Technical E-Paper

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Introduction to the MIMO ANTENNAS design

Francesco Zaccarini
ElettroMagnetic Services s.r.l.

In current wireless communication networks, ranging from 4G-5G networks to *WiFi* and *IoT* applications, the use of multi-antenna systems, both at the transmitting and receiving terminals of the radio link, allows for a drastic increase in channel capacity and, for the same connection speed, extends service coverage.

A device that uses *MIMO* technology therefore employs more than one antenna: these radiating elements must therefore have suitable technical characteristics, whether they implement a multi-port antenna or are integrated within a client device or a mobile terminal.

Fully aware that this is a complex subject that cannot be exhaustively covered in this context, in the following technical in-depth analysis we will provide a brief introduction to *MIMO* antennas and the main parameters that need to be considered during the antennas design phase.

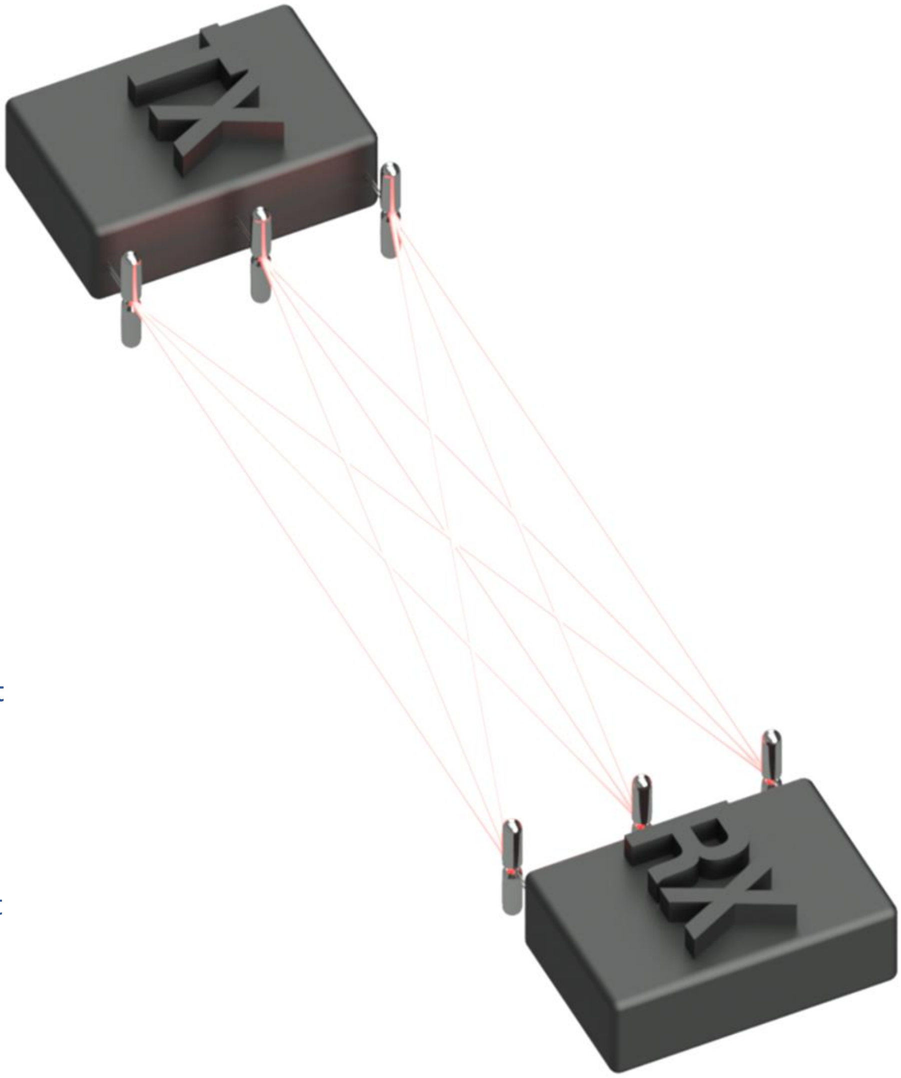

Figure 1.1
Basic diagram of a *MIMO* System (Multiple Input Multiple Output).

1. Multi-antenna systems: from “diversity” to MIMO.

Figure 1.2
DCS/UMTS panels in dual polarization.

For decades, the radio wave propagation mechanism known as *multipath*, which affects the VHF frequency bands and higher in scenarios characterized by numerous natural and/or artificial obstacles, has been a hindrance to the realization of stable and reliable communication systems.

In a traditional transmitter-receiver radio link (*SISO, Single Input Single Output*), which uses a single antenna at each end of the link, the simultaneous presence of multiple electromagnetic rays (direct and reflected) arriving at the receiver through different paths can indeed cause phenomena of attenuation or cancellation of the received signal (*fading*), as the latter is the vector sum of a large number of contributions, according to a certain statistical distribution.

In most cases, all these reflected signals act as interferences on the radio signal, whose power available at the receiver's input is substantially attributable to the direct, or main, ray. Under these conditions, the quality of the signal degrades very quickly: consider, for example, the "ghosts" sometimes visible in television images, a characteristic effect of *multipath* on the analog signal.

In the early 1990s GSM/DECT base stations (**Figure 1.2**), the negative effects of multipath were reduced by introducing *spatial diversity* or *polarization diversity* reception. These techniques allow for increased reliability of the radio channel by using two separate antennas installed at a certain distance from each other, or employing two orthogonal polarizations (H/V or +45°/-45°) embedded in the same panel.

In this way, assuming a high statistical independence between the two signals arriving at one or the other antenna, the total probability of channel outage is reduced, becoming substantially equal to the product of the outage probabilities of the individual channels associated with the different antennas, thereby increasing the reliability of the connection.

This leads us to the mid-2000s, when *MIMO* technology (*Multiple Input Multiple Output*, **Figure 1.1**) is commercially introduced. Contrary to *diversity*, which seeks to minimize the effects of *multipath*, *MIMO* utilizes this propagation mechanism as an actual resource.

This technology employs a certain number of antennas, potentially even a large number, both on the transmitting and receiving side of the link, and associates a certain data stream with each possible transmitting-receiving antenna pair through a principle of *spatial multiplexing*.

The *multipath* mechanism then allows for the transmission of multiple data streams from the different antennas of the transmitter to those of the receiver, thus dividing the channel capacity among the various electromagnetic rays that characterize the transmission medium.

Conversely, it is interesting to note how a multi-antenna system based on this principle does not function adequately in the case of a radio link in which the *multipath* mechanism is absent.

2. *Diversity* techniques for antennas.

Whether it's *diversity* reception or the more sophisticated *MIMO* technology, the two or more antennas used must be independent of each other, meaning the signals they individually receive should be as *uncorrelated* as possible.

This fundamental characteristic that the antennas must have is achieved using three criteria or, most often, a combination of them:

a) *Spatial diversity;*

b) *Polarization diversity;*

c) *Beam diversity.*

In *spatial diversity*, the decorrelation between the captured signals is achieved by placing the antennas at a certain distance from each other (expressed in terms of wavelengths λ).

In *polarization diversity*, the decorrelation between the received signals is achieved using antennas with mutually orthogonal characteristic polarizations, for example, H and V or inclined at +45° and -45°.

In *beam diversity*, the decorrelation between the received signals is achieved through radiation patterns that are heading different regions of space and, possibly, complementary.

3. Two significant parameters of MIMO antennas.

The degree of independence between the ports of a multi-antenna system is described by the *correlation coefficient* and the *isolation*. To better clarify these two parameters, let's imagine referring to a receiving system that uses only two antennas.

The *correlation coefficient* is an indicator of how similar the radiation patterns of the two antennas are to each other, or how much they are capable of performing a sort of spatial filtering of the electromagnetic rays that arrive at the receiver from different directions and with different polarizations. The calculation of the correlation coefficient, which varies between 0 (antennas with completely distinct radiation patterns) and 1 (antennas with identical radiation patterns), is quite complex and derives from measuring the directivity functions of the individual antennas over the entire solid angle.

The *isolation* between the two antennas, defined as $-20 \cdot \log 10|S12|$ (in dB), instead defines the degree of decoupling between the radiating elements, measured at their respective ports 1 and 2.

It is important to note that there is often a link between the similarity of the radiation patterns and their isolation: in the literature, one can find closed expressions, simpler than those derived from radiation measurements, that in particular cases allow estimating the correlation coefficient from the *S* parameters of the two antennas, therefore in a much more convenient way than radiation measurements.

Since a mathematical in-depth analysis goes beyond the scope of this article, let's just clarify these concepts intuitively, through the images of **Figure 2.1** and **Figure 2.2**, which show two dipoles with which it is possible to understand the above description.

In the first figure, situation (***a***) shows two antennas very close to each other and characterized by a high degree of near-field coupling as well as by two almost overlapping radiation patterns: in this case, the worst scenario, there is a correlation coefficient close to 1.

Example (***b***) represents a pair of collinear dipoles, therefore characterized by good isolation but beams with the same shape and polarization characteristics.

Conversely, in the second figure, we refer to two ideal situations. Example (***c***) shows two dipoles in a back-to-back configuration which allow for both high isolation and two distinct, complementary radiation patterns.

Finally, configuration (***d***) highlights two dipoles in orthogonal polarization: a scheme that allows for both good isolation and a low correlation index between the patterns. In both cases, the correlation coefficients are close to 0.

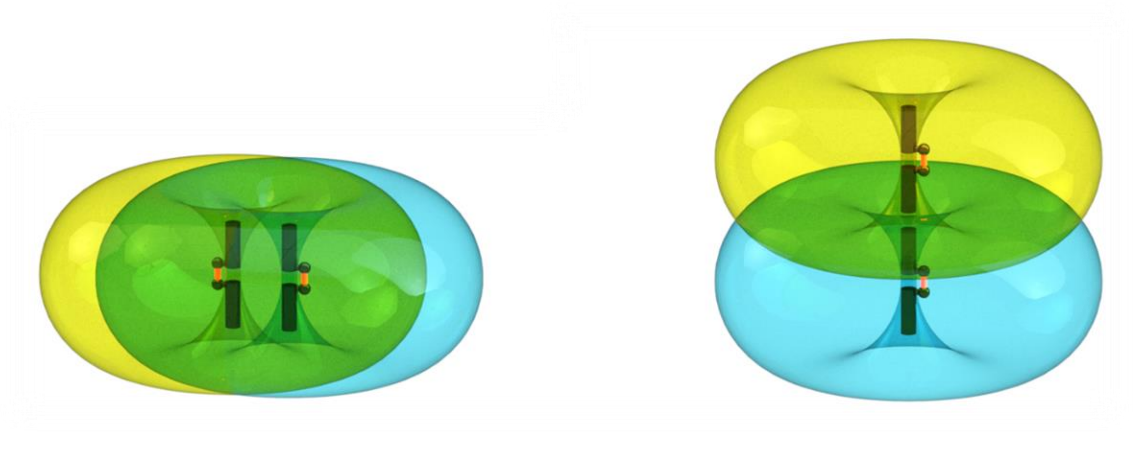

Figure 2.1

Examples of non-ideal cases (high correlation coefficient): (***a***) a pair of antennas with almost overlapping radiation patterns. (***b***) a pair of antennas with good isolation and partially overlapping radiation patterns.

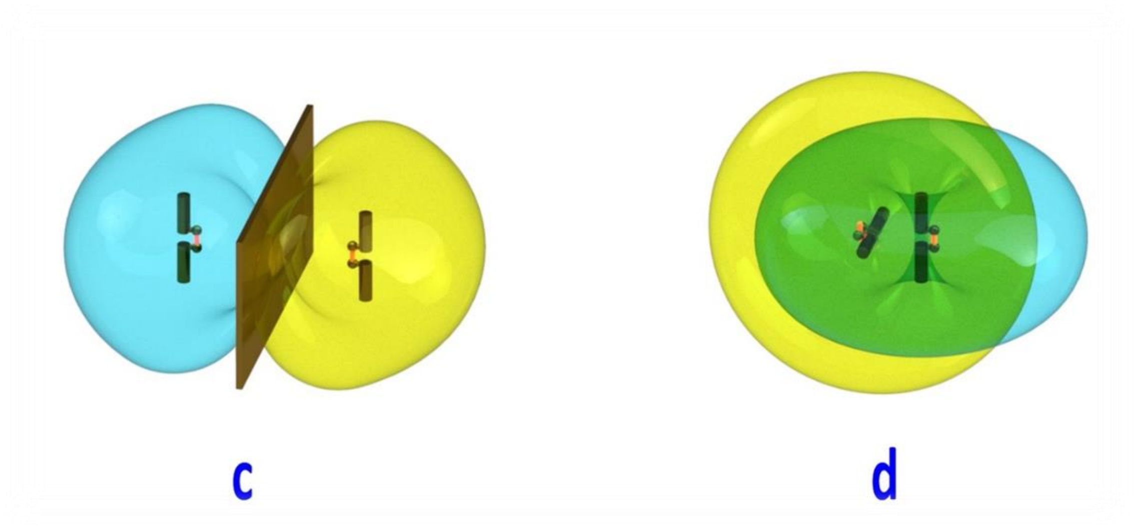

Figure 2.2

Examples of ideal situations (low correlation coefficient): (***c***) a pair of antennas with high isolation and complementary radiation patterns. (***d***) a pair of antennas with high isolation and radiation patterns with orthogonal polarizations.

4. The *MIMO* antennas design.

In a *MIMO* device, which exploits the physical mechanism of *multipath* to increase channel capacity, the *diversity* techniques illustrated in paragraph 2 are fundamental to the design of the multi-antenna system.

Indeed, the performance of such a system depends on numerous factors, such as:

- The antennas should have a certain degree of directivity, controllable through the degrees of freedom that are possible in the design;
- The antennas should have some form of cross-polar discrimination;
- The antennas should have radiation beams oriented in different directions, possibly complementary to each other, so as to cover the entire solid angle or a large part of it;
- The mutual coupling between the antennas should be minimal (corresponding to a good level of isolation);
- In a multi-antenna system, the mutual proximity of the radiating elements should not lead to a reduction in their efficiency;
- In a multi-antenna system, the mutual proximity of the radiating elements should not worsen their matching, and all ports should be adequately matched to their nominal characteristic impedance (50Ω).

For example, if we consider a real product like the router in **Figure 3.1** and refer to the above points, it is intuitive to estimate the impact that each of these factors has on the antennas, which are parallel, closely spaced omnidirectional coaxial dipoles: at the very least, they should be appropriately oriented during the installation of the device in order to remain as decoupled as possible. Indeed, as can be seen from the figure itself, in practice, industrial and/or commercial choices often prevail, leading to the creation of antennas that are not entirely suitable to fully exploit the potential of *MIMO* technology.

Figur3 3.1

Practical implementation of a multi-antenna *MIMO* system on a *WiFi* router for industrial applications.

Although each custom implementation is a unique case, we can divide *MIMO* antenna projects into two main criteria, useful for understanding the challenges that can be encountered in undertaking such realizations:

a) *Projects of conventional antennas or antennas integrated into the device;*
b) *Projects of single-band antennas or multi-band antennas.*

Based on these broad categories, we then consider some types of antennas.

Conventional antennas.

With this term, we refer to non-integrated antennas, i.e., external to the apparatus and therefore compatible with multiple devices or installations. For these antennas, the possibility of relaxing the dimensional constraint by creating larger and more spaced radiating elements (in terms of λ), allows for better isolation specifications and more directive radiation patterns, favouring the implementation of the *diversity* techniques mentioned above.

This type of project indeed allows for:

- Using standard radiating elements (dipole, patch, etc.), achieving a better shape and directivity of the radiation beam, as well as a well-defined characteristic polarization;
- Using radiating elements with a symmetrical current distribution, an important requirement for achieving a high degree of isolation in dual-polarization antennas;
- Isolating the radiating elements from common ground or image planes, by introducing balancing devices at the feeding points (*balun*).

Figure 3.2 shows two examples of *custom*, *conventional* antennas for *diversity* and *MIMO* applications.

In the first case, in the *photo on the left*, a system of antennas at 2.4 GHz and 5.8 GHz with bidirectional arrays in horizontal and vertical polarization is depicted: this system, developed specifically for *Smart-Road* applications and installed on the side of the highway, must ensure optimal performance and coverage characteristics with the numerous vehicles in motion. These vehicles also represent the main cause of radio signal reflections and the presence of *multipath*.

In the second case (*photo on the right*), a compact *MIMO* antenna on PCB, operating in the 690÷960MHz and 1700÷2700 MHz bands, is shown: in this case, dual-resonance dipoles arranged to achieve polarization diversity and, albeit to a lesser extent, in the radiation beam, were used.

Figure 3.2
Examples of conventional antennas for *diversity* and *MIMO*.

Integrated antennas.

In integrated antennas, i.e., those embedded within a device or apparatus, the development of a multi-antenna system is of fundamental importance for recent applications in the field of *5G*, *WiFi*, and *IoT*.

As can be inferred, in this case, the approach to design is different, and is characterized by the following factors:

- Existence of dimensional constraints that force the coexistence of multiple radiating elements in confined spaces;
- Other electrical and electronic components, and the mechanical structure of the device can influence the electrical characteristics of the antennas;
- The need to use radiating elements with reduced dimensions (short antennas) and therefore less directive;
- Use of types of radiating elements that appreciably deviate from canonical structures;
- High asymmetries in the currents;
- Multiple antennas sharing the same ground plane, which usually consists of the *"GND layer"* of the PCB.

All these factors lead to the need to carefully study the type and placement of the radiating elements, using special techniques to improve isolation between antennas.

Let's take an example referring to **Figure 3.3**, where two PCBs with integrated *IFA* (*Inverted F Antenna*) antennas are shown, sharing the same ground plane.

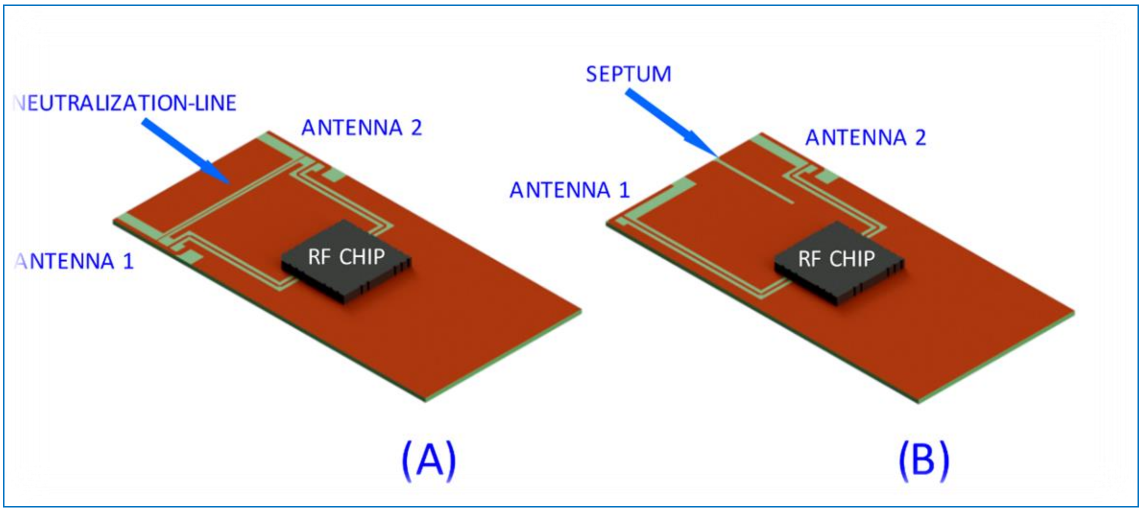

Figure 3.3
Examples of *MIMO* antennas integrated on PCB, with possible circuit elements to improve isolation.

In example (**A**), the antennas have the same polarization, and the degree of diversity between the two radiation patterns is given exclusively by the asymmetry of the ground plane relative to the individual radiating elements.

It is intuitive to state that the radiation patterns are symmetrical with respect to the longitudinal plane that identifies the geometric symmetry of the PCB (**Figure 3.4**).

The improvement in the degree of isolation between the two radiating elements is achieved through a *neutralization line* that electrically connects the two radiating elements and acts as a kind of *notch*, with a principle that resembles that used in the resonators of RF filters.

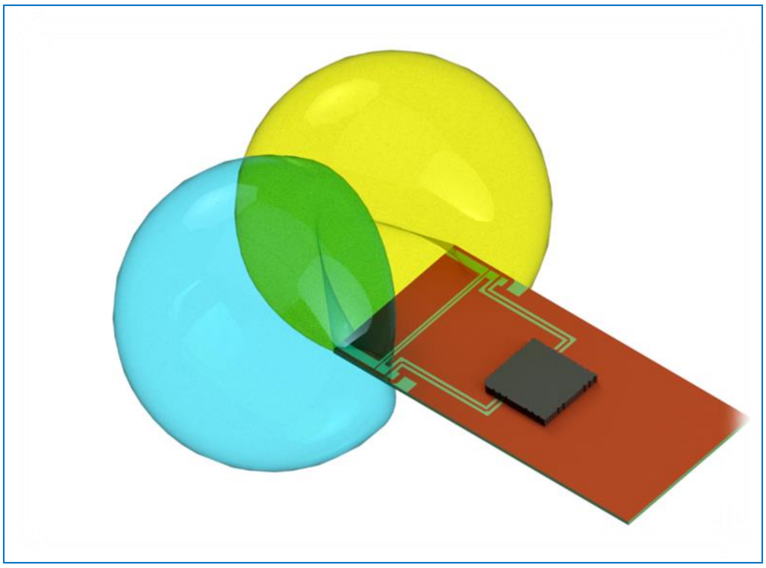

Figure 3.4
Schematic representation of the radiation patterns of the *IFA* antennas in **Figure 3.3 (A)**.

A second example is that of case (**B**), where the two *IFAs* are placed on two perpendicular sides of the *PCB*, thus implementing polarization diversity. Since in this type of antennas a significant contribution to the radiation is given by the edges of the PCB, we should not expect to achieve high values of *XPD*.

Here too, the two radiating elements share the same *ground layer* of the printed circuit board: the optimization of isolation is achieved by inserting a partition (implemented with a *notch* in the PCB copper) to separate the two current distributions impressed by the individual radiating elements.

Other techniques can be used to improve isolation, and in integrated antennas, each individual scenario must be studied case by case.

Despite the availability of sophisticated electromagnetic simulation software, it is not at all obvious that computer simulations will always yield truthful results, as it often becomes difficult in practice to adequately model all the components and structures that are in proximity to the integrated antennas.

5. Conclusions.

The purpose of this technical in-depth analysis is to provide a brief introduction to *MIMO* technology, briefly explaining how suitable, custom-developed antennas can further improve the performance of these innovative multi-antenna systems.

Indeed, it is possible to create a multi-antenna system whose radiating elements are customized based on the installation characteristics and use of the system itself, thus making the best use of the presence of multiple paths in that particular operational scenario where the *MIMO* device will operate.

More than a hundred years after the birth of wireless, once again the antenna, or in this case *antennas*, remain the strong point of a radio communication system, and competence and experience in making them remain always fundamental.

All the information and experiences reported in this article are the result of the design, development, and implementation of professional custom antennas carried out by ElettroMagnetic Services Srl using the AntennaCustomizer method.

For questions, clarifications, or further information on this or other topics regarding professional antennas, please contact bollini@elettromagneticservices.com.

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