LoS MIMO-Arrays vs. LoS MIMO-Surfaces

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Abstract—The wireless research community has expressed major interest in the sub-terahertz band for enabling mobile communications in future wireless networks. The sub-terahertz band offers a large amount of available bandwidth and, therefore, the promise to realize wireless communications at optical speeds. At such high frequency bands, the transceivers need to have larger apertures and need to be deployed more densely than at lower frequency bands. These factors proportionally increase the far-field limit and the spherical curvature of the electromagnetic waves cannot be ignored anymore. This offers the opportunity to realize spatial multiplexing even in line-of-sight channels. In this paper, we overview and compare existing design options to realize spatial multiplexing in line-of-sight multi-antenna channels.

Index Terms—Sub-terahertz, line-of-sight, multiple-input multiple-output, metamaterials, holographic surfaces.

I. INTRODUCTION

The wireless research community has recently expressed major interest in investigating the opportunities offered by the sub-terahertz (sub-THz) band (30-300 GHz) for future mobile communications [1]. At these high frequencies, point-to-point multiple-input multiple-output (MIMO) links can support the transmission of multiple data streams even in line-of-sight (LoS) channels, by capitalizing on the large aperture of the transceivers, the short transmission range between them, and the small wavelength that characterizes sub-THz signals [2], [3]. The transmission of multiple data streams on the same physical resource is usually referred to as spatial multiplexing, multimode communication, or high-rank transmission. At sub-THz frequencies, the electromagnetic waves exhibit a distinct spherical wavefront, which shifts traditional design paradigms based on far-field beamforming antenna-arrays towards near-field focused electrically-large surfaces [4], [5], offering the opportunity of integrating communication and radar sensing in a single transceiver as well [6].

LoS MIMO communication is not a new field of research and several works exist in the literature, e.g., [7], [8], [9]. However, conventional spatial multiplexing MIMO schemes have inherently relied on the underlying existence of rich-scattering channels. In point-to-point MIMO links characterized by large-aperture transceivers (also known as extra-large MIMO or XL-MIMO), short distances among the antenna arrays (short-range MIMO), and high frequencies, however, multipath propagation may not be rich enough but, at the same time, multipath propagation becomes not essential to support multimode communications. In light of this emerging trend in wireless communications, which is fueled by the interest in utilizing the sub-THz frequency band, in this article we describe the main existing options to realize spatial multiplexing LoS MIMO communications, and discuss their advantages and limitations. For brevity, we focus our attention on high signal-to-noise ratio (SNR) scenarios, where spatial multiplexing is the desired choice. In general, it is known that the rank of the channel needs to be optimized as a function of the SNR [10].

Specifically, we discuss three main design principles and architectures (see Fig. 1): (1) MIMO-surfaces (also known as holographic surfaces) that are virtually continuous electromagnetic objects whose array elements are spaced less than half-wavelength; (2) half-wavelength spaced MIMO-arrays, which is nowadays the typical implementation; and (3) optimally-spaced MIMO-arrays, in which the element spacing is larger than half-wavelength. For ease of discussion, we refer to linear antenna-arrays and, therefore, we consider MIMO-lines instead of MIMO-surfaces. MIMO-lines and MIMO-surfaces are tightly intertwined [7], [11]. With the term antenna we refer to each of the three implementations, considering the antenna-array as a whole electromagnetic object.

II. SPATIAL MULTIPLEXING IN LO S MIMO CHANNELS

The possibility of supporting spatial multiplexing in LoS MIMO channels depends on the interplay of

1) large-aperture antennas
2) short-range links
3) high carrier frequencies

and, specifically, on their relationship according to the concept of Fraunhofer distance of an antenna, which determines the
boundary between the far-field region and the radiating near-field region (i.e., the Fresnel region).

Conventionaly, the space around a transmit antenna is divided into several regions, which depend on the characteristics of the field emitted by the antenna itself. The closest area to the antenna corresponds to the reactive near-field region, where the reactive components of the field are dominant. By increasing the observation distance from the antenna, there is the radiating near-field region (or Fresnel region), and then the far-field region (or Fraunhofer region). The boundary of the radiating near-field region and the far-field region is conventionally identified by the so-called Fraunhofer distance, which is defined as [12]

\[ r_{ff} = \frac{2L^2}{\lambda} \]  

(1)

where \( L \) is the antenna size, and \( \lambda \) is the wavelength. For antenna-arrays composed of several array elements, \( L \) is to be intended as the whole length (aperture) of the antenna.

When two antennas are in the far-field of each other, the rank \( (R) \) of the corresponding LoS MIMO channel is \( R = 1 \) [12]. Therefore, a single communication mode (a plane wave) is well-coupled between the two antennas. In the Fresnel region, on the other hand, the number of communication modes can be larger than one, thus supporting spatial multiplexing even in LoS MIMO channels [7].

The near-field and far-field regions are usually referred to as the whole length (aperture) of the antenna.

III. LOS MIMO: MODELS AND ARCHITECTURES

In this section, we discuss three main design principles and architectures to support spatial multiplexing in LoS MIMO channels (see Fig. 1): (1) MIMO-lines that are virtually continuous electromagnetic objects whose array elements are spaced less than half-wavelength; (2) half-wavelength spaced MIMO-arrays, which is nowadays the de facto implementation; and (3) optimally-spaced MIMO-arrays, in which the element spacing is larger than half-wavelength.

A. MIMO-Lines

As a first option, we consider highly-flexible antennas that are realized, for example, with metasurfaces [5]. These structures can approximate ideal apertures, and possess almost complete control and design of the electrical currents on their surface when they operate as transmitters, and complete control in terms of sensing the incident electromagnetic fields when they operate as receivers. In the recent literature, these structures are referred to as holographic MIMO [3], continuous aperture MIMO [15], or large intelligent surfaces [16].

As far as MIMO-lines are concerned, the number of communication modes that can be supported in LoS channels is theoretically infinite, since they operate in an infinite-dimensional space. In practice, due to the finite size of the surfaces, only a finite number of modes are, however, strongly coupled. Specifically, the electromagnetic waves that correspond to strongly coupled modes reach the receiving MIMO-line with sufficient power. The electromagnetic waves that correspond to weakly coupled modes, on the other hand, are mostly spread away from the receiving MIMO-line [7]. The number of strongly coupled modes is usually referred to as the degrees of freedom (DoF) of the system. In the sequel, this is denoted by \( R = \text{DoF} \).

Under the paraxial propagation condition, the number of strongly coupled communication modes is given, with good approximation, by [7]

\[ R \approx \max \left\{ 1, \frac{L_T L_R}{\lambda D} \right\} \]  

(2)

where \( L_T \) and \( L_R \) are the lengths of the transmitting and receiving MIMO-line, respectively, and \( D \) is the distance between their center-points. In particular, (2) is valid when \( L_T, L_T \ll D \). Differently, when such a condition does not hold, the authors of [13] have shown that the number of strongly coupled communication modes is well approximated by

\[ R \approx 1 + \frac{2L_T L_R}{\lambda \sqrt{4D^2 + L_R^2}} \]  

(3)

if \( L_R \gg L_T \).

The expression in (3) is applicable in the so-called geometric near-field region, which is the operating region in which the distance between the transmitting and receiving antennas is comparable with the their sizes. It is worth mentioning that the geometric near-field region is different from the Fraunhofer far-field distance, since the latter depends on the wavelength as well. Specifically, (3) accounts for the fact that the maximum number of communication modes is upper-bounded by the antenna with the smallest size, i.e., the transmitting surface in (3). Indeed, we obtain \( R_{\text{max}} \rightarrow 2L_T/\lambda \) if \( L_R \rightarrow \infty \).

In order to leverage the \( R \) communication modes in (2) or (3), and to transmit \( R \) modulated symbols in an interference-free manner, it is necessary to appropriately engineer the electric field (or the surface currents) on the transmitting and receiving antennas. This is sketched in Fig. 2. Specifically, the electric field on the aperture of the two antennas can be
expressed in terms of two basis functions \(a_1, a_2, \ldots, a_R\) at the transmitter and \(b_1, b_2, \ldots, b_R\) at the receiver, respectively, such that each basis function in the transmitting domain contributes only to one basis function in the receiving domain. The resulting \(R\) connected basis functions correspond to the strongly coupled communication modes (whose intensity is denoted by \(c_1, c_2, \ldots, c_R\) in Fig. 2).

In mathematical terms, by virtue of the (scalar) one-dimensional Fresnel-Kirchhoff diffraction integral, we have [11, Eq. (1)]

\[
E_R(x_R) \propto \int_{L_T} G(x_T, x_R) E_T(x_T) \, dx_T
\]

(4)

with

\[
G(x_T, x_R) = \sum_{n=1}^{\infty} c_n a_n(x_T) b_n(x_R)
\]

\[
\approx \sum_{n=1}^{R} c_n a_n(x_T) b_n(x_R)
\]

(5)

(6)

where \(E_T(x_T)\) and \(E_R(x_R)\) are the electric fields on the aperture of the transmitting and receiving antennas, respectively, and \(G(x_T, x_R)\) is the Green function in free space.

The obtained analytical formulation in (6) is similar to that of spatial multiplexing in conventional MIMO-arrays [12], with the caveat that MIMO-arrays operate in a finite-dimensional space whose dimension is determined by the number of array elements at the transmitting and receiving antennas.

B. Half-Wavelength Spaced MIMO-Arrays

In state-of-the-art MIMO communications, the antenna elements of MIMO-arrays are usually spaced at the critical distance of \(\lambda/2\). Let us assume that \(N\) and \(M\) array elements are available at the MIMO transmitter and MIMO receiver, respectively. Let \(g_{n,m}\) denote the complex channel between the \(n\)th element of the transmitting array and the \(m\)th element of the receiving array, with \(n = 1, \ldots, N\) and \(m = 1, \ldots, M\). The channel elements can be arranged in an \(M \times N\) channel matrix \(G = \{g_{n,m}\}\) whose rank \(\hat{R}\) determines the number of communication modes, and hence the spatial multiplexing gain. By definition, the rank is upper-bounded by

\[
R_{\text{max}} = \min \{N, M\}.
\]

(7)

When the transmitting and receiving MIMO-arrays are in the Fraunhofer far-field region of each other, the channel rank is \(R = 1\), even if \(N, M > 1\) [12]. If the two MIMO-arrays are in the Fresnel region of each other, on the other hand, the channel rank is \(1 \leq R \leq R_{\text{max}}\). However, the rank cannot be larger than the rank of a MIMO-line, which is approximately equal to (2) or (3). Specifically, from (2) and (3), we have, respectively, the following equations under the paraxial approximation:

\[
R \approx \min \left\{ \max \left\{ 1, \frac{L_T L_R}{\lambda D}, \frac{N}{M} \right\} \right\}
\]

(8)

and

\[
R \approx \min \left\{ 1 + \frac{2L_T L_R}{\lambda \sqrt{D^2 + L_R^2}}, \frac{N}{M} \right\}.
\]

(9)

In the limit \(M \to \infty\) (i.e., \(L_R \to \infty\)), the channel rank tends to

\[
R \approx \min \left\{ 1 + \frac{2L_T}{\lambda}, N \right\}
\]

(10)

which shows that the number of communication modes depends on the electrical length of the MIMO-array with the smallest size.

C. Optimally-Spaced MIMO-Arrays

A third option to support spatial multiplexing in LoS MIMO channels is to optimize the locations of the array elements at the transmitting and receiving antennas [8]. Let us assume that the transmitting and receiving MIMO-arrays have lengths \(L_T\) and \(L_R\), respectively, and that they are made of \(N = M\) array elements. Assuming that the array elements are evenly distributed, the inter-distances between them at the transmitting and receiving antennas are \(d_T = L_T/(N - 1)\) and \(d_R = L_R/(M - 1)\), respectively.

The rationale behind the design of optimally-spaced MIMO-arrays is to identify the locations of the array elements to ensure that the rank of the channel is \(R = N\). A rank-\(N\) channel can be established provided that the array elements are equally spaced by the Rayleigh distance [8]. Without posing limits on the sizes \(L_T\) and \(L_R\), the Rayleigh spacing results in the following condition:

\[
d_T d_R = \frac{\lambda D}{N}, \quad d_T = d_R = \frac{\lambda d_{\text{opt}}}{\sqrt{D N}} = \frac{\sqrt{D N}}{\lambda}
\]

(11)

Equation (11) is derived under the assumption that the lengths \(L_T\) and \(L_R\) can be optimized based on the optimal inter-distance \(d_{\text{opt}}\). If the lengths \(L_T\) and \(L_R\) are, on the other hand, fixed, the number of communication modes that can be supported while preserving the orthogonality is [8]

\[
R_{\text{max}} = 1 + \frac{L_T L_R}{2\lambda D} + \sqrt{\left(1 + \frac{L_T L_R}{2\lambda D}\right)^2 - 1}
\]

(12)
It is interesting to note that (12) is approximately equal to (2), even though the analytical derivation is different. By direct inspection of (12), we note that \( d_{\text{opt}} \) is, in general, greater than \( \lambda \), which implies that spatial multiplexing in LoS conditions requires the deployment of sparse MIMO-arrays.

D. Comparison Among the Three Considered Implementations

In the previous sub-sections, we have presented three different architectures to support spatial multiplexing in LoS MIMO channels. We have observed that all of them provide the same number of (effective or strongly coupled) communication modes. However, the three architectures have different implementation requirements, and, therefore, complexity and deployment tradeoffs. Specifically, the following considerations are in order.

Optimally-spaced MIMO-arrays. This architecture is able to support a number of communication modes that coincides with the number of antenna elements, provided that no constraints are imposed on the physical size of the array structure. Compared with critically-spaced MIMO-arrays with the same size, a major benefit of optimally-spaced MIMO-arrays is requiring a number of radio frequency chains that is equal to the number of communication modes, which is a parsimonious implementation design [7]. However, optimally-spaced MIMO-arrays usually offer a lower beamforming gain compared with critically-spaced MIMO-arrays of the same size, since the latter have a larger number of array elements. This may be an unfavorable feature for transmission at high frequency bands [8]. In addition, the optimal inter-distance \( d_{\text{opt}} \) depends on the transmission distance \( D \). As a result, the locations of the array elements need to be varied with the transmission distance [10], which may not always be possible. Also, the size of the resulting array structure may be large. To circumvent these issues, rotations or the electronic selection of multiple antenna arrays with a radial disposition may be utilized [9].

Half-wavelength spaced MIMO-arrays. Critically spaced MIMO-arrays provide a solution to circumvent the need of varying the locations of the array elements as a function of the transmission distance. The larger number of array elements, in addition, provides larger beamforming gains if the size of the two structures is the same [8]. This architectural solution, however, necessitates a number of radio frequency chains that is equal to the number of array elements, which is usually greater than the number of communication modes supported by the LoS MIMO channel. Specifically, we have

\[
\frac{L_T L_R}{\lambda D} \leq \left\lfloor \frac{2 L_T}{\lambda} \right\rfloor + \left\lfloor \frac{2 L_R}{\lambda} \right\rfloor
\]

where the left-hand side denotes the number of radio frequency chains required for optimally-spaced MIMO arrays and MIMO-lines, and the right-hand side denotes the number of radio frequency chains required for half-wavelength spaced MIMO-arrays.

An option to reduce the number of radio frequency chains consists of utilizing arrays of sub-arrays, in which each sub-array is centered at the location identified by the optimal inter-distance in (11) and the elements of each sub-array are critically spaced at \( \lambda/2 \). The number of radio frequency chains is equal to the rank of the channel, but the centers of the sub-arrays need to be varied with the transmission distance [8].

MIMO-lines. MIMO-lines enable the design of hybrid MIMO architectures with a number of radio frequency chains that is equal to the rank of the channel, provided that optimal basis functions are utilized for engineering the electric fields on the transmitting and receiving apertures (as illustrated in Fig. 2) [2]. If the number of radio frequency chains is given, in addition, the number of effective communication modes can be inherently adapted to the transmission distance, the apertures of the antennas, and the operating frequency, provided that the basis functions on the transmitting and receiving apertures are appropriately chosen [11]. Compared to \( (\lambda/2) \)-spaced MIMO-arrays, the benefits of continuous-aperture MIMO-antennas are well known, and include the possibility of reducing the grating lobes and providing higher performance for large values of oblique angles of incidence [15]. Moreover, quasi-continuous sub-wavelength implementations offer the possibility to exploit the mutual coupling among the antenna elements by design, and to realize super-directive MIMO-antennas [17]. In fact, \( (\lambda/2) \)-spaced MIMO-arrays are sufficient to sense an electric field, provided that the observation plane is at distances from the transmitting and receiving antennas where the evanescent waves can be ignored [18, Section 1.4.3]. Otherwise, it is necessary to consider inter-distances shorter than half-wavelength. However, the critical spacing at \( \lambda/2 \) renders the mutual coupling among the antenna elements negligible, thus simplifying the antenna design.

IV. Conclusion

In this paper, we have overviewed and compared existing design options to support spatial multiplexing in LoS MIMO channels, by considering implementations based on MIMO-arrays and MIMO-surfaces.

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