A Quick Look to 6G Antenna Concepts as seen from the Deep Physical Layer Level

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Abstract

The race for the 6G has started, and new exciting ideas on 6G antennas are on the table. This contribution gives a look to the 6G ideas from a novel angle of view, the Deep Physical Layer (DPL), a layer added at the very botton level of the OSI stack, in which the analysis is carried out at the electromagnetic field level. It is suggested that the performance of the communication system can be quantified using the space-time Number of Degrees of Freedom (ST-NDF), allowing a simple comparison among the different solutions.

1 Introduction

Triggered by the research on the Massive MIMO [1], that showed the advantages of the use of antennas with a large (hundreds or thousands) number of elements, new ideas based on the use of very large radiating and/or scatter-ing/reflecting surfaces as well as distributed cooperative antennas have been proposed for 6G [2, 3].

Understanding of the real potential of these large radiating systems requires an analysis at the level of the electromagnetic field [4, 5]. This suggests to introduce a further layer placed at the base of the OSI stack, i.e. a lower level than the classic 'physical layer' of the OSI stack. We will be call this layer the "Deep Physical Layer".

The aim of this paper is to introduce the DPL clarifying the connection with the higher layers, and in particular the Physical Layer (PL), and showing how the DPL can help the analysis of 6G radiating systems. The approach followed in this paper uses some theoretical results obtained in a number of papers [6, 7, 8, 9] and is particularly suitable for the analysis of large radiating structures, allowing to discuss the electromagnetic properties of the different radiating systems proposed for 6G using a unified approach.

2 The Deep Physical Layer

As discussed in the Introduction, the *Deep Physical Layer* is placed at a lower level compared to the physical layer. At this layer level the communication process is described in terms of physical observables instead of bits. The performance at this layer level is limited by the first principles. In



Figure 1. The Deep Physical Layer is placed at the very bottom of the OSI stack.



Figure 2. A graphic view of the relationship between the Physical Layer and the Deep Physical Layer; A models the radiation process; X is the set of all the possible current distributions of the radiating system; Y is the set of all the possible field on the observation area, i.e. the area where the recievers are placed.

other words, the limitations in terms of information transmission at this layer level is related to the law of physics, and hence are unbreakable. The specific elements and laws depend on the observable used to convey information. In this paper we limit the discussion on systems based on electromagnetic field propagation. Accordingly, the deep physical layer regards field configurations, and the limitations are given by the Maxwell's equation. However, it is understood that other observables can be used for communication, as for example quantum bits. These communication systems can be modeled by a proper choice of the elements of the Deep Physical Layer and of the laws to which the elements obey.

Fig. 2 shows the connection between the Physical Layer and the Deep Physical Layer. The counterpart of different sequences of bits at the PL are different current density distributions on the transmitting antenna at the DPL. Using a functional approach, the current distribution associated to a specific sequence of bits is represented by a functional point in the set X of all the possible physically realizable current distribution on the transmitting antenna. The radiation process maps the X set into the Y set, whose elements are field configurations on the observation domain accessible to the observer, i.e. the receiver. A detailed explanation of the transmission process at the DPL can be found in [6, 7, 8, 9, 10].

As preliminary step, we recall that it is possible to introduce the (spatial)-bandwidth W of the electromagnetic field. The theory is well established in the electromagnetic community, and the interested reader can find details of the theory and its implication in space-time communication systems in the scientific literature, as f.i. [11]-[7]. We recall only that the electromagnetic field radiated by a (not super directive) source having finite spatial extension on an observation surface is an almost (spatially) band limited function [11]. The (spatial) bandwidth, let W be, is proportional to the electrical extension of the source. Let Ω the extension of the observation surface on which a proper parameterization (required to exclude the geometrical factors) is considered [12], [6]. For electrically large radiating systems the amount of information that can be encoded in the spatial waveforms is proportional to the space-(spatial) bandwidth product $W\Omega$ [6].

The value of the space-(spatial) bandwidth product is available for many standard geometries. In particular, in case of electrically large radiating systems (that is the case of interest) it turns out not larger than $\simeq 4 \text{Area}(\Sigma)/(\lambda^2)$, wherein $\text{Area}(\Sigma)$ is the area of the minimum convex surface Σ enclosing the source [12], [6].

The results can be applied also to scattering surfaces, since the spatial bandwidth does not change. As noted above, this approach allows a unified analysis of the amount of information transmissible by a communication system. Just as the data to be transmitted can be distributed over time and



Figure 3. The Number of Degrees of Freedom of time domain waveforms (i.e. field variation in time),called TNDF, and of the space-domain (i.e. field variation in space), called SNDF; for small bandwidth *B* the total NDF is approximatively the product of the two NDF

frequency keeping the area (i.e. the time-frequency product) constant, in the same way they can be distributed in the spatial domain and in the domain of the spatial frequency keeping the area (i.e. the space-frequency product) constant (see Fig.3).

Consequently, considering a space-time signal having (time) bandwidth *B*, spatial-bandwidth *W*, and observed in a period of time *T* and on an observation domain having Ω parameterized extension, information reliably transmissible in small bandwidth *B* is proportional to the product $ST - NDF = 4BTW\Omega$ [7], where *w* stands for 'spatial-bandwidth' and *s* for space. (for large bandwidth we must take into account the dependence of the SNDF with the frequency in case of geometrically-fixed field source; for details please see [7]). It must be noted that polarization allows to obtain an extra number of degrees of freedom [7].

An increase of the NDF has a direct impact on the other layers. For example, an increase of the spatial NDF allows a lower spatial correlation at the Physical Layer level, and at the end an improvement of the communication system.

The DPL allows to analyze and compare the many different ideas regarding 6G antennas (including Very large aperture Massive MIMO, Distributed MIMO, Cell-free Massive MIMO, Holographic Massive MIMO, Large intelligent surface, Intelligent reflecting surface, Reconfigurable reflectarrays, Software-controlled metasurfaces, Intelligent walls) in terms of ST-NDF. In particular, Fig. 5 shows the SNDF (proportional to the area of the rectangles) considering different generations of cellular communication systems. 1G, 2G and 3G are represented by a simple point since they use only one SNDF. The figure clearly show the trend toward larger SNDF. The effective use of SNDF is strictly related to an efficient antenna design in terms of transmitted information. Indeed, provided that a proper design of the antenna is carried out, no particular advantages in terms of SNDF are obtained using continuous aperture instead of array antennas. This suggests that, more than in the past, correct



Figure 4. The effect of an increase of the NDF at the Deep Physical Layer Level positively affects all the layers of the OSI stack.



Figure 5. A pictorial view of the characteristics of the different cellular systems generations in terms of Spatial NDF (that is proportional to the area of the rectangles).

antenna design has a great deal of relevance in 6G.

References

- T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE* transactions on wireless communications, vol. 9, no. 11, pp. 3590–3600, 2010.
- [2] E. Björnson, L. Sanguinetti, H. Wymeersch, J. Hoydis, and T. L. Marzetta, "Massive mimo is a reality. what is next?: Five promising research directions for antenna arrays," *Digital Signal Processing*, vol. 94, pp. 3–20, 2019.
- [3] E. C. Strinati, S. Barbarossa, J. L. Gonzalez-Jimenez, D. Kténas, N. Cassiau, and C. Dehos, "6g: The next frontier," *arXiv preprint arXiv:1901.03239*, 2019.
- [4] A. Pizzo, T. L. Marzetta, and L. Sanguinetti, "Spatial characterization of holographic mimo channels," *arXiv preprint arXiv:1911.04853*, 2019.
- [5] —, "Degrees of freedom of holographic mimo channels," *arXiv preprint arXiv:1911.07516*, 2019.
- [6] M. D. Migliore, "On the role of the number of degrees of freedom of the field in mimo channels," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 2, pp. 620–628, 2006.
- [7] —, "On electromagnetics and information theory," *IEEE transactions on antennas and propagation*, vol. 56, no. 10, pp. 3188–3200, 2008.
- [8] —, "Horse (electromagnetics) is more important than horseman (information) for wireless transmission," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 4, pp. 2046–2055, 2018.
- [9] —, "An intuitive electromagnetic approach to mimo communication systems [wireless corner]," *IEEE Antennas and Propagation Magazine*, vol. 48, no. 3, pp. 128–137, 2006.
- [10] —, "Who cares about the horse? a gentle introduction to information in electromagnetic theory [wireless corner]," *IEEE Antennas and Propagation Magazine*, vol. 62, no. 5, pp. 126–137, 2020.
- [11] O. Bucci and G. Franceschetti, "On the spatial bandwidth of scattered fields," *IEEE transactions on antennas and propagation*, vol. 35, no. 12, pp. 1445–1455, 1987.
- [12] O. M. Bucci, C. Gennarelli, and C. Savarese, "Representation of electromagnetic fields over arbitrary surfaces by a finite and nonredundant number of samples," *IEEE Transactions on Antennas and Propagation*, vol. 46, no. 3, pp. 351–359, 1998.