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Demystifying MIMO for microwave

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MIMO is an attractive solution for increasing spectral efficiency when spectrum is a scarce resource. It is instrumental for future implementations of 100Gbps over microwave. However, there are many things to consider in order to reach the optimal MIMO installation.

Multiple-Input Multiple-Output (MIMO) is a well-established antenna technology for enhancing spectral efficiency and/or reliability in wireless communication, and is being successfully used in 3GPP and Wi-Fi technologies. In a MIMO system, multiple antennas are deployed at both the transmitter and receiver side of a link. The multiple antennas can be used for either: 1) increasing the spectral efficiency (bps/Hz – bits per second and Hz) of the link by transmitting multiple data streams over the channel (also called spatial multiplexing) or 2) increasing the reliability of the link by exploiting the diversity gain introduced by the use of multiple antennas (also called spatial diversity).

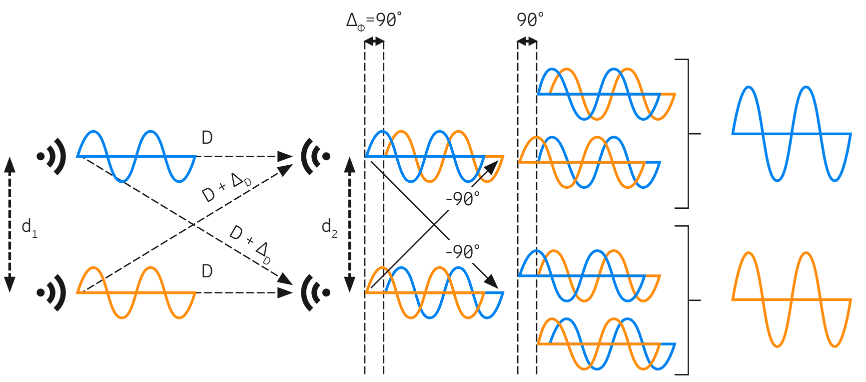
A MIMO channel can be decomposed into multiple Single-Input Single-Output (SISO) channels over the same time and frequency. These channels are sometimes referred to as sub-channels of the overall MIMO channel. It is the use of these sub-channels in parallel over the same time and frequency channel that provides spatial multiplexing in MIMO. For example, a properly designed MIMO system with 8 transmit and 8 receive antennas (8x8 MIMO) will have 8 sub-channels for spatial multiplexing. In other words, the 8x8 system will have up to 8 times the capacity of a single antenna system. For example, assuming that 6 bits per data symbol (64 QAM) is used in an 8x8 MIMO system over an E-band signal bandwidth of 2.25GHz – the overall rate will be 6 (bits per symbol) x 8 (data streams) x 2.25 (GHz) = 108Gbps. Through this, MIMO acts as an enabler for reaching 100Gbps and beyond.

In general, there is a trade-off between spatial multiplexing and diversity gain, meaning that one typically chooses which to prioritize. For example, in microwave long-haul links, spatial diversity receivers are commonly used to combat multipath fading, therefore offering protection to critical backhaul links. In a spatial diversity system, the data information is conveyed over different sub-channels, which increases the link protection as it is unlikely that all sub-channels will fade at the same time. This also means that a spatial diversity system typically has increased availability of a certain data rate compared to a non-diversity system. In contrast to spatial diversity, a spatial multiplexing system instead uses all of the sub-channels to transmit multiple data streams in order to increase the spectral efficiency of the link. High spectral efficiency is important when spectrum is a scarce resource, which makes MIMO an attractive solution.

Principles of MIMO for microwave

The main intention in utilizing MIMO is in relation to multiple stream transmissions, in order to further enhance the spectral efficiency in microwave links. Spectral efficiency is enhanced by up to N times compared to a SISO system, where N is the MIMO order, limited by the number of antennas used in the MIMO system. In MIMO systems, it is possible to deploy any number of transmit and receive antennas, but a symmetric system is the most common,

Figure 12: MIMO for microwave transmission – the principle



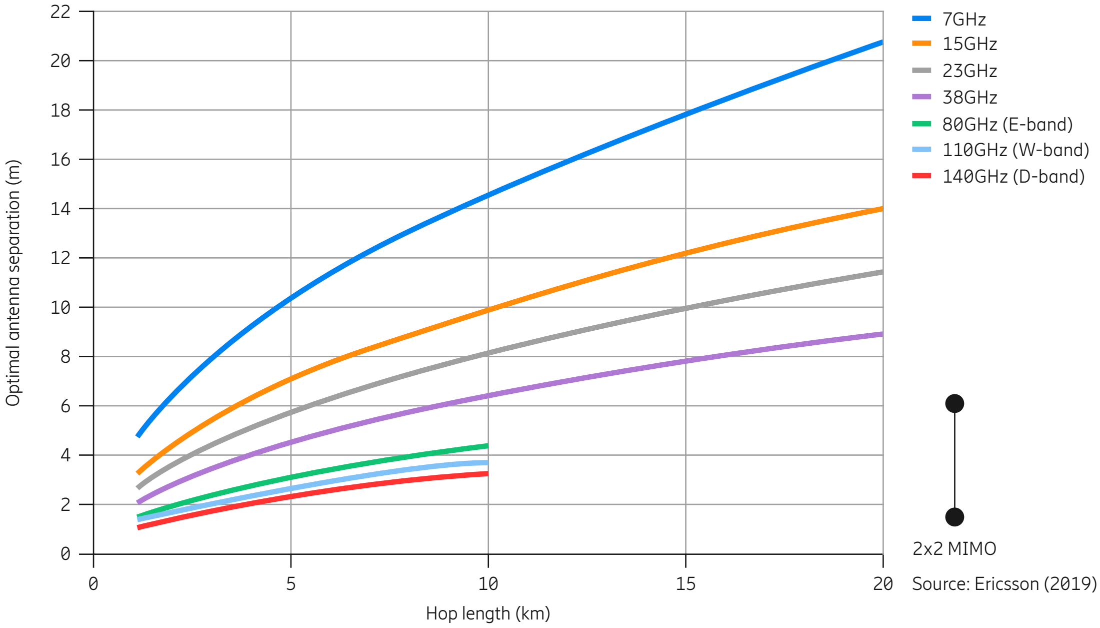
Source: Ericsson (2019)

Spatially separated antennas give a path phase difference of Δ_Φ

Optimal antenna separation:
$d_1 d_2 = D\lambda/2$
gives $\Delta_\Phi = 90°$

Principle of MIMO for microwave transmission where the spatially separated antennas gives a path length difference of Δ_D, which corresponds to a phase difference of 90deg between the direct path and the cross path. By phase shifting by 90deg and summing the received signal, the two data streams are are restored perfectly and without any losses.

Figure 13: Optimal antenna separations for a 2x2 MIMO system



Source: Ericsson (2019)

where the number of transmit antennas equals the number of receive antennas (a NxN MIMO system). Dual-polarized antennas may also be used in MIMO systems. For example, a system with two dual-polarized antennas on each side of the link is equivalent to a 4x4 MIMO system. When it comes to deployment, the antennas may appear in different arrangements. For example, the antennas in a 4x4 MIMO system may be deployed in a square grid, along a line, or even in an L-shape if required. Often, physical site constraints dictate the deployment.

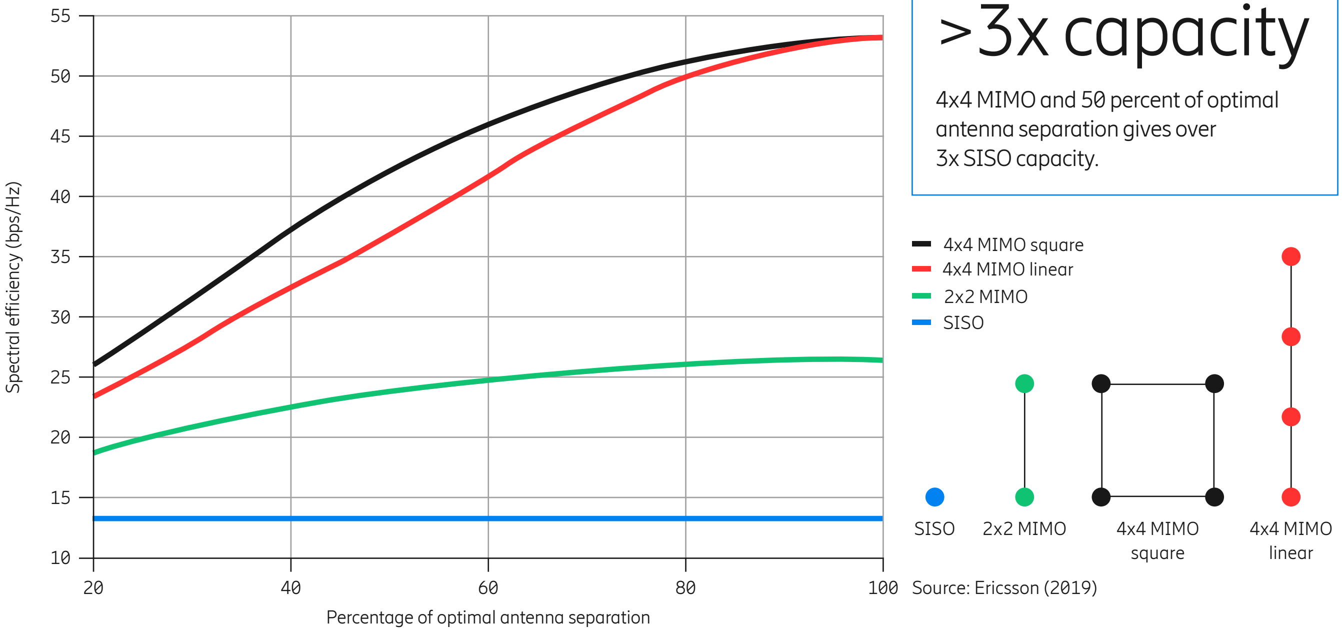
Figure 12 illustrates the principle of a 2x2 MIMO system, where a first transmit antenna is used to transmit a first signal data stream (blue), while a second transmit antenna (separated by a distance d_1 from the first antenna) is used to transmit a second signal data stream (orange). Both signal data streams are received by two receiving antennas (separated by a distance d_2) that are located at a distance D away from the transmitting antennas. Both signals are received by each one of the receiving antennas, which causes them to interfere with each other. However, it is possible to deploy the antennas in terms of separations d_1 and d_2 in such a way that there is an optimal phase shift Δ_Φ of 90 degrees between the cross-channels relative to the direct channels. This means that by employing a proper interference cancellation scheme in the receiver, the interfering signals can be completely removed from the signals of interest. This can be done perfectly and without any performance loss if the Δ_Φ corresponds to a 90 degree phase shift and, correspondingly, a Δ_Φ of 90 degrees is said to be given by the optimal antenna separation. There are many antenna separations that give a Δ_Φ of 90 degrees, but the optimal one is defined as the smallest separation, depending on the hop length D and wavelength λ (or frequency).

Figure 13 shows the optimal antenna separation in a 2x2 MIMO system for different frequencies versus hop length.

Figure 14: MIMO capacity depending on antenna arrangement

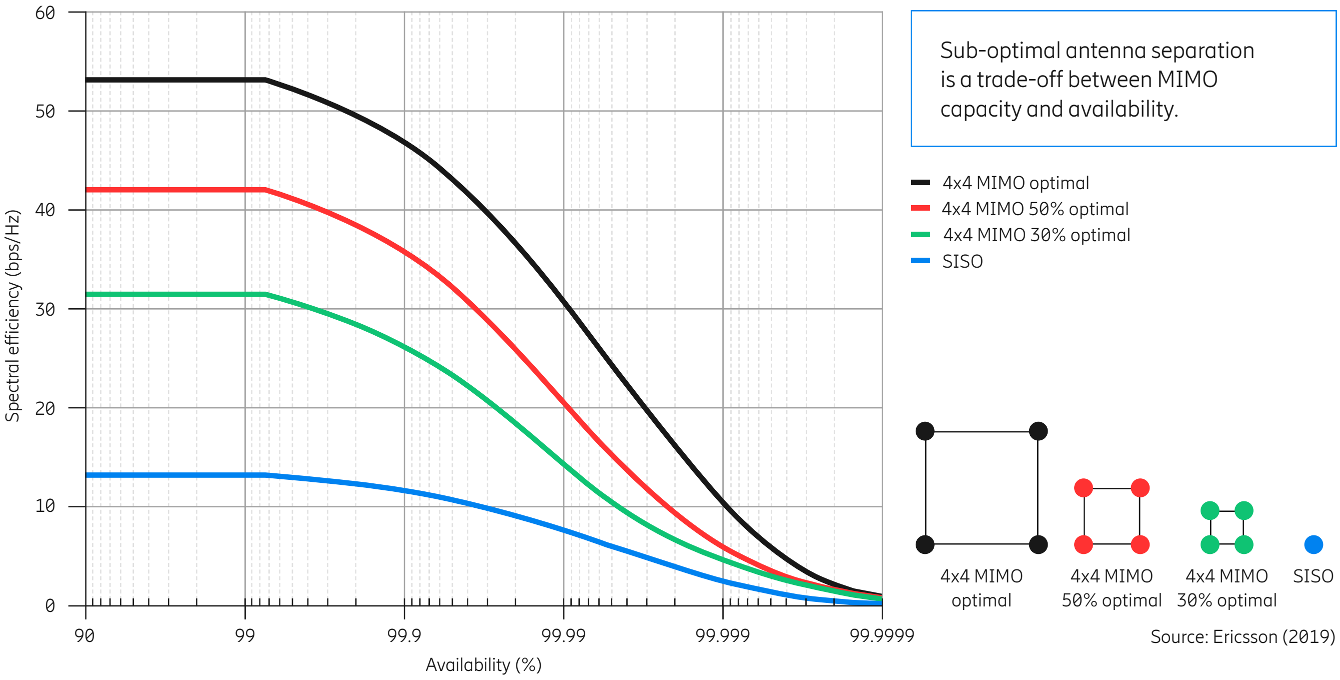
>3x capacity

4x4 MIMO and 50 percent of optimal antenna separation gives over 3x SISO capacity.



Source: Ericsson (2019)

Figure 15: MIMO capacity and availability trade-off for sub-optimal antenna arrangements



Sub-optimal antenna separation is a trade-off between MIMO capacity and availability.

Source: Ericsson (2019)

Higher frequency or shorter hop lengths allow for the use of smaller antenna separations, which makes the MIMO installation more compact. It should also be mentioned that it is possible to use sub-optimal antenna separations, as it may not be practical in some deployments to use the optimal antenna separation, due to it simply being too large. The effect of sub-optimal antenna spacing is shown in Figure 14, where the MIMO capacity (spectral efficiency) is plotted against various degrees of sub-optimal antenna spacing for different MIMO antenna deployments. It shows how the capacity drops as the antennas become more sub-optimally spaced. However, even at 30 to 50 percent of optimal spacing, there is a huge capacity gain over a SISO system. The figure also shows that different antenna arrangements have different properties when the antennas are sub-optimally spaced. The square 4x4 MIMO deployment is more robust in comparison to sub-optimal spacing at the Signal-to-Noise Ratio (SNR) used in this example (the typical SNR of a microwave radio link).

In principle, the use of sub-optimal antenna separations will give a penalty in system gain, which in practice translates to a loss in availability. Figure 15 shows the effect of sub-optimal antenna separation in 4x4 MIMO systems deployed in square arrangements. It should be noted that the capacity drops when reducing the antenna spacing for fixed availability. Equally, it should also be noted that the availability will be lessened when reducing the antenna spacing for a fixed capacity. Therefore, the use of sub-optimal antenna spacing is a trade-off between MIMO capacity and availability.

A way to reduce the loss in capacity (or availability) when using sub-optimal antenna spacing is to use something called precoding. Precoding can be seen as a generalization of beamforming, where each data stream is transmitted over all (or a subset of) the antennas and with individual weighting (amplitude and phase) across the antennas. For example, the weighting can be chosen so that the Signal-to-Interference-and-Noise Ratio (SINR) of each data stream is maximized at the receiver side. Precoding will, therefore, put constraints on the phase synchronization of the radios in order to work properly. In MIMO systems without precoding, each individual data stream is transmitted from a single antenna, as depicted in the 2x2 MIMO system in Figure 12.

Optimizing MIMO for maximum effect

MIMO is a spectral-efficient multiple-antenna technology that can be used when the available spectrum is scarce or to enable >100Gbps in wide-band channels. The optimal antenna arrangement depends on the desired MIMO order, frequency and hop length. Sub-optimal antenna arrangements are possible, and sometimes even required, due to site installation constraints, but they will give a performance penalty in terms of reduced capacity and/or availability. Precoding over phase-synchronized transmitters can, to some extent, alleviate the penalty of using sub-optimally spaced antennas.

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