to losses in the medium that cause the waves in the far-field to attenuate more quickly and finally to zero. The antenna efficiency is proportional to its gain (Balanis, 2005),

$$G(\theta, \phi) = \eta \cdot D(\theta, \phi)$$

Here, η is the total efficiency factor and $D(\theta, \phi)$ is the antenna directivity, which is obtained from the antenna normalized power pattern that is observed in the far-field. Typically, the antenna efficiency cannot be accurately computed with full-wave electromagnetic simulators as the losses in the material and from mismatch are usually ignored. In fact, in many EM simulators, η is set by default to 1, which corresponds to 100% efficiency, i.e.

$$G(\theta, \phi) = D(\theta, \phi)$$

For a more realistic presentation of the antenna performance into the channel for prorogation model analysis, the gain *G* should be taken as defined in the first equation where it is scaled by the antenna efficiency, and not as defined in the second equation. Therefore, in our analyses, the measured antenna efficiencies are used and these are given in Table II, where all losses are accounted for. As expected, the highest efficiency is measured in the FS scenario since there are no losses into the user's tissue or from losses as a result of reflections back into the transmitter RF circuitry. The largest loss in efficiency is seen in the voice scenario. Notice that as the near-field environment surrounding the antenna, in this case the user, becomes asymmetrical with respect to the antennas. This is reflected in the efficiencies of the two antennas where these become asymmetrical as well. The loss of

efficiency, as will be discussed later, is reflected in the channel power transfer factor, and in turn, on the link throughput.

Scenario	Antenna 1	Antenna 2
Free Space	45	44.5
Head	35	34
Head & Hand	15	11
Data	23	22

Table II. Measured efficiency (%) in different usage scenarios
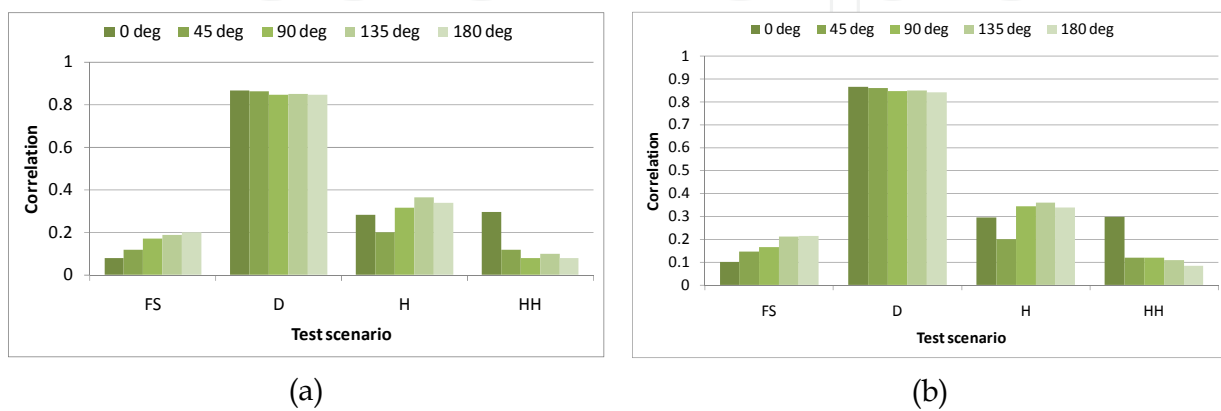

(a)

(b)

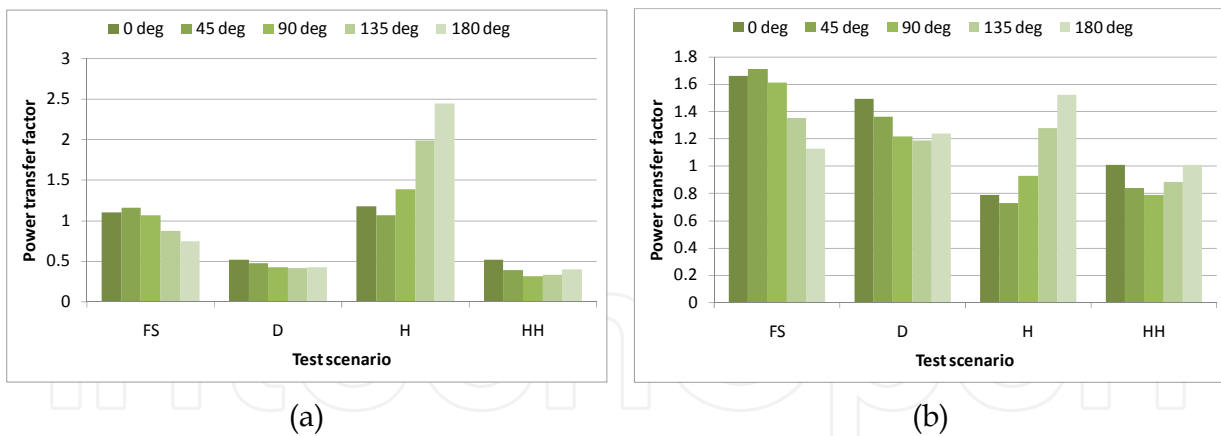Fig 10. Correlation values: (a) without including the antenna efficiency, and (b) including the antenna efficiency

(a)

(b)

Fig. 11. Channel power transferred in different usage scenarios at 20 dB SNR: (a) without including the antenna efficiency, and (b) including the antenna efficiency

The correlation values are shown in Fig. 10 for the different usage scenarios with and without including the antenna efficiencies at different oreintations of the user with respect to the servering BS. Notice that including the antenna efficiency did not have a major effect on the correlation values and in all user orientations. This is expected because the correlation is mainly defined by the normalized far-field radiation patterns of the two antennas. The performance of the correlation values can be predicted looking at the behavior of the radiation patterns, see for example Figs. 13(d)-16(d).

The channel power transfer factor with and without the antenna efficiency is given in Fig. 11. Two main observations can be made. The first is that power transfer factor is much less than the actual amount when the efficiency is not included. For example, in the H case and at user orientation 180°, the channel power is 1.5 dB which corresponds to a 0.5 dB decrease from the maximum and this comes from the antenna efficiency being at about 35%. However, it is not always the case that the reduction in the antenna efficiency can be linearly reflected into the channel power factor. As discussed in Section 4, it depends how dominant the propagation environement is and how the antenna radiation pattern interacts with the propagation envirnment . In some scenarios, such as the H scenario, the pattern shape would have a larger effect on the power especially since the pattern becomes directional due to the user's head and the performance becomes much more related to the user's orientation, see Fig. 14(d).

An important remark to make here is that accounting for the antenna efficiency cannot be considered as a linear scale factored into the SNR as many might think . It needs to be a weighted factor in accociation to the behavior of the antenna far-field radiation pattern, which ties into the user's orientation (Ali, 2010).

5.3 Link analysis

Lets analyze the effects of the antenna efficiency at the link level and investigate the performance of the system based on the antenna properties and the channel statistics. For this, an in-house MIMO-OFDM system based on 3GPP Release 8 standard (TSG-RAN TR 36.211, 2009) is used for the analysis. The channel matrices output from the integration of the EM and the SCM model, as discribed in Sections 2 and 3, are inputs into the link simulator. The evaluation is based on the throughput of the system in the different usage scenarios. Table III shows the simulation parameters of the LTE link simulator.

The link throughput in the different usage scenarios with and without the antenna efficiencies at 0° user orientation is given in Fig. 12. Notice that it takes 5 dBs more to achieve 1 Mbps moving from a FS scenario to the data scenario when efficiency is not included. In reality, however, this would take more than 15 dB as can be seen from the curves when efficiency is included. Furthermore, the difference in the performance is more pronounced in the variation of the efficiencies in the different usage scenarios; see Table II. Generally, including the antenna efficiency costs the system higher SNR to achieve the same performance compared to the case when the efficiency is ignored, becoming more pronounced with the higher SNR.

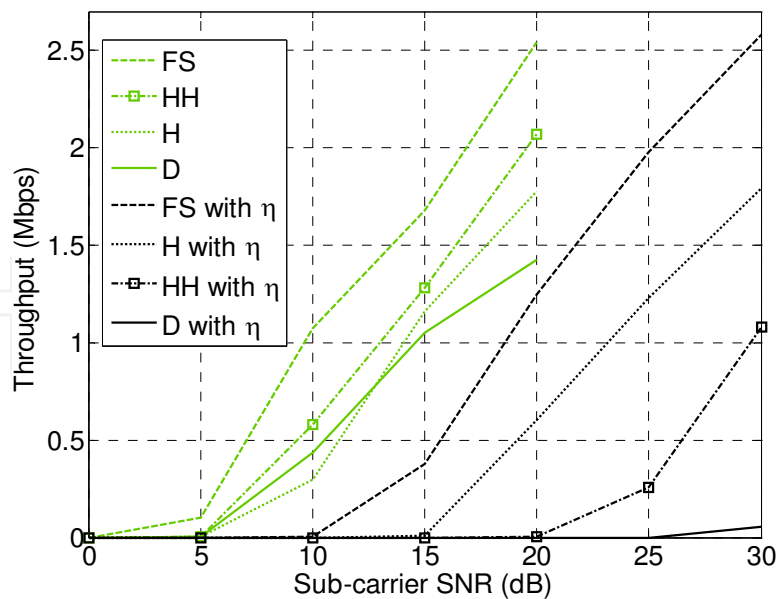| Parameter	Setting
• MIMO Mode	Spatial Multiplexing
• Antenna configuration	2×2
• Equalization	MMSE
• Channel Estimation	known
• Modulation	16QAM
• Coding rate	1/2
• HARQ	Enables (with one re-transmission)
• Correlation	Low

Table III. LTE Link simulation parameters

Fig. 12. Link throughput in the different usage scenarios with and without including the antenna efficiency and at 0º orientation

Notice that the link throughput showed a better performance of the voice scenario over the H scenario when the efficiency is ignored, which aligns well with the correlation results of Fig. 10(a). However, as we mentioned before, the correlation factor alone is not sufficient to accurately predict the performance. Therefore, the combined channel power in addition to including the antenna efficiencies is required. This is established in the black throughput curves in Fig. 12 where the H scenario shows improved performance relative to the HH scenario.

6. How deterministic is the multi-antenna design problem?

A handset antenna design can be thought of as a determanistic problem where its solution falls into the average of the general statistical problem. From this prespective, the mobile network operator would confine the handset manufacturer to an antenna performance with some minimum requirments taking into account their network and the physical area that it services.
The change in the antenna properties can be significant depending on the operating frequency and on the operational mode of the antenna. This is illustrated in Figs. 13-16 through the far-field radiation patterns. In all these simulations, the same multi-antenna configuration is used that is based on a typical PIFA design. Nevertheless, its radiation properties change significantly with the frequency and with the usage scenario. Assuming that the propagation environement changes slow enough allowing us to neglect its effects, the same antenna can easily have a performance that measures differently moving from one usage scenario to another, or from one frequency to another. Therefore, our one determanistic antenna design needs to solve the problem in multiple situations.
Now including the propagation channel environement into the discussion, which, as explained earleir in the chapter, could in some scenarios be the dominating factor in the performance equation, the problem randomness becomes even more pronounced. With a randomly changing and dominant environment, we are faced with the folowing challenge: How well can we predict the performance of our multi-antenna system?
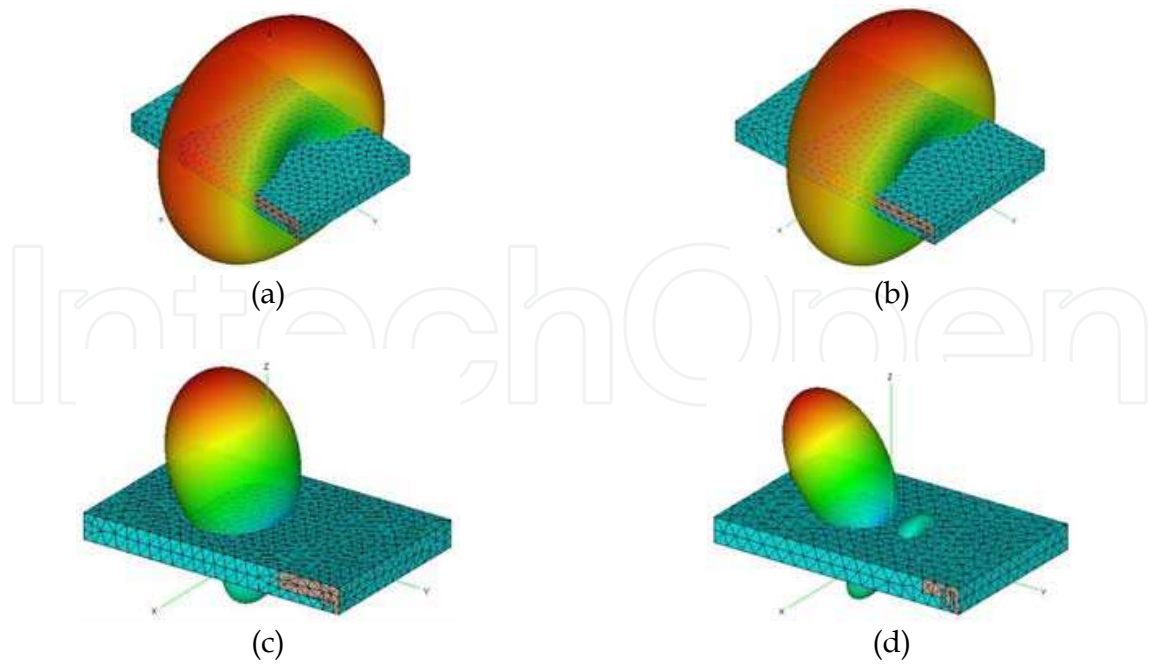
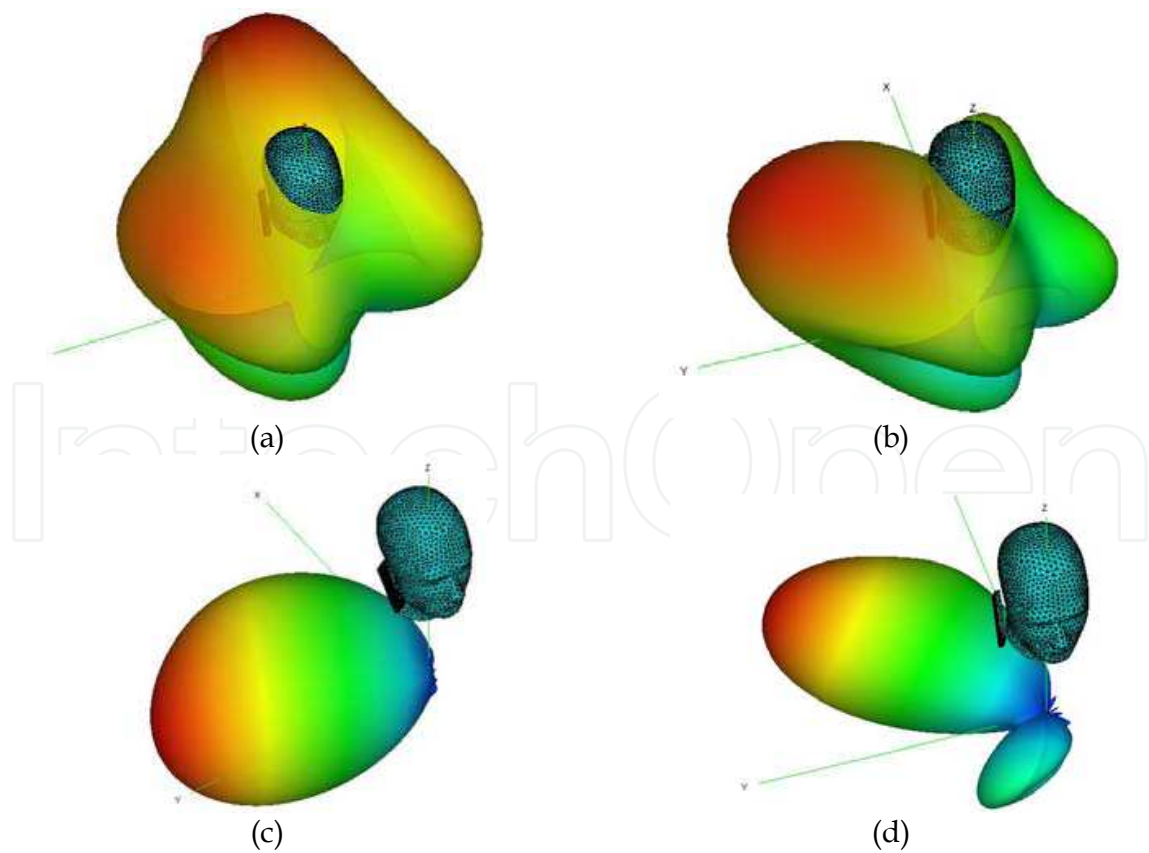Fig. 13. The total radation pattern in FS: (a) at 700 MHz, (b) at 950 MHz, (c) at 1880 MHz, and (d) at 2.6 GHz

Fig. 14. The total radation pattern in the presence of the user head: (a) at 700 MHz, (b) at 950 MHz, (c) at 1880 MHz, and (d) at 2.6 GHz
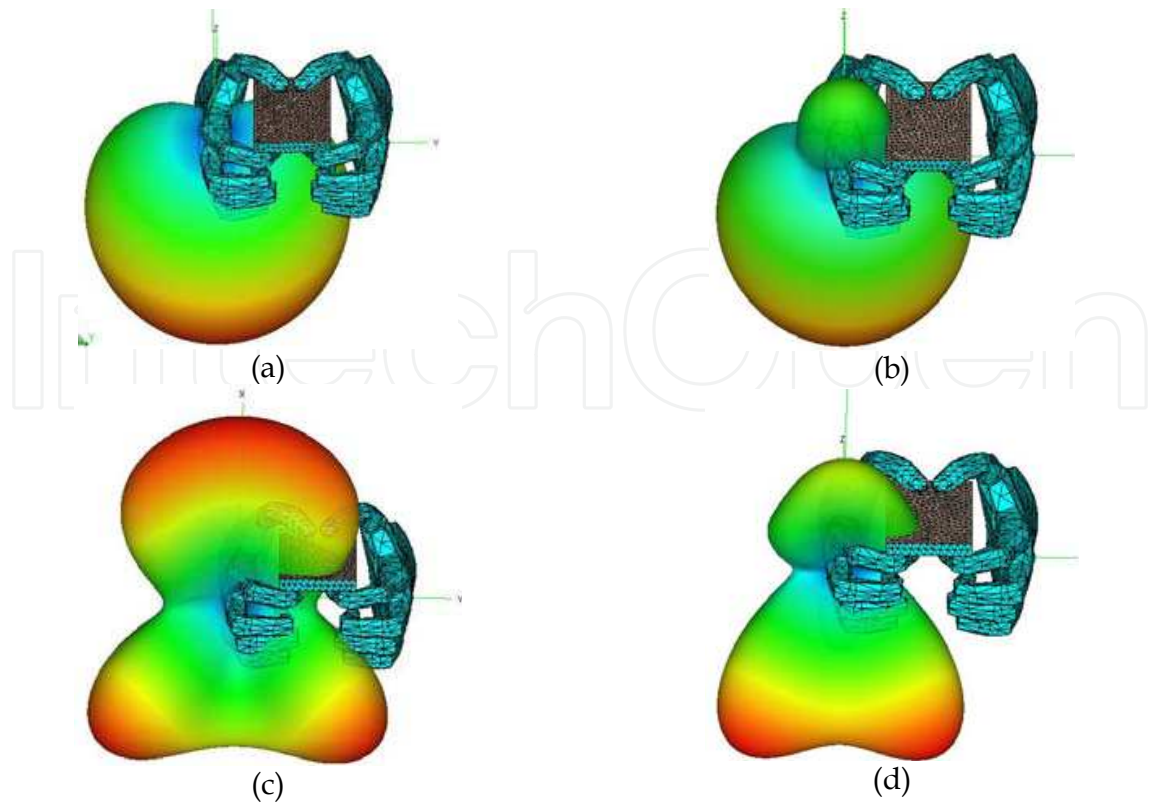
(a)

(b)

(c)

(d)

Fig. 15. The total radation pattern in the data position: (a) at 700 MHz, (b) at 950 MHz, (c) at 1880 MHz, and (d) at 2.6 GHz
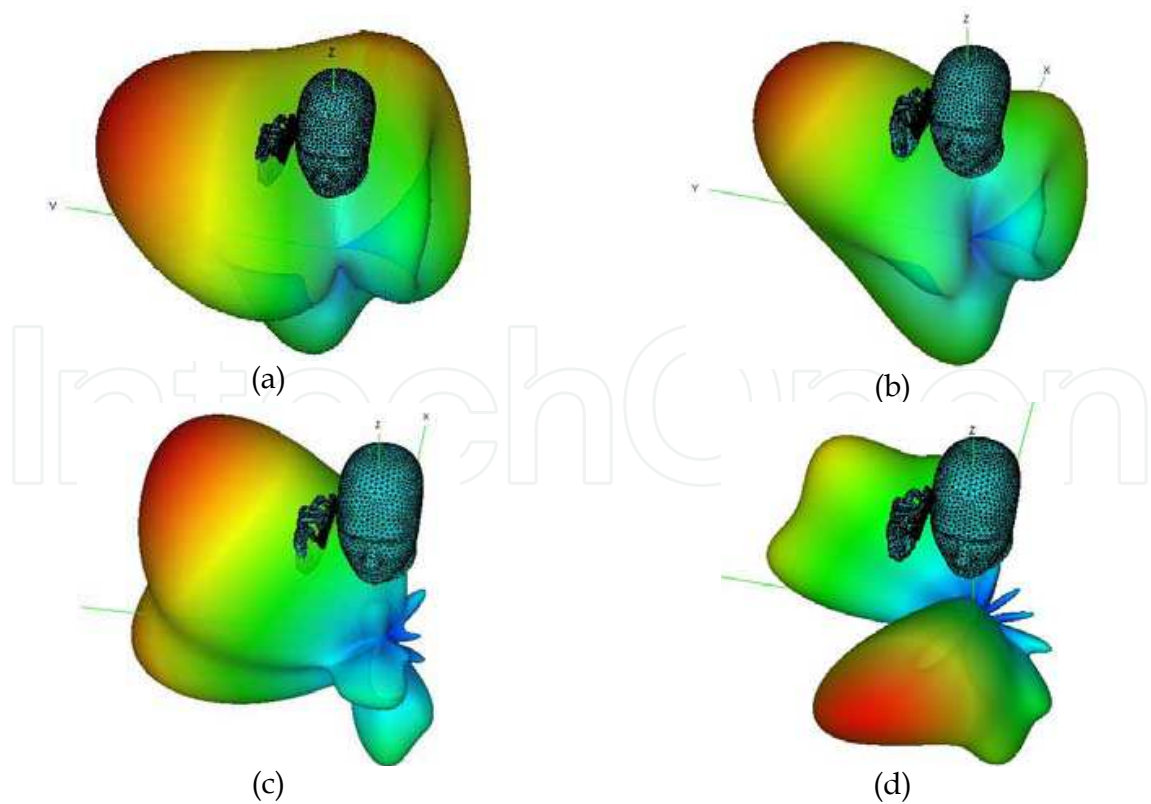

(a)

(b)

(c)

(d)

Fig. 16. The total radation pattern in the voice position: (a) at 700 MHz, (b) at 950 MHz, (c) at 1880 MHz, and (d) at 2.6 GHz

What we need to look at in the design of a MIMO antenna problem is the scalar parameters that better describe the antenna performance. In other words, since the radiation pattern can change significantly with the user and interact unpredictably with the channel, we cannot really count on it as a design target. Hence, quantities that by definition depend on the antenna radiation pattern, such as correlation; can become weak performance metrics in the evaluation. On the other hand, quantities such as the antenna efficiency and gain are to some extent controlled by the designer, of course, under the constraints of the laws of physics. Hence, the target should be to design a high efficiency multi-antenna system rather than a low correlation system and expect that the MIMO system performance would be good.

7. Final remarks

Ideally, the performance of a multi-antenna handset ought to be measured with the actual interaction of the antennas, the RF front ends, and the baseband processing elements. It also is useful to test the device with a performance metric or the figure of merit consistent with user operation and experience to provide a real-world metric. However, if the evaluation needs to take place at an early stage during the design process – where modelling and simulations are used – then careful measures need to be considered in the evaluation.

In evaluating a multi-antenna system it is important to include the complete antenna information, or enough of it, into the performance analysis. Incomplete information could very much lead to mistaken performance predictions. To this same point, the propagation channel environment can be a dominating factor in the performance equation and, therefore, its assumptions need to be laid out clearly as well. The performance in many cases would be scenario dependant.

A multi-antenna system designed with the antenna efficiency in mind could yield a system performance that is more likely to satisfy the performance requirements than a design that is based on weak or random performance metrics, such as correlation values. The design procedure could also be a simpler one. The key equation here becomes what would the target antenna efficiency be? And if known, how would replacing a high-efficiency antenna with two relatively lower efficiency antennas affect the multi-antenna system performance? Key questions from the author's view point yet to be answered.

8. Acknowledgment

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MIMO Systems, Theory and Applications

Edited by Dr. Hossein Khaleghi Bizaki

In recent years, it was realized that the MIMO communication systems seems to be inevitable in accelerated evolution of high data rates applications due to their potential to dramatically increase the spectral efficiency and simultaneously sending individual information to the corresponding users in wireless systems. This book, intends to provide highlights of the current research topics in the field of MIMO system, to offer a snapshot of the recent advances and major issues faced today by the researchers in the MIMO related areas. The book is written by specialists working in universities and research centers all over the world to cover the fundamental principles and main advanced topics on high data rates wireless communications systems over MIMO channels. Moreover, the book has the advantage of providing a collection of applications that are completely independent and self-contained; thus, the interested reader can choose any chapter and skip to another without losing continuity.

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