Holographic Communication using Intelligent Surfaces

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Abstract

Holographic communication is intended as an holistic way to manipulate with unprecedented flexibility the electromagnetic field generated or sensed by an antenna. This is of particular interest when using large antennas at high frequency (e.g., the millimeter wave or terahertz), whose operating condition may easily fall in the Fresnel propagation region (radiating near-field), where the classical plane wave propagation assumption is no longer valid. This paper analyzes the optimal communication involving large intelligent surfaces, realized for example with metamaterials as possible enabling technology for holographic communication. It is shown that traditional propagation models must be revised and that, when exploiting spherical wave propagation in the Fresnel region with large surfaces, new opportunities are opened, for example, in terms of the number of orthogonal communication channels.

Index Terms

Holographic communication; intelligent surfaces; fundamental limits; degrees of freedom; communication modes.

I. HOLOGRAPHIC COMMUNICATION

The increasing demand of ubiquitous, reliable, fast and scalable wireless services is pushing today’s radio technology towards its ultimate limits. The current deployment of the fifth-generation (5G) wireless networks is expected to exploit increasingly multiple-input multiple-output (MIMO) techniques and cell densification, in order to serve a large number of users per area with the required throughput. However, for the sixth-generation (6G) wireless networks, even more stringent requirements are set in terms of data-rate, number of users, reliability, with the goal of enabling massively novel applications, for instance, in the fields of industrial Internet-of-things (IIoT) and autonomous driving. In this context, a significant increase of the number of antennas is required (massive-MIMO), in conjunction with the exploitation of higher frequencies, where larger bandwidth is available \[1\].

The use of millimeter wave and terahertz technologies translates into a larger path-loss, which can be partially compensated by antennas densification and large antenna arrays. \[2\]. Indeed, the shift towards large antennas and high frequency poses new challenges since traditional models based on the assumption of far-field electromagnetic
Figure 1. Fraunhofer region boundary as a function of the frequency, for different antenna size $D$. Practical operating distances in the millimeter wave band follow below the Fraunhofer boundary (i.e., in the Fresnel region of the antenna).

(EM) propagation fail, but opens new opportunities at the same time. In fact, in classical operating conditions, i.e., in the Fraunhofer region of the antenna, the radio link is much longer than the antenna dimension, so that plane wave propagation is assumed. Conversely, when the antenna size becomes comparable to the link distance, operating conditions fall within the Fresnel region in which (radiating) near-field propagation takes place. Fig. 1 shows the commonly-assumed boundary between the Fresnel and Fraunhofer regions as a function of the operating frequency, from ultra-high frequency (UHF) to terahertz, considering different sizes of the antenna. Notably, the lower part of the graph corresponds to the operation in the Fresnel region, whereas the upper part corresponds to the operation in the Fraunhofer region. As it is evident from the figure, when antennas between 10 cm and 1 m are considered for applications in the millimeter wave band, typical operating distances between 1 and 100 meters are included almost entirely in the Fresnel region, where plane wave approximation of the wave front does not hold anymore, and spherical wave front propagation must be considered instead. If, from one side, operation below the Fraunhofer region boundary requires the consideration of new models capable of accounting for this regime, from the other side it opens new unexplored possibilities to enhance the communication performance.

In this context, to fully exploit the characteristics offered by different EM propagation regimes and thus approach the ultimate limits of the wireless channel, the complete control of the EM field generated/sensed by antennas should be reached. This is the concept of holographic communication. The term holography derives from the ancient greek ὅλος, holos, (all), and γράφει, grafe, (writing, drawing) and it literally means “describe everything”. The holographic capability of a transmitting antenna in the near-field consists in the possibility to generate any
current density distribution on its surface, in order to obtain the maximum flexibility in the design of the radiated EM field (amplitude, wave front, polarization...). Similarly, the holographic capability at the receiving antenna side consists in the possibility to weight the impinging electric field according to a desired function, thus manipulating the way the antenna receives the information without the need of any physical modification of its shape.

From the technological point of view, metamaterials represent appealing candidates toward the creation of intelligent surfaces, which can lead to a viable way of realizing highly-flexible antennas [3]–[7]. In fact, metamaterials enable the manipulation of the EM field or the local control of amplitude and phase reflecting behavior at an unprecedented level, thus enabling the design of specific characteristics in terms of reflection, refraction, absorption, polarization, focusing and steering, when used as reflecting surfaces. In the last years, the idea of deploying semi-passive reconfigurable reflecting elements in the environment has attracted a considerable research attention. Such solutions, based on additional entities referred to as intelligent reconfigurable surfaces (IRSs) or reconfigurable intelligent surfaces (RISs), are able to create artificial multipath or additional communication channels between a transmitter and a receiver, thus increasing the coverage and the degrees-of-freedom (DoF) of wireless communication [8], [9]. As active antennas, intelligent surfaces can be exploited to increase the number of design variables allowing to operate directly at EM level by processing electromagnetic waves with unprecedented level of flexibility and resolution. When such antennas are electrically large, they are referred to as large intelligent surfaces (LISs) [10]; this definition will be adopted in the rest of the paper. Due to the large size, the radio propagation at millimeter...
waves and even in the terahertz band may occur in the near-field region of the antenna even at practical distances, and thus traditional assumptions resorting to planar wave front cannot be anymore considered valid. The adoption of LISs provides high flexibility in network design as well as the potential to achieve the goals of next generation wireless networks, but it also opens several fundamental questions that are still unsolved, such as understanding the theoretical limits of these communication technologies and how to achieve them in practice.

This paper presents the fundamentals of communication with LISs. In particular, the limits of traditional communication models and the new opportunities offered by the spherical wave front propagation in the Fresnel region are discussed, showing that it is possible to increase significantly the number of orthogonal communication channels between a couple of LISs, even in line-of-sight (LOS) and without the need of rich multipath propagation. Finally, the main open research directions in this field are highlighted.

II. INFORMATION-THEORETICAL OPTIMAL COMMUNICATION BETWEEN LISs

A LIS denotes an intelligent metasurface whose size $D$ is much larger than the operating wavelength, and often comparable to the radio link distance $d$ (see Fig. [2]). When such conditions hold, it is fundamental to account for proper modeling of the EM propagation. In fact, with LISs, classical models for antenna arrays may fail to describe correctly the actual wireless link characteristics in terms of path-loss and number of communication modes, i.e., orthogonal EM channels, that can be exploited for communication, as they typically assume far-field conditions. In addition, classical models are based on specific current distributions related to the antenna shape (e.g., dipole, patch, spiral...), without accounting for the flexibility in generating these distributions offered by metasurfaces (holographic capability). Therefore, the models adopted for the description of communication with LISs must account for this design flexibility thus relying directly on considerations concerning the transportation of information with EM waves in the continuous wireless channel (EM information theory).

In order to abstract from the specific implementation of the metasurface, we model the intelligent surface as a continuous array of an infinite number of infinitesimal antennas. The wireless communication exploiting an uncountable infinite number of antennas in a finite space has been recently defined as holographic MIMO [9], [11]. In this manner, implementation-related aspects concerning the mutual coupling among the metasurface elements are not involved in the discussion.

Optimal communication between LISs, considering a continuum of infinitesimal antennas and the continuous wireless channel, can be modeled as the problem of communicating between a couple a spatial regions (or volumes in the case the antenna thickness is not considered negligible). This enables moving away from the classical MIMO model of point-defined antennas, which can be considered as a particular case of this general formulation, where the continuous space EM channel and continuous signals (propagating waves) are sampled according to a specific placement of the array elements. Then, communication is viewed as a functional analysis problem depending only on geometric relationships, whose goal is to determine the optimal set of EM functions at transmitter and receiver sides to transfer information between the spatial regions. In this manner, the ultimate limits for communication, namely the intrinsic capacity of the continuous-space wireless channel, can be investigated independently of the
Figure 3. Optimal communication between intelligent surfaces. Example of orthogonal basis function used at the transmitting surface, whose combination gives the current density $J(s)$. By proper design, orthogonal functions are obtained also on the receiving antenna surface, whose linear combination gives the electric field $E(r)$. Parallel orthogonal channels with coupling intensities $\{\xi_n\}$, namely communication modes, can be realized.

Specific technology and number of antenna elements.

In the pictorial example of Fig. 2, a LIS placed on a large wall (e.g., base station) communicates with an antenna embedded in a portable device in LOS channel condition. Specifically, with reference to Figs. 2 and 3, we consider a set of functions $\{\phi_n(s)\}$ with $s \in S_T$, representing any complete basis set of the transmitting surface $S_T$, and a set of functions $\{\psi_n(r)\}$ with $r \in S_R$, representing any complete basis set of the receiving surface $S_R$, for $n = 0, \ldots, \infty$. As a consequence, any current density $J(s)$ on the surface $S_T$ can be represented as a proper linear combination of the transmitting basis functions $\{\phi_n(s)\}$, while a proper linear combination of the receiving basis functions $\{\psi_n(r)\}$ describes the electric field $E(r)$ on the surface $S_R$. Among the possible choices of the basis sets, an interesting case is that for which the communication operator, which puts into relation the transmit basis function $\phi_n(s)$ with the receiving basis function $\psi_n(r)$, is diagonal, meaning that there is a one-to-one correspondence between $\phi_n(s)$ and $\psi_n(r)$ through a multiplicative coupling coefficient $\xi_n$, with as large coupling intensity as possible. This is the concept of communication mode [12].
In order to determine the communication modes, an eigenfunctions problem starting from an electromagnetic
description of the continuous wireless channel must be solved; the kernel of the problem is connected to the Green
function putting in relationship the effect on a given point of the receiving surface (wave) with an infinitesimal point-
wise excitation given on the transmitting surface. The solution to the eigenfunctions problem gives the information-
theoretical optimal communication strategy, and the current density excitation $\phi_n(s)$ at transmitter side will produce
an effect (electric field) $\psi_n(r)$ at receiver side, without the excitation of the other modes [13]. Therefore, multiple
parallel and orthogonal channels can be established, as depicted in Fig. 3. Notice that, in analogy with MIMO, we
can see the transmitting function as a form a pre-coding vector, and the receiving function as a form of combining
vector, but at EM level.

In practice, since the spatial regions of the antennas are confined, the number of significant (large) eigenvalues
is limited. Therefore, the number of communication modes is defined conventionally as the minimum number $N$ of
eigenvalues sufficient to describe the signals within a given level of accuracy, e.g., compared to the noise intensity.
This translates into the possibility to represent any current and field distribution as the combination of a limited
number of communication modes allowing significant information transfer. More specifically, we obtain the input-
output representation in terms of $N$ parallel channels (the communication modes) $y_n = \xi_n x_n + w_n$, for $n = 1, 2, \ldots, N$,
being $w_n$ the additive white Gaussian noise (AWGN), where the $N$ input data streams $\{x_n\}$ are associated to the basis
functions $\{\phi_n(s)\}$ in $S_T$, and they are recovered at the receiver after the (spatial) correlation of the received electric
field with the corresponding basis functions $\{\psi_n(r)\}$ in $S_R$, as shown in Fig. 3. The eigenfunction decomposition
ensures that the current distribution $\phi_1(s)$ in $S_T$ leads to the electric field $\xi_1 \psi_1(r)$ within $S_R$ with the largest
intensity $|\xi_1|^2$. The current distribution $\phi_2(s)$ in $S_T$ leads to the electric field $\xi_2 \psi_2(r)$ within $S_R$, orthogonal to
$\xi_1 \psi_1(r)$, with the second largest intensity $|\xi_2|^2$, and so on. Each pair of functions $(\phi_n(s), \psi_n(r))$ determines a spatial
dimension of the system across which one can establish an orthogonal communication which can be exploited to
maximize the capacity using the waterfilling approach. A large level of coupling means that the generated wave is
confined approximately within the space between $S_T$ and $S_R$, thus impressing a current on the receiving surface
$S_R$. Instead, a low level of coupling denotes that the generated wave is mainly dispersed away from the receiver’s
surface $S_R$.

Finding the solution of the eigenfunctions problem, thus defining the optimal set of basis functions and coupling
coefficients at transmitter and received side, requires extensive and sometimes prohibitive simulations if large
surfaces are considered. In particular, a discretization into a fine mesh of the transmitting and receiving regions can
be realized, then solving numerically the eigenfunctions problem and applying singular value decomposition (SVD)
for resorting to the simplest description of the communication operator. Some analytical results related to specific
geometric configurations can be found in [13] from which some interesting insights can be obtained. Examples of
basis functions for square surfaces are reported in Fig. 3.
III. COMMUNICATION MODES

When the size of both surfaces is small compared to the distance $d$ separating them, the number of communication modes $N$ is known from results originally obtained for optical communication by resorting to diffraction theory. Specifically, it is $N = A_T A_R / (\lambda d)^2$, where $A_T = |S_T|$ and $A_R = |S_R|$ are the areas of the two surfaces and $\lambda$ is the wavelength. In the far-field, for large $d$, the number of communication modes $N$ is unitary in LOS propagation, and the coupling intensity (i.e., the channel gain) scales with $d^2$. This result comes from the analytical solution of the eigenfunctions problem leading to prolate spheroidal wave functions (PSWFs) as eigenfunctions, whose eigenvalues are in fact almost equally-sized up to a certain limit, then dropping rapidly to zero \cite{14}. Specifically, it is based on the paraxial approximation for parallel and collinear surfaces, and it can be exploited also in the Fresnel region of the surfaces, but under the condition that the link distance $d$ remains much larger than the surface’s size $D$. When using LISs, the previous result might be no longer valid as it is likely the surfaces work in their Fresnel region and with link distance $d$ comparable with the surface’s size $D$, as depicted in Fig. 2.

We report now some recent results obtained for communication between a relatively small surface and a LIS \cite{13}. Fig. 4 shows the number of communication modes $N$ that can be obtained in this configuration. In particular, a transmitting surface of area $A_T = 5 \times 5 \text{ cm}^2$, and frequencies of 28 GHz and 60 GHz are considered. Both the cases of parallel and perpendicular orientations among the LISs are reported, as well the case of LISs with different
aspect ratios, i.e., a square LIS of area $A_R$, and a rectangular LIS of the same area, with 4:1 aspect ratio between height and width. Obviously, due to the reciprocity of the radio medium, the transmitting and receiving surfaces role can be exchanged. The number of communication modes is plotted as a function of the ratio $d^2/A_R$. It is evident how a large number of communication modes can be obtained even in the LOS scenario (no exploitation of multipath), thus boosting significantly the channel capacity at EM level. The result known for the small antenna approximation is also reported for comparison; it can be noticed that without accounting for the near-field behavior, a large overestimation of the number of communication modes is obtained, especially when a rectangular LIS is considered.

When the distance among the surfaces increases, the number of communication modes decreases and the small surface approximation becomes valid. Under this condition, $N$ is lowered by a factor $\sqrt{d/A_R}$ in the perpendicular configuration. Differently from the far-field condition, where no communication can be established among perpendicular surfaces, this is not true in the near-field, for which a significant number of communication modes can still be obtained, especially when the surface’s size is comparable with the link distance.

For very large distances, the limit $N = 1$ arises. On the other extreme cases, i.e., when the LIS becomes very large, the number of communication modes for parallel surfaces is given by $\pi A_T/A^2$ [13] and it depends only on the area of the transmitting surface, i.e., the smallest surface, normalized with respect to the square wavelength. It is interesting that the same limit arises also for perpendicular surfaces.

IV. POWER SCALING LAW

As for the number of communication modes, the near-field characteristics must be accounted also in deriving the power scaling law between a transmitter and a receiver, namely the channel power gain. When multiple communication modes are excited, the gain is considered as the ratio between the overall received power and the overall transmitted power which equals the sum of the coupling intensity of all the communication modes and it depends only on the geometric configuration [14].

Fig. 5 reports the channel power gain in the communication between an isotropic antenna and a square LIS in the same configuration as in the previous section. Notice that, due to the assumption of isotropic transmitter, the channel power gain is independent of the operating frequency. For comparison, the classical Friis formula, which can be obtained also by considering the small antenna approximation and the solution resorting to the PSWFs (thus valid in the Fraunhofer region and, in part, in the Fresnel region), is reported. It is evident that the classical Friis formula is no longer valid when using LISs at small distances between the surfaces. This is due to the operating region in the early Fresnel region, with surface’s size comparable with the link distance, whose peculiarity is not captured by classical path-loss modelling. In fact, according to the Friis formula, increasing the size of both the transmit and receive surfaces could lead to the increasing of the power gain at any level. This is in contrast with the law of conservation of energy, for which the received power cannot overcome the transmitted one. When one of the two surfaces becomes large, thus working in the near-field, an intrinsic limitation arises, and the maximum channel power gain (with respect to the isotropic antenna) saturates to $1/3$ ($-4.77$ dB) [13]. Thus, with an infinite-size
square LIS, no more than 1/3 of the transmitted power can be collected. The limit arises naturally, and it is due to three phenomena happening with LIS: when the surface becomes large (i) the distance from the point source to the specific location of the receiving LIS can be substantially larger than the link distance (i.e., distance from the point source to the LIS center), thus producing higher attenuation; (ii) points far from the LIS center exhibits a smaller local effective area as seen by the transmitter; (iii) the polarization mismatch increases for points far from the LIS center [15].

It is interesting to underline that the result of Fig. 5 is general, and it does not depend on the operating frequency, but it is determined only by geometric factors normalized to the wavelength. The point at which the channel power gain diverges from that predicted by the Friis formula corresponds to a link distance $d$ close to the surface’s size $D$, for square surfaces, while it is larger for rectangular surfaces. This is different from the classical definition of the boundary between Fraunhofer and Fresnel regions, which is frequency-dependent. Power scaling laws for more complex scenarios involving the presence of RIS and relays can be found in [15].

V. RESEARCH DIRECTIONS AND CONCLUSION

Reaching the ultimate limits in wireless communication cannot disregard the physical limits of EM propagation, especially when operating at high frequencies and with large antennas. Along this direction, in this paper we have discussed the theoretical implications when using LIS as active antennas, by showing the limitations of current
models and the opportunities offered when operating in the near-field regime. In fact, while in the far-field only one communication mode can be established in LOS, an increased number of communication modes can be obtained in the Fresnel region, and hence the opportunity to boost the capacity. However, the approaching of this potential improvement with practical systems requires solving several theoretical and technological challenges, some of them summarized in the following.

- **Metasurface technology:** Despite the considerable advances in metamaterials technology, which have seen the introduction of different solutions for the implementation of LIS, such as dynamic metasurface antennas (DMA) based on waveguide-fed metasurface [16], [17] and multi-beam antennas [5], a considerable gap needs to be filled toward fully flexible LISs.

- **EM-based signal processing:** In perspective, the flexibility offered by metamaterial paves the way to shift some functionalities that are typically performed in the digital domain directly at EM level with the purpose to tackle complexity issues and reduce significantly the latency, as the processing would be realized at the speed of light [4].

- **Network EM theory of information:** There is the need of a full understanding of the fundamental performance limits as well as the development of practical algorithms for wireless networks composed of multiple users, base stations, scatterers, relays and RIS under different geometrical configurations [15], [18]–[21].

- **Channel models:** One peculiarity of LISs is that the communication channel may be no longer stationary along the surface and the EM propagation may happen in the near-field condition where the wave front is spherical [22], [23]. Ad hoc channel models should be developed and validated to account for such non-stationarity, including non-stationary polarization and the effect of multipath caused by near/far-field random scatterers.

- **Channel estimation and localization:** The estimation of the channel state information (CSI) is usually one of the most critical tasks in wireless communication. Moreover, when operating in the near-field, the channel is even more informative thus increasing the associated complexity in estimation [8], [24]. On the other hand, when moving at higher frequencies, obstacles may completely block the signal and multipath components become sparse so that communication is mainly enabled by LOS conditions. As a consequence, the CSI is expected to be highly correlated to the geometric configuration of antennas, i.e., the relative position and orientation, so that CSI estimation and localization tasks become intimately linked and they can be tackled jointly.

Holographic communication is an holistic way to manipulate the EM field, generated or sensed by an antenna, with the maximum flexibility. Such flexibility can be enabled by new metamaterials designed for the realization of LISs and RIS. New wireless networks operating at millimeter wave and terahertz are expected to gain significant benefits in terms of increased capacity, reliability, and nodes densification. Perhaps, more than in the past, this process will require a tight synergy between the design at digital and EM levels by leveraging the advances in EM theory of information.
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