

Antenna Systems for MIMO User Terminals

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Abstract - The paper discusses the application of MIMO techniques to typical user devices for use in a variety of physical environments. It provides a non-mathematical overview of the major issues which need to be addressed in order to apply MIMO techniques effectively in the real world.

INTRODUCTION

It is the common vision of the wireless community that the future will see an increasing number of intelligent devices interconnected by means of radio systems. These devices will include data terminals, cameras, display devices, video players and a whole variety of new systems. The user requires an increasingly high quality of experience and this is driving a demand for increasing bandwidth, security of communication, and guaranteed quality of service.

Connection to existing wireless devices is characterized by relatively low throughput and uncertainty in the connectivity which can be provided. During the last few years extensive work has been carried out into methods by which the data rate and the reliability of wireless-connected devices can be improved, and the application of MIMO techniques is increasingly seen as a powerful tool by which connectivity and throughput can be increased. In a MIMO system both ends of a link – whether between a base station and a user device, or a peer-to-peer connection between devices – are provided with multiple radio transmitters and receivers (hence the terminology: multiple-in multiple-out). Providing two transmitters at one end of a link and four receivers at the other end, each with an independent antenna, provides eight sub-channels between the devices that can be used to increase throughput and provide more reliable connectivity. The extent to which the achieved improvements will approach the theoretical maximum will depend on a wide variety of factors including the extent of multipath propagation and presence of co-channel interference.

A move towards MIMO systems increases the complexity of the radio equipment on a user device, but increasing levels of integration are able to manage this despite the ever-shrinking real-estate available in many user devices. While the dimensions of mobile phones, PDAs and laptop computers may now be reasonably stable, the user expectation of increasing functionality increases the competition for available board space, volume and weight. The limited battery life of more complex user devices puts a high premium on power consumption, and this in turn requires that the efficiency of antenna systems is maintained or even improved, despite the fact that we now require several antennas on each device, so space for antennas is critically short.

Matters are further complicated by the fact that many user devices require connectivity to multiple services operating in many different frequency bands. It is becoming increasingly common for a single device to provide connection, perhaps simultaneously, to mobile phone networks (at 800/900, 1800/1900 and 2100MHz), GPS, Bluetooth and WiFi/Wimax.

The four typical user devices which will be referred to below are laptop computers, mobile data terminals, PDAs and mobile phones.

THE RADIO ENVIRONMENT

The selection and disposition of antennas for a user terminal will reflect both the way in which it is expected that it will be used and the environment in which it will be expected to operate. To take a familiar example, my mobile phone is expected to operate when held in my hand and placed to my ear, clipped to my belt, clipped into a hands-free kit in my car, and lying on my desk; I use it in buildings, city streets and rural environments in a country with plentiful base stations, and also in countries (like the US and China) where out-of town districts may be poorly served. These scenarios have major differences in the available C/I ratio and the profusion (or even existence) of multiple propagation paths between a local base station and my phone, as well as in the spatial and time dispersion characteristics of the multipath signals.

To be fully effective, new systems must either provide benefits in all these environments, or must provide some degree of adaptivity to make optimal use of their resources in each situation, perhaps falling back to a beamforming approach when propagation is dominated by a single component. There are several different MIMO algorithms which differ in relative performance according to both the multipath environment and the number and spacing of antennas at each end of the link; in the absence of rich multipath, better performance may be obtained by falling back to a diversity or beamforming technique.

The dependence of the performance of a system on the signal environment increases the task of assessing the effectiveness of any proposed system, as any propagation model is restricted to a small subset of the possible propagation environments in which a real-world system will be used. The situation is worst in a mobile environment, as the characteristics of the channel may change rapidly; managing the behavior of the system can then create a significant overhead, both in terms of the use of channel capacity, computational burden at the user terminal and drain on its battery.

The effective operation of a MIMO system demands that the antennas associated with each channel are essentially independent (otherwise we could simply combine the channels into a single antenna) and receive different samples of the incoming signal. To make the most of the signals received we need to be able to receive multiple signals received from different spatial directions and to make use of signals received with arbitrary polarizations; in addition it is useful to sample these signals at physically separate locations in space where the relative phases of different multipath components will be different.

ANTENNA SYSTEMS

The lack of physical space on a device implies that any antennas for the frequencies of interest will be small in terms of their operating wavelength. This inhibits antenna system design in several ways:

- Directivity will be very limited, and there will be significant overlap between the beams formed by each antenna, even if they are intended to point radially away from the device;
- Gain will be small – not only do the elements have low directivity but their reduced physical dimensions will result in relatively low efficiency, so peak gains will not significantly exceed 0dBi;
- The polarization response of small antennas is difficult to characterize, and it is difficult to ensure a high degree of polarization discrimination between antennas;
- On devices with small effective groundplanes the currents flowing in the groundplane may form a coupling mechanism which will increase the correlation between the signals output from each antenna independently;
- The small dimensions of many user terminals limit the spatial separation available;
- When a device is intended to be held or worn by the user, antennas in some locations on the device will suffer major reductions in gain.

This list makes the situation appear unpromising, so we will now examine the significance of each of these effects and the possibilities for creating an effective system on a typical user device.

1. Small antennas

The greatest problem in accommodating antennas in small devices arises when the frequency is lowest. The 800/900MHz bands are allocated world-wide for mobile cellular systems and a ubiquitous infrastructure has been created over the past 15 years or so. The GSM air interface standard does not currently provide for the use of MIMO techniques, so for much of the world there is unlikely to be a requirement for MIMO antennas in the foreseeable future. Although there are regional non-GSM systems at frequencies between 1.5GHz and 1.9GHz, the most likely candidate system for improved systems is the 3G IMTS W-CDMA system. This operates in the band 1.9 – 2.17GHz, corresponding to a mean wavelength of 150mm, so we could consider antennas of the order of 0.1 – 0.15 wavelengths.

Antenna designers can produce multi-band antennas with generally similar characteristics to single-band antennas and similar dimensions to one for the lowest band covered, so it is reasonable to expect compact antennas covering 3G, WLAN and WiMax with dimensions of perhaps 20mm x 10mm x 5mm. Using ceramic hybrid antenna techniques these small dimensions can be achieved with enhanced resistance to detuning caused by nearby objects or hands.

A further advance in antenna techniques is likely to be the increased integration of antennas with the RF circuit components, reducing the total board area required for each radio system.

2. Antenna radiation patterns, directivity and gain

Small antennas generally have radiation patterns similar to those of short dipoles; these are modified by the presence of the groundplane on which the antenna is mounted.

It is clearly possible to provide increased de-correlation between antenna outputs by making them more directional. Increased directivity may enhance performance in a rich multipath situation, but degrade performance in a low-multipath scenario if none of the antennas is aligned with the dominant signal. At 5GHz compact antennas can provide cardioidal radiation patterns with front-to-back ratios of around 12dB and a half-power beamwidth close to 180°. Figs. 1 and 2 show a simple test rig with four 3G antennas on a PCB with the dimensions of a typical PDA.

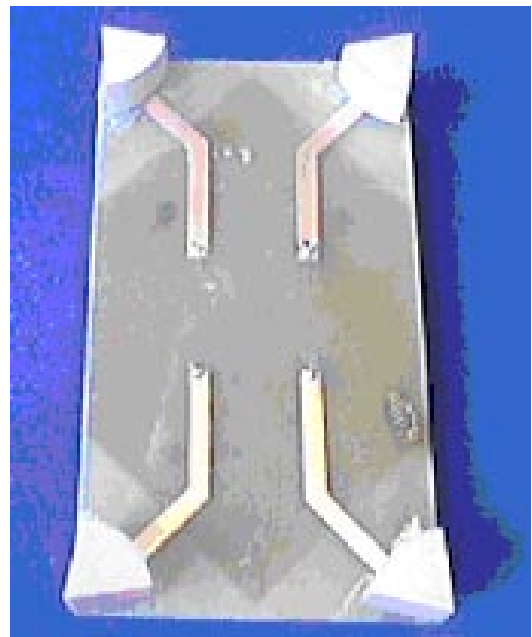


Fig. 1: A PDA test platform fitted with four ceramic antennas for radiation pattern measurement

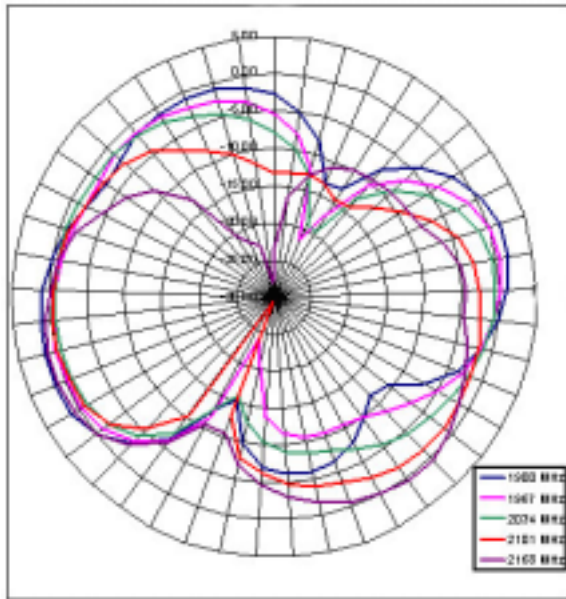


Fig. 2: Co-polar radiation patterns for the arrangement shown in Fig 1, measured in the plane of the board

Small antennas have low gains, with efficiencies (including mismatch losses) often less than 50% when the antenna measured in place on the terminal. (See also 7 below). Every effort must be made to improve antenna gain and to reduce the loss between the antenna and the radio. Providing a high level of de-correlation – or more smaller antennas – at the expense of losing significant gain, is simply not worthwhile.

3. Polarization response

In many situations a signal originally transmitted with linear polarization becomes de-polarized after multiple reflections, arriving at the user terminal as multiple elliptically-polarized components. A dual-polar antenna will capture more of the total available signal power than a single-polarized antenna, and as a further bonus the signals in each polarization will usually show low correlation.

The potential for polarization diversity at the user terminal can be enhanced by using circular or slant-linear polarization at the base station.

Antenna designers working on mobile phones and PDAs have not usually needed to consider the polarization performance of their antennas, so it will be a challenge to devise new antennas with polarization usefully orthogonal to the present styles of design. The placement of antennas around the screen of a laptop solves the problem easily, but providing orthogonal polarizations from antennas on a PDA may require new solutions – or the adoption of a clamshell-style hinged cover containing antennas.

Fortunately only modest polarization discrimination is needed to provide substantial benefit. Two antennas with cross-polar discrimination of only 10dB will provide much of the benefit both in terms of coupling most of the signal power available and maintaining the de-correlation between the incoming signals.

1. Coupling

Direct coupling via groundplane currents is troublesome on small devices at 800/900MHz. The radiation patterns of most mobile phones at 800/900MHz are similar to the pattern of a dipole oriented along the long axis of the phone, and examination of the currents in the groundplane show substantial currents are induced into it by the antenna. These groundplane currents form a coupling mechanism between antennas. This problem can be addressed by using balanced antennas, but the achievement of adequate bandwidth from small structures is difficult.

The situation at 1900MHz and above is better, and higher isolations can be achieved between physically separate antennas.

2. Separation

In a profuse multipath situation a MIMO system will operate with very small antenna separations, typically not much larger than a half wavelength. The often-quoted spacing between half-wave dipoles or quarter-wave monopoles for minimum correlation is 0.67 wavelengths, but this assumes isotropic multipath signals. In a sparse multipath situation the effectiveness of the system will depend much more heavily on the antenna separation. As the antennas are separated the phases of signals arriving from two different directions will change at a rate dependent on their angular separation. So with limited separation we can expect that a device may operate well in an environment with a large angular spread between the multipath components, but it will become progressively less effective as the angular spread diminishes. Fortunately a wide angular spread is typical of mobile terminal environments in buildings, city streets and in-car locations.

3. Proximity and masking effects

If a user's hand is placed over an antenna in such a way as to completely obscure it, the signal to/from that antenna will fall by between 10dB and 20dB. This is not a problem of antenna performance, but is a property of hands, which reflect and absorb EM radiation.

If a user's hand is simply placed in proximity to an antenna we will see a change in the input impedance of the antenna; the extent of this change is a property of the antenna. Ceramic antennas, for example, substantially constrain the physical extent of their stored-energy near-fields to the boundary of the antenna, with the result that they can be demonstrated to exhibit less variability of input impedance as a hand approaches than is the case with a classical antenna.

4. Adaptivity

It is very clear that some elements of directivity must be provided if the system is to provide the best performance in a wide variety of circumstances. As an example, if one or more antennas provides a very low receive signal (they lie under the user's hand or are facing directions from which no multipath components are arriving) it is likely that a signal transmitted by that antenna would simply represent wasted power. On the other

hand too much effort to precisely match the transmitted power to the available antennas in proportion to the received power may not be worthwhile.

5. Internal equipment RF losses

The current generation of phones has seen a major extension in the functionality of the handset at the same time as a reduction in physical size and the adoption of a variety of phone configurations intended to attract the buyer's eye (and money). In many user devices the antennas are connected by long and lossy cables.

The design of some current user terminals displays an ascendancy of styling and presentation over technical functionality. If the industry is to provide the user with the best possible level of performance it is very important that the functional requirements for effective antenna placement, connection and accommodation are embraced at the outset of the design process. This is not an argument for utilitarian and unstylish devices, but a suggestion that the technical requirements are properly regarded as being the essential reason for the existence of the device.

6. Link balance

When designing a complete system it is important to consider the relative capabilities of the links in both directions between the base station and the user terminal, and to match the capabilities to the intended range of applications.

The design of an effective MIMO system will require a careful balance between the factors discussed above.

CONCLUSION

The adoption of MIMO techniques can significantly enhance the capabilities of the physical layer of many mobile radio systems. This paper has described some of the parameters, particularly those related to the antenna systems on the user terminals, that will need careful optimization in the design of next-generation systems.

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