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Big, Bigger, Biggest. What should we expect from 6G antennas?

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Abstract

With the deployment of the first 5G communication systems the race toward 6G is started. New exciting ideas on a wireless-based hyper connected human-machine world are on the table. Antennas are not outside this race, and a large and enthusiastic effort is currently made to image new solutions for radiating systems. This paper represents a small contribution to this discussion.

1 Introduction

After a long and complex process, specifications for 5G have been almost completed and while the wireless operators are timidly starting the field tests, fearing for the ARPU (Average Revenue Per User) of this new technology, discussion on the next 6G generation has already started in the academic and industrial community [2, 3, 4, 5]. Antennas, that played a very limited role in the previous generation, for the first time are at center of the interest, and reconfigurable antennas has been only not proposed but also implemented in the 5G trials currently performed. This trend is expected to continue in the future, and to lead the development even more sophisticated antennas for 6G [2]. Why this interest for sophisticated antennas? The first 4 generations of cellular communication systems were characterized by different access techniques from relatively simple FDMA of the first generation to the sophisticated OFDMA of 4^{th}. However, the transition from 4G to 5G has not seen a similar jump. The selection of OFDMA also for 5G, chosen in spite of a large research for new 5G solutions, is an indication of a growing difficulty in improving the efficiency of the use of temporal and spectral resources of the communication channel. The consequence is a renewed interest in the efficient use of space resources. Spatial Division Multiple Access (SDMA) techniques in wireless communication are not new. Attempts to use SDMA techniques have also been made in generations prior to 5G but without success. The reasons were technical and commercial. The more sophisticated use of time/frequency resources of the channel requires hardware available on the market, while SDMA requires the development of basically new hardware, i.e. *low cost* reconfigurable antennas. Until the improvement given by a better use of time/frequency resources were sufficiently cheap, SDMA remained in the shadow. 5G represented a turning point. Indeed, 5G implements a number of possible SDMA techniques (part of them considered also in 4G) in the standard, from simple antenna beam switching to sophisticated MU-MIMO techniques. Triggered by the research on the Massive MIMO [6], that showed the advantages of the use of antennas with a large (hundreds or thousands) number of elements [7], new ideas based on the use of very large radiating and/or scattering/reflecting surfaces have been proposed for 6G. Indeed, all the many techniques that have bee proposed [2], [8], f.i. Extremely large aperture arrays, Cell-free Massive MIMO, Distributed MIMO, Holographic Massive MIMO, Large intelligent surface, Intelligent walls, Software-controlled metasurfaces, etc..., involve very large arrays or continuous radiating/scattering surfaces. The most part of the discussions on the 'future antennas' are qualitative, without any attempt to try an extrapolation from the past technological trend. In this contribution some hypothesis of 6G antennas are discussed considering the technological innovation trend of the past cellular systems generations. The author is well aware of the 'instability' of such an extrapolation. However, with all the necessary precautions, it could give some (very) rough indications of what we must expect.

2 The Number of Degrees of Freedom of space-time communication systems as an indication of the technological trend

Quantify the 'technological trend' is extremely complex. The first problem regards the quantity that must be taken into account. In this paper the technological trend is analyzed in terms of Number of Degrees of Freedom of the space-time signal per unit time available in a cell. Quantification of the Degrees of Freedom (DF) associated to the time-variation of the signal can be obtained in terms of band and observation time. As well know, a bandlimited signal having bandwidth B and observed in a temporal period T has a number of Degrees of Freedom $NDF_{tf} \simeq 2BT$, wherein the subscript tf stands for time-frequency. In this paper we will not enter into the details of the bandlimited function theory and, "cutting with ax", we will consider $NDF_{tf} = 2BT$.

Quantification of the contribution of the space domain per cell in cellular systems is a bit tricky since the way in which

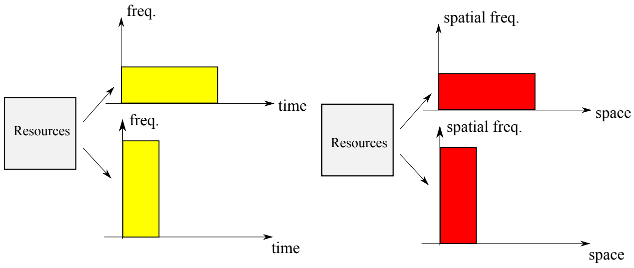

Figure 1. Just as the data to be transmitted can be distributed over time and frequency in various ways as long as the area (i.e. the time-frequency product) is kept constant, in the same way they can be distributed in the spatial domain and in the domain of the spatial frequencies keeping the area (i.e. the space-spatial frequency product) constant.

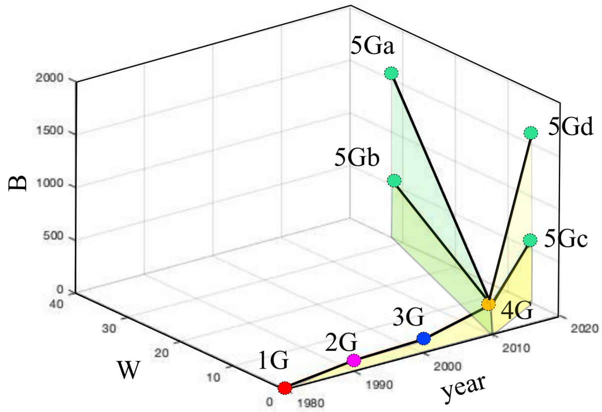

Figure 2. The trend of the first 5 generations of cellular systems in terms of bandwidth B, spatial bandwidth W and approximative year of first deployment; the position of 5G in this scheme depends on the choice of the operators; 5Ga is the most ambitious scenario, with an aggressive use of millimeter band and an optimal use of the spatial bandwidth; 5Gb refers to the same scenario of 5Gb but in a non millimeter cell; 5Gc and 5Gd scenario refer to a non millimeter cell and a millimeter cell that use the spatial resources in a suboptimal way.

spatial resource is treated is often quite different from the way in which time and frequency resources are treated in cellular systems. For example, let us consider how 5G treats the space resource. In 5G the use of the space resource is related to the concept of 'antenna port'. More specifically, *an antenna port is defined such that the channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed*. Antenna port is a very operative concept that is related to the channel response; transmission of N symbols using spatial multiplexing technique requires N different antenna ports. In this paper we use a more abstract approach that parallels the one used to quantify the temporal resources of a channel. Information in the space domain is associated to space variation of the electromagnetic field configuration, exactly like information in the time domain is associated to variation of the electromagnetic field configuration in time. An important characteristic of the time-waveforms is the bandwidth B. At the same way, an important characteristic of the space-waveform is the (spatial) bandwidth W. In this paper the properties of the spatial bandwidth will not be described in details. 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. [10]-[14]. We recall only that the electromagnetic field radiated by a (not superdirective) source having finite spatial extension on an observation surface is an almost (spatially) bandlimited function [10]. 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 [11], [12]. 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 $W\Omega$ [12]. 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 $\simeq 4\mathbf{Area}(\Sigma)/(\lambda^2)$, wherein $\mathbf{Area}(\Sigma)$ is the area of the minimum convex surface Σ enclosing the source [11], [13]. 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 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.1). 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 is proportional to the product $NDF_{btws} = 4BTW\Omega$ [13], where w stands for 'spatial-bandwidth' and s for space. It must be noted that polarization allows an to obtain an extra number of degrees of freedom; however, such extra degrees of freedom are not used for multiplexing but only for diversity by currently deployed cellular communication systems, and will not be considered in this paper. Finally, since we are interested in modeling a base station - multi users communication systems, and the resources are reused in each cell, in the following we will consider the Number of Degrees of Freedom of the communication system per unit time and unit cell supposing that the observation domain surrounds the source (i.e. the receivers are placed all around the base station). The Number of Degrees of Freedom per unit time and unit cell will be called simple the Number of Degrees of Freedom per cell (NDFpc). Its vale is $NDFpc = 4BW$.

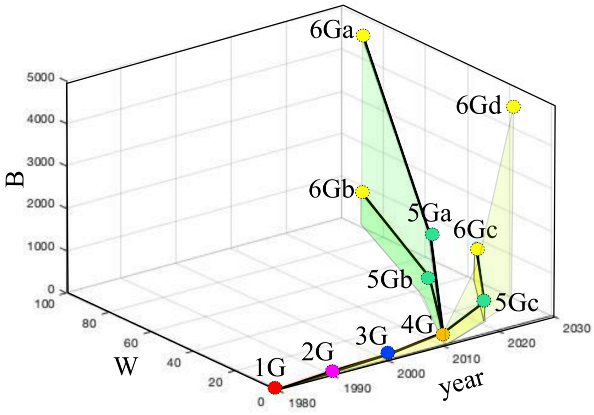

Figure 3. A projection toward 6G ; the position of 6G in this scheme depends on the choice of the operators; 6Ga and 6Gb refer to a millimeter and non millimeter cell with an optimal use of the spatial bandwidth; 6Gc refers to a non millimeter cell that use the spatial resources offered by a medium dimension (around 100 radiating elements) array in an optimal way; 6Gd refers a millimeter cells using the spatial resource in a suboptimal way.

3 Study the past, if you would divine the future

As an indication of the past trend of the use of time-space resources in cellular systems, let us consider the following three quantities for each of the first five generations: the total bandwidth assigned, the space bandwidth used, and the approximated year of first deployment of the wireless generation. These quantities evaluated for the first 5 generations are plotted in Fig 2. The curve shows the trend in the last 50 years. The $NDFpc$ is given by the product of the bandwidth B and the spatial bandwidth W. We can note a new generation every ten years. According to the past trend, we can expect the 6^{th} generation around 2030. The plot clearly shows that the increase of the (time signal) bandwidth is a constant trend. In the past generations this was the only way to increase the available Number of Degrees of Freedom per cell. It is understood that many technological improvements and new signal processing algorithms helped the increase of the network capacity from 1G to 4G. However, they basically allowed a better use of the available $NDFpc$, that represents the resources at the lowest physical level. 4G introduced the MIMO technology, that allows to take advantage of the spatial bandwidth to transmit information. However, the spatial bandwidth of MIMO systems is relatively small, allowing a limited increase of the network capacity. 5G represents a huge step forward in the potentially available number of degrees of freedom, thanks to the extension of the lower band (FR1), the introduction of the millimeter band (FR2) and to the use of MU-MIMO systems. The huge potential improvement of 5G is clear observable by the position of the point 5Ga in the figure, in which a full potentiality of a 32 λ^2 radiating aperture (almost equivalent to the potentiality of the 8×8 radiating element arrays that are currently under development for 5G systems) is considered in a FR2 cell. It is worth noting that the exact value of the $NDFpc$ depends on the technological details, f.i. the specific radiating system. However, these details are inessentials in the identification of the trend of the technology. The figures shows that curve regarding the enlargement of the bandwidth has a break point in 5G, with a tremendous increase of the (time signal) bandwidth. However, this is the *maximum potential* number of degrees of freedom that can be used. In practice, millimeter waves, that give the most part of the contribute to the $NDFpc$, will not be used everywhere. This substantially reduces the $NDFpc$. If we consider a cell using FR1 (i.e. not using the millimeter band) we have the point 5Gb, and the $NDFpc$ drastically decreases. It is interesting to note that in this case the most important contribution to the $NDFpc$ is given by the increase of the spatial bandwidth. However, this result supposes an optimal use of the available spatial bandwidth. Many proposed solutions for 5G represent a trade-off between the high computational complexity required to use the space resources in an optima way and the lower cost associated to a less effective use of the available spatial bandwidth. For example, a smart computational low-cost solution is to reduce the number of users that have access to the available spatial bandwidth to a fraction of the maximum one [6]. This is equivalent to sample a band-limited function at a sampling rate that is a fraction of the Nyquist rate, obtaining uncorrelated samples with high probability. If we suppose to apply such a computationally efficient technique we have the point 5Gc. Finally, in case of a millimeter cell with a moderate use of space resource, the point 5Gc moves vertically obtaining the point 5Gd. Indeed, this is the most probable scenario for millimeter wave cells. In millimeter cells the bandwidth is so large that an aggressive MU-MIMO approach is economically not advantageous, and a limited use of the space resources with more conventional antenna architectures like phased arrays with a limited number of beams appears more attractive. But what we must expect in 6G? The past offers four different scenarios, that are shown in Fig. 3. The scenario depicted by point 5Ga, i.e. optimal use of all the space-time resources in millimeter cells, brings toward the point 6Ga, characterized by a very aggressive use of higher millimeter frequency band and by extremely large spatial bandwidth antennas. This is the scenario often discussed in many papers on 6G technology. In this scenario the largest improvement is given by the (time signal) bandwidth in the high millimeter range. If we consider a non millimeter cell, point 5Gb brings to the scenario 6Gb. In this scenario improvement in the bandwidth is limited, pushing the development of large antennas for MU-MIMO. However, there is a third scenario, that is the development of the point 5Gc. Indeed, the developed of 5G according to the scenario depicted in 5Gc leaves a lot of space to improve the efficiency of the use of the spatial bandwidth. In this case, 6G would be more focused toward the optimal use of the available space resources than on the development of extremely large spatial bandwidth antennas, giving the point 6Gc in case of non millimeter cells. Finally, millimeter cells will use larger bandwidth with a low or moderate use of the space bandwidth, giving the scenario 6Gd. According to these last two scenarios, it is not completely unlikely that antennas with a 'moderate' number of elements will still dominate the market in the future. There are some other indications supporting these last two scenarios. The "path" from the 1G to the 6G generation is more continuous in case of 6Gc and 6Gd, indicating a smoother technological transition among the generations of the cellular systems. This smoother transition well matches with non-military market, in which industries have usually more conservative projects compared to military market. There is also a 'trend' in the past regarding the expectations and the real performances of communication systems. If we analyze expectations and true performances, it seems that odd generations were less able than even generations to reach the expectations, and that in some way expectations of odd generations were fully reached by the even ones.

4 Conclusions

These brief notes suggest that the 6G antennas could be less revolutionary than we might expect today. Future is always difficult to predict, and the past teaches that the best solution is not always the winner. Even if much better solutions, like extremely large spatial bandwidth antennas or large electronically controllable surfaces, are technically possible, the effort required to drop the costs of such radiating/scattering systems is large. A more conservative view predicts that in the non-millimeter range the market will be dominated by full active antennas with a number of elements comparable with the one used in the 5G antennas currently under development (around one hundred), while phased arrays will continue to be used in millimeter cells for coverage of dense-user scenarios. In this scenario space will not longer be considered as a completely 'free' resource, and 6G will see a great effort toward the optimal use of the available spatial bandwidth, with a strong synergy between the communications and the electromagnetic community. This does not mean that some of the new ideas proposed for 6G will not have their market also in this 'conservative' scenario. For example, ideas like 'strip antennas', i.e. a long chain of simple radiating/receiving elements, are extremely interesting for applications in tunnels, railways, freeways, and so on. Loosely speaking. big industries are generally conservative, and tend to take small steps. Their propensity to capital risk for the important technological innovations required by the development of large, low-cost active antennas will probably critically depend on the market response to 5G. As in the past, the success of a technology depends more on the ARPU than on the SNR.

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