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Holographic Communication using Intelligent Surfaces

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***Abstract*—Holographic communication is intended as a holistic way to manipulate with an 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., at millimeter-wave or terahertz), whose operating condition may easily fall in the Fresnel region (radiating near-field), where the classical plane wave propagation assumption is no longer valid. This article 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 near-field region, new opportunities are opened, for example, in terms of feasible orthogonal communication channels.**

***Index Terms*—Holographic communication, intelligent surfaces, fundamental limits, degrees of freedom, communication modes.**

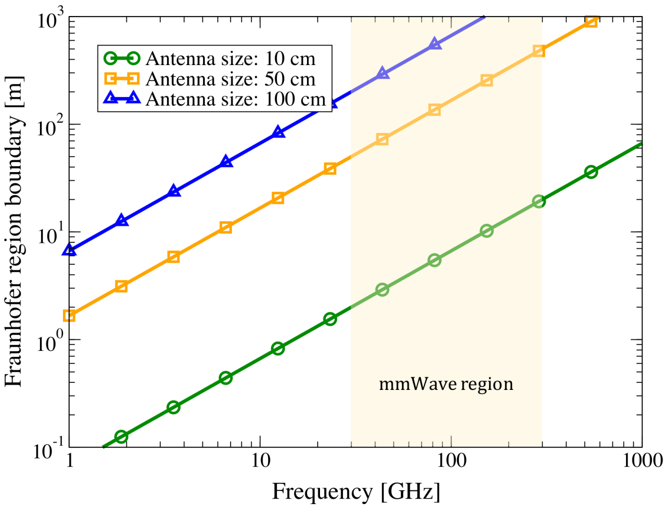

Fig. 1. Fraunhofer region boundary as a function of the frequency, for different antenna sizes. The area above each curve corresponds to the operation in the Fraunhofer region; the area below each curve corresponds to operation in the Fresnel region. Practical operating distances in the millimeter-wave band fall below the Fraunhofer boundary.

I. Holographic Communication

THE increasing demand for 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 in 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 higher path-loss, which can be partially compensated by antennas densification and large antenna arrays. Indeed, the shift towards large antennas and high frequency poses new challenges since traditional models based on the assumption of far-field electromagnetic (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 distance 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. Figure 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 the plane wave approximation of the wavefront does not hold anymore, and spherical wavefront 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 enables 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 the antennas should be

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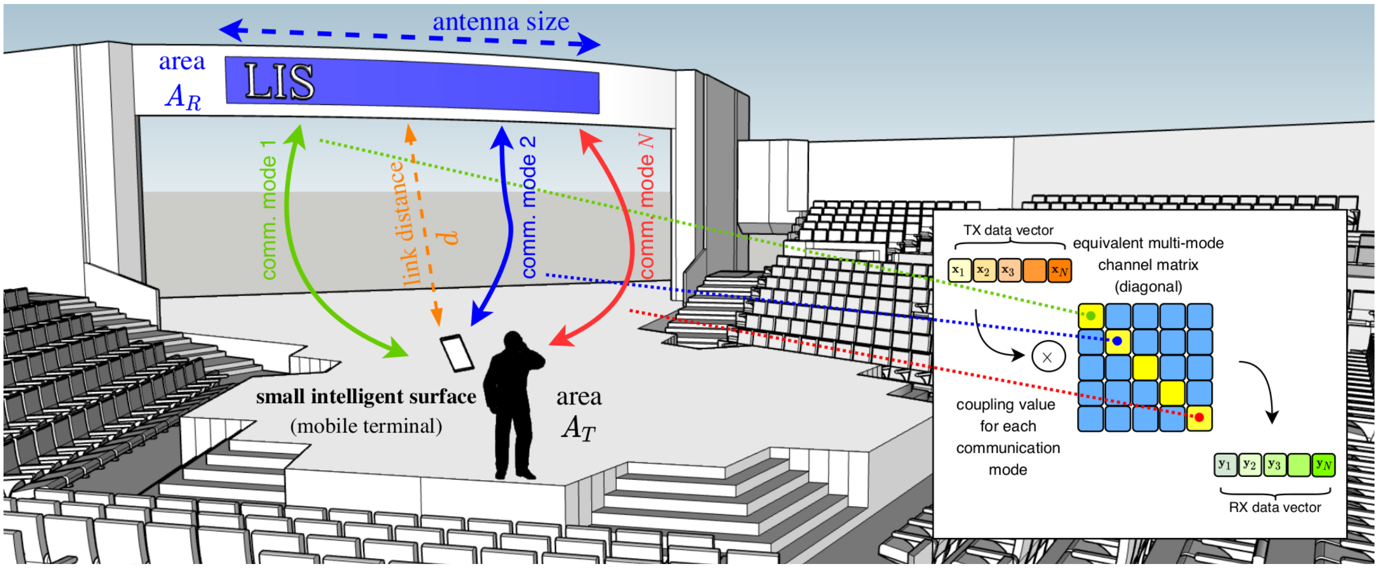

Fig. 2. Scenario with a LIS-based antenna communicating with a mobile terminal equipped with a small intelligent surface using multiple *communication modes* in LOS conditions, corresponding to parallel channels at EM level.

reached. This is the concept of *holographic communication*. The term *holography* derives from the ancient greek ὅλος, *holos*, (all), and γραφή, *grafè*, (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, wavefront, polarization, etc). Similarly, the holographic capability at the receiving antenna side consists in the possibility to correlate the impinging electric field with the desired function (in space), 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 [2]–[5]. In fact, metamaterials allow 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 reflecting surfaces (IRSs), 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 [6]. 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 [5]. When such antennas are electrically large, they are referred to as large intelligent surfaces (LISs) [7]; this definition will be adopted in the rest of the article. Due to the large size, the radio propagation at millimeter-wave 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 wavefront 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 wavefront propagation in the near-field 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 is much larger than the operating wavelength, and often comparable to the radio link distance. 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*, as they typically assume far-field conditions. The number of communications modes, that is, orthogonal EM channels, determines the DoF available for communication. In addition, classical models are based on specific current distributions related to the antenna shape (e.g.,

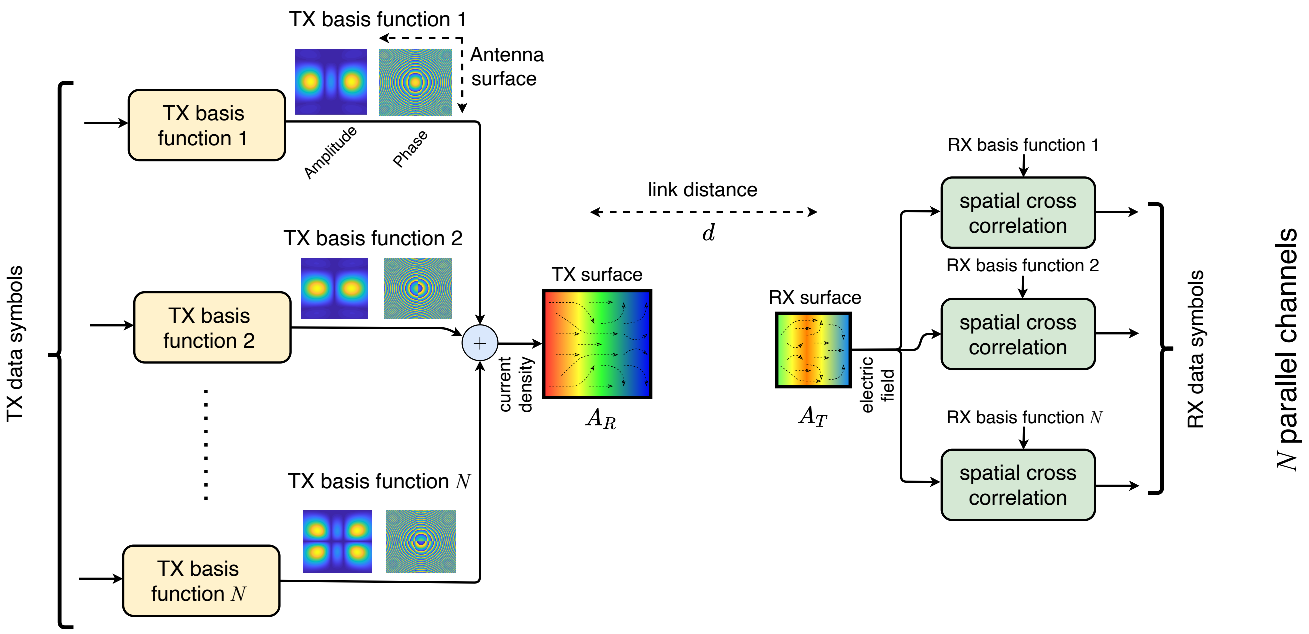

Fig. 3. Optimal communication between intelligent surfaces consisting in N orthogonal channels that can be associated to N parallel data streams. Examples of orthogonal basis functions used at the transmitting surface are depicted in each branch, whose combination gives the current density. By proper design, orthogonal functions are obtained also on the receiving surface, whose linear combination gives the electric field.

dipole, patch, spiral, etc), 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, it is possible to model the intelligent surface as a continuous array of an infinite number of infinitesimal antennas (i.e., a continuous aperture). The wireless communication exploiting an uncountable infinite number of antennas in a finite space has been recently defined as *holographic MIMO* [8]. In this manner, implementation-related aspects of the LIS, concerning for example the mutual coupling among the elements of the metasurface, 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 of 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 regions of space. In this manner, the ultimate limits for communication, namely the intrinsic capacity of the continuous-space wireless channel, can be investigated independently of the 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 representing any complete basis set of the transmitting surface, and a set of functions representing any complete basis set of the receiving surface. The number of functions both at transmitter and receiver side is, in general, countable infinite. As a consequence, any current density on the transmitting surface can be represented as a proper linear combination of the transmitting basis functions, while a proper linear combination of the receiving basis functions describes the electric field on the receiving surface. Among the possible choices of the basis sets, an interesting case is that for which the communication operator, which puts into relation the transmitting basis functions with the receiving basis functions, is diagonal (see Fig. 2). In this case, there is a one-to-one correspondence between each couple of functions on the two surfaces through a multiplicative coupling coefficient, and no mutual coupling is present with other couples. This is the concept of *communication mode* [9].

In order to determine the communication modes, an eigenfunctions problem starting from the EM description of the continuous wireless channel must be solved; the kernel of the problem is connected to the Green function putting in a relationship the effect on a given point of the receiving surface (wave) with an infinitesimal point-wise excitation current given on the transmitting surface. The solution to the eigenfunctions problem gives the information-theoretical optimal communication strategy. Specifically, a current density excitation equal to the ith basis function at transmitter side will produce an effect (electric field) proportional to the ith basis function at receiver side, without the excitation of the other modes, and with a coupling intensity given by the ith eigenvalue [10]. 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 regions of the antennas are confined, the number of significant (large) eigenvalues is limited. Therefore, the number of communication modes, that is, the DoF of the channel, 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) where the N input data streams are associated to the basis functions on the transmitting surface, and they are recovered at the receiver after the correlation (in space) of the received electric field with the corresponding basis functions on the receiving surface, as shown in Fig. 3. Each pair of functions determines a dimension of the system across which it is possible to establish an orthogonal communication that can be exploited to maximize the capacity using the water filling approach. A large level of coupling means that the generated wave is confined approximately within the space between the transmitting and receiving surfaces, thus impressing a current on the receiving surface. Instead, a low level of coupling denotes that the generated wave is mainly dispersed away from the receiver's surface.

Finding the solution of the eigenfunctions problem, thus defining the optimal set of basis functions and coupling coefficients at the transmitter and received side, requires, in general, numerical simulations. 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 the singular value decomposition (SVD). Some analytical results related to specific geometric configurations can be found in [10] from which some interesting insights can be obtained. Examples of basis functions for square surfaces are reported in Fig. 3. From the figure, it is evident that orthogonality does not imply necessarily not overlapped spatial waveforms. Therefore, beamsteering antennas, typically aimed at realizing almost not overlapped beams, are not optimal in general.

In the following, a discussion and some examples related to the number of communication modes and the power scaling law are presented. These two figures of merit are the key ingredients to derive the system capacity and they are directly connected to the most important system parameters (operating frequency, link distance, size of surfaces).

III. COMMUNICATION MODES

When the size of both surfaces is small compared to the distance separating them, the number of communication modes N is known from results originally obtained for optical communication. Specifically, the number of communication modes is given by the product of the transmitting and receiving surface areas, divided by the square of the distance-wavelength product. In the far-field, for large link distance, the number of communication modes N is unitary in LOS propagation, and the coupling intensity (i.e., the channel gain) scales down with the square of the distance. 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 [9]. Specifically, it is based on the paraxial approximation for parallel surfaces aligned along their boresight direction, and it can be exploited also in the near-field region of the surfaces, but under the condition that the link distance remains much larger than the surface's size. In the rest of the article, we refer to this case as small surfaces approximation. When using LISs, the previous condition might be no longer valid as it is likely the surfaces work in their near-field region and with link distance comparable with the surface's size, as depicted in Fig. 2.

We report now some recent results related to the communication between a relatively small intelligent surface and a LIS [10]. In particular, a transmitting small intelligent surface of an area of $5 \times 5\,\text{cm}^2$ (typical smartphone dimension), and frequencies of 28 GHz and 60 GHz are considered. Notice that, in the communication between a small intelligent surface and a LIS, the near-field region boundaries will be different for the two surfaces due to their different sizes. Then, it is likely that the LIS will be in the far-field of the small intelligent surfaces, while the small surface will be in the near-field of the LIS. In the following, we will refer to the far-field condition when both surfaces are in the far-field of their counterpart. Figure 4 shows the number of communication modes N that can be obtained in this configuration. Both the cases of parallel and perpendicular orientations among the LISs are reported, as well as the case of LISs with different aspect ratios, i.e., a square LIS, and a rectangular LIS of the same area, with 4:1 aspect ratio between its height and width. Obviously, due to the reciprocity of the radio medium, the transmitting and receiving surfaces role can be exchanged without affecting the results. The number of communication modes is plotted as a function of the ratio between the squared distance and the area of the receiving surface. 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. The result known for the small surface 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.

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

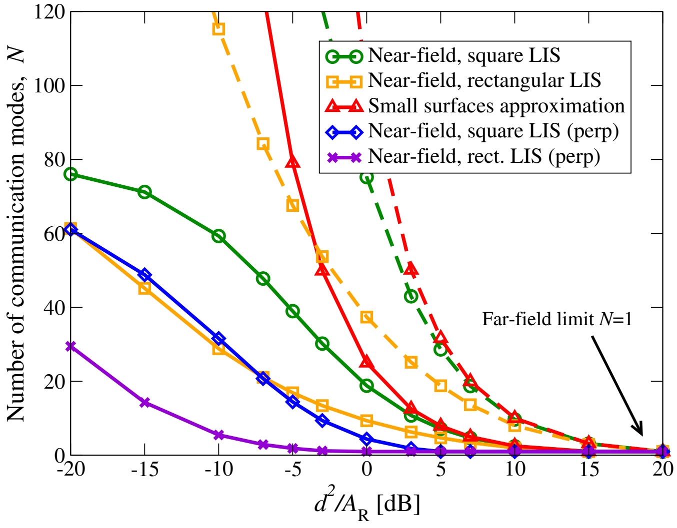

Fig. 4. Number of communication modes N as a function of the ratio d^2/A_R, where d is the link distance and A_R the LIS area, for square and rectangular LISs. Continuous lines refer to 28 GHz. Dashed lines refer to 60 GHz. For 28 GHz, parallel and perpendicular orientations among the surfaces are shown. Comparison with the result using the small surfaces approximation (red lines with △). In the far-field, $N = 1$ for LOS conditions.

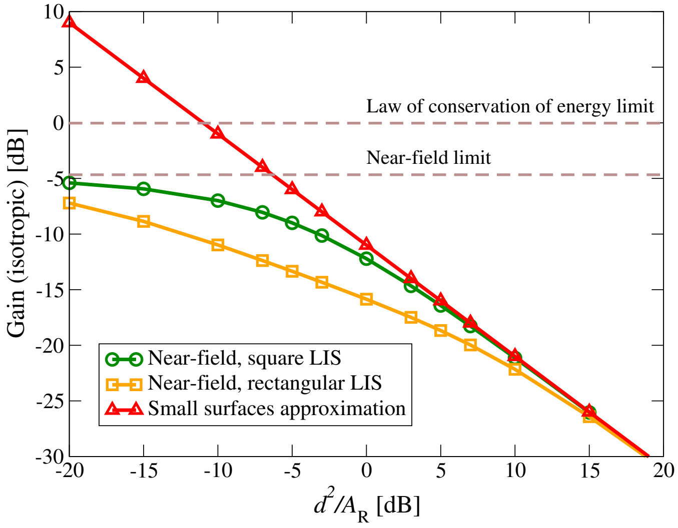

Fig. 5. Channel power gain with respect to the ratio d^2/A_R, where d is the link distance and A_R the LIS area, considering an isotropic antenna at transmitter side. Red line with △ corresponds to the traditional Friis formula, not valid when the link distance becomes comparable with the surface's size (violation of the law of conservation of energy).

the surface's size is comparable with the link distance, and even if one of the two surfaces is not very large. 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 depends only on the area of the transmitting surface, i.e., the smallest surface, normalized with respect to the square wavelength [10]. This represents the theoretical bound on the number of communication modes that can be established between two surfaces.

It is important to underline that the results of Fig. 4 refer to a LOS determinist channel. For multipath channels, ad-hoc models, even statistical, capable of capturing the channel spatial non-stationarity in the near-field should be investigated, as it will be discussed in Sec. V. However, LOS-based communication is also of great practical interest for future applications based on mm-wave and even more with the terahertz technology; in fact, it is well known that the channel tends to become sparse with the increase of the frequency and, due to the highly directional nature of propagation using beamforming techniques and large antennas, the LOS component is dominant.

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 [9].

Figure 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 surfaces approximation and the solution resorting to the PSWFs (thus valid in the Fraunhofer region and, in part, in the near-field region), is reported. It is evident that the classical Friis formula is no longer valid when using LISs at a small distance between the surfaces. This is due to the operating region in the early near-field 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) [10]. 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 LISs: 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 [11].

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

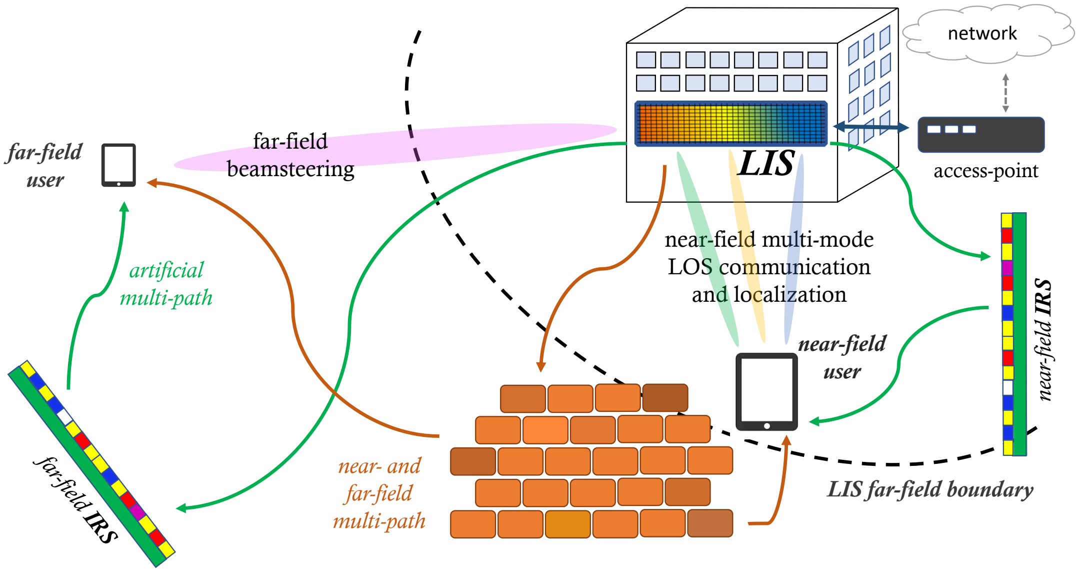

Fig. 6. Complex and realistic scenario with a LIS communicating with multiple users, both in the near- and far-field, eventually assisted by multiple IRSs, in the LIS near- and far-field themselves.

to a link distance close to the surface's size, for square surfaces, while it is larger for rectangular surfaces. This is different from the classical definition of the boundary between far-field and near-field regions, which is frequency-dependent. Power scaling laws for more complex scenarios involving the presence of IRSs and relays can be found in [11].

V. RESEARCH DIRECTIONS

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. 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 [12] and multi-beam antennas [5], a considerable gap needs to be filled towards the realization of fully flexible LISs. Practical designs will have to account also for trade-offs between flexibility in shaping the EM field and complexity, with a special emphasis on energy consumption for low-energy portable devices [2]. For instance, the DMA technology allows for a significant reduction of the number of RF chains (i.e., cost, energy consumption and complexity) with respect to the conventional full-digital and hybrid massive MIMO architectures [12].
- *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].
- *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 wavefront is spherical [13], [14]. 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. The presence of mutipath components generated by scatterers located in the near-field can be in principle exploited to augment the communication modes, and hence the system capacity.
- *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 [6]. 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.
- *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 the optimization of complex wireless networks composed of multiple users, base stations, scatters, relays, and IRSs under different geometrical configurations, as illustrated in Fig. 6 [2], [11], [15]. The feasibility of such optimization

is linked to the capability of finding the right balance between the accuracy of the EM models for LISs/IRSs and their level of abstraction.

VI. CONCLUSION

Holographic communication is a holistic way to manipulate the EM field, with maximum flexibility. Such flexibility can be enabled by new metamaterials designed for the realization of LISs and IRSs. Within this context, in this paper we have discussed the theoretical implications when using LIS as active antennas, by highlighting 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 near-field region, and hence the possibility to boost the capacity. New wireless networks operating at millimeter-wave and terahertz are expected to gain significant benefits in terms of increased capacity, reliability, and nodes densification, even if several theoretical and technological issues have still to be solved, as discussed in this paper. 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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