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Realizing Ultra-Massive MIMO (1024 × 1024) communication in the (0.06–10) Terahertz band

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ABSTRACT

The increasing demand for higher bandwidth and higher speed wireless communication motivates the exploration of higher frequency bands. The Terahertz (THz) band (0.06–10 THz) is envisioned as one of the key players to meet the demand for such higher bandwidth and data rates. However, the available bandwidth at THz frequencies comes with the cost of a much higher propagation loss. Due to the power limitations of compact solid-state THz transceivers, this results in very short communication distances of approximately one meter. In this paper, the concept of Ultra-Massive Multiple Input Multiple Output (UM MIMO) communication is introduced as a way to increase the communication distance and the achievable capacity of THz-band communication networks. The very small size of THz plasmonic nano-antennas, which leverage the properties of nanomaterials and metamaterials, enables the development of very large plasmonic arrays in very small footprints. For frequencies in the 0.06–1 THz range, metamaterials enable the design of plasmonic antenna arrays with hundreds of elements in a few square centimeters (e.g., 144 elements in 1 cm^2 at 60 GHz). In the 1–10 THz band, graphene-based plasmonic nano-antenna arrays with thousands of elements can be embedded in a few square millimeters (e.g., 1024 elements in 1 mm^2 at 1 THz). The resulting arrays can be utilized both in transmission and in reception (e.g., 1024 × 1024 UM MIMO at 1 THz) to support different modes, from razor-sharp UM beamforming to UM spatial multiplexing, as well as multi-band communication schemes. After introducing the main properties of plasmonic nano-antenna arrays, the working modes of UM MIMO are presented, and preliminary results are provided to highlight the potential of this paradigm. Finally, open challenges and potential solutions to enable UM MIMO communication are described.

1. Introduction

Wireless data rates have doubled every eighteen months for the last three decades. Following this trend, Terabit-per-second (Tbps) links are expected to become a reality within the next five years. The limited bandwidth in wireless communication systems under 5 GHz motivates the utilization of higher frequency bands. In this direction, millimeter-wave (mm-wave) communication (30–300 GHz) has been heavily investigated in the recent years. Despite the opportunities that come with such systems, the total consecutive available bandwidth for mm-wave communication is still less than 10 GHz. This would require a physical layer efficiency of almost 100 bit/s/Hz to

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support Tbps, which is several times higher than that of the state of the art for existing communication systems. This result motivates the exploration of even higher frequency bands.

In this context, Terahertz (THz) band (0.06–10 THz) communication is envisioned as a key wireless technology to enable Tbps links [1–3]. The available bandwidth in the THz band drastically changes with distance, and ranges from almost 10 THz for distances below one meter to multiple transmission windows hundreds of GHz wide each for longer distances [4]. However, this very large bandwidth comes at the cost of a very high propagation loss. On the one hand, the much smaller effective area of THz antennas, which is proportional to the square of the carrier signal wavelength, results in a very high spreading loss. On the other hand, the absorption from water vapor molecules further increases the path-loss and limits the available bandwidth for distances above several meters.

Given the limited output power of THz transceivers, high-gain directional antennas are needed to communicate over distances beyond a few meters. Similarly as in lower frequency communication systems, antenna arrays can be utilized to implement Multiple Input Multiple Output (MIMO) communication systems, which are able to increase either the communication distance by means of beamforming, or the achievable data rates by means of spatial multiplexing. For example, MIMO systems with 2, 4 or 8 antennas in transmission and in reception are common in current wireless communication standards, such as IEEE 802.11ac or 4G LTE-A networks. In these applications, due to the limited available bandwidth, MIMO is mainly utilized to increase the spectral efficiency and achievable data rates by exploiting spatially uncorrelated channels.

More recently, the concept of Massive MIMO has been introduced [5–8]. In this case, much larger antenna arrays with tens to hundreds of elements are utilized to increase the spectral efficiency. Moreover, by creating two-dimensional or planar antenna arrays instead of one-dimensional or linear arrays, the radiated signals can be controlled both in the elevation and the azimuth directions, thus enabling 3D or Full-Dimension (FD) MIMO [9]. However, there are several shortcomings which limit their use in practical applications. In particular,

- At frequencies under 5 GHz, the size of the arrays is in the order of a few square meters for tens of antennas, which limits their deployment to base stations only.
- For mm-wave systems, the footprint of the arrays is in the order of a few square centimeters for tens of antennas. While this enables their integration in mobile devices, this number would not be enough to overcome the higher path-loss at mm-wave frequencies over several tens of meters.
- When moving to the THz band, antennas become even smaller and many more elements can be embedded in the same footprint. For example, the size of an array with a hundred elements is in the order of a few square millimeters. However, a much larger number of elements would be needed to overcome the path-loss in the THz band. While it would be possible to embed a thousand antennas in a few square centimeters, there would be many challenges in dynamically controlling such an array with traditional architectures, which would limit the feasibility of this approach.

To overcome these limitations, the unique properties of novel plasmonic materials can be leveraged. In particular, instead of relying on conventional metals, nanomaterials such as graphene and metamaterials can be utilized to build miniature nano-antennas and nano-transceivers which can efficiently operate in the THz band [10,11]. Their very small size enables their integration in very dense plasmonic nano-antenna arrays, which bring unprecedented opportunities for THz communication.

In this paper, we present the concept of Ultra-Massive (UM) MIMO communication in the THz band. UM MIMO communication relies on the possibility to integrate a very large number of nano-antennas in very small footprints to increase the communication distance and the achievable data rates at THz-band frequencies. For frequencies in the 0.06–1 THz range, metamaterials enable the design of plasmonic antenna arrays with hundreds of elements in a few square centimeters (e.g., 144 elements in 1 cm^2 at 60 GHz). In the 1–10 THz band, graphene-based plasmonic nano-antenna arrays with thousands of elements can be embedded in a few square millimeters (e.g., 1024 elements in 1 mm^2 at 1 THz). The resulting nano-antenna arrays can be utilized both at the transmitter and the receiver to simultaneously overcome the spreading loss problem, by focusing the transmitted signal in space, and the molecular absorption loss problem, by focusing the spectrum of the transmitted signal in the absorption-free windows. As a result, wireless Tbps links can be established between compact electronic devices which are several tens of meters apart.

The rest of the paper is organized as follows. In Section 2, we describe the main peculiarities of THz plasmonic nano-antenna arrays and highlight the opportunities that nanomaterials and metamaterials bring into the game. In Section 3, we present the concept of UM MIMO communication, describe its working modes and provide preliminary numerical results to emphasize the potential of this paradigm. Finally, we identify the open challenges and potential solutions to enable UM MIMO communication in Section 4, and conclude the paper in Section 5.

2. Plasmonic nano-antenna arrays

2.1. Miniaturization of the antennas

In general terms, the length of a resonant antenna is approximately half of the wavelength at the resonance frequency. In the THz band, the wavelength ranges from 5 mm at 60 GHz to just 30 μm at 10 THz. For example, a metallic antenna tuned to resonate at 1 THz needs to be approximately $l_m \approx \lambda/2 = 150\ \mu\text{m}$ long. While this result already shows the potential for the development of very large THz antenna arrays, even more substantial gains can be achieved by utilizing plasmonic materials to develop nano-antennas and nano-transceivers.

Plasmonic materials are metals or metal-like materials which support the propagation of Surface Plasmon Polariton (SPP) waves. SPP waves are confined electromagnetic waves that appear at the interface between a metal and a dielectric as a result of global oscillations of the electrical charges. Different plasmonic materials can support

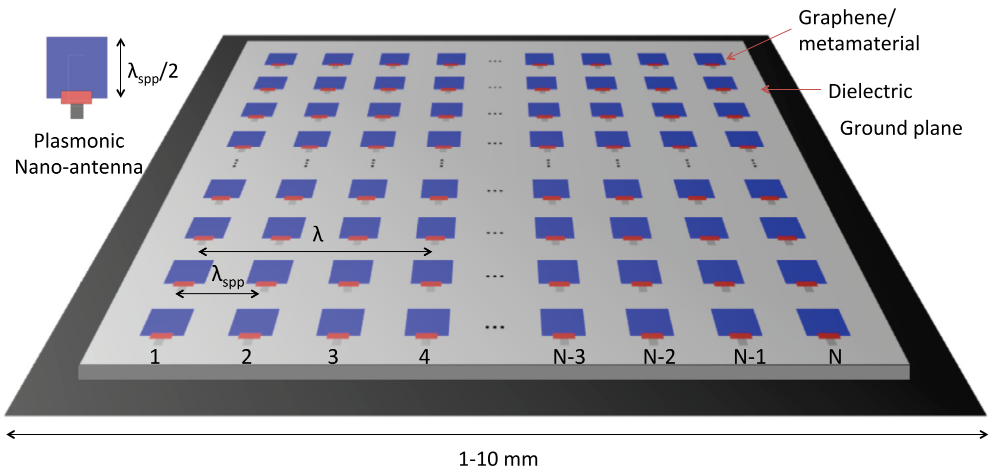

Fig. 1. A square uniform plasmonic nano-antenna array.

SPP waves at different frequencies. Noble metals such as gold and silver support SPP waves at infrared and optical frequencies. Graphene, a one-atom-thick carbon-based nanomaterial with unprecedented mechanical, electrical and optical properties [12,13], supports the propagation of SPP waves at THz-band frequencies. Metamaterials, i.e., engineered arrangements of nano-structured building blocks, can be designed to support SPP waves at many frequency bands, including mm-wave frequencies [14,11].

The unique propagation properties of SPP waves enable the development of novel plasmonic nano-antennas. In particular, SPP waves propagate at a much lower speed than EM waves in free space. As a result, the SPP wavelength λ_{spp} is much smaller than the free-space wavelength λ. The ratio $\gamma = \lambda/\lambda_{spp} > 1$ is known as the confinement factor and depends on the plasmonic material and the system frequency. The confinement factor can be obtained by solving the SPP wave dispersion equation with the boundary conditions imposed by the specific device geometry [10]. Different from metallic antennas, the resonance length of a plasmonic antenna is given by $l_p \approx \lambda_{spp}/2 = \lambda/(2\gamma)$ and, thus, plasmonic antennas are much smaller than the metallic antennas.

Motivated by these properties, in [10], we proposed the utilization of graphene to develop THz plasmonic nano-antennas. The confinement factor γ in graphene ranges between 10 and 100. As a result, graphene-based plasmonic nano-antennas are just a few micrometers long and only hundreds of nanometers wide, i.e., almost two orders of magnitude smaller than the metallic THz antennas. Moreover, the resonance frequency of graphene-based plasmonic nano-antennas can be dynamically tuned [15,10,16]. In particular, the propagation properties of the SPP waves in graphene depend on its dynamic complex conductivity. The conductivity, on its turn, depends on the dimensions of the graphene structure and its Fermi energy, i.e., the highest energy-band occupied by the electrons in the material. Interestingly, the Fermi energy can be easily modified by means of material doping or electrostatic bias. As a result, the SPP wave propagation properties and, thus, the confinement factor can be dynamically tuned.

However, the short propagation length of SPP waves in graphene for frequencies under 1 THz limits the performance of graphene-based plasmonic nano-antennas at lower frequencies. Alternatively, plasmonic metamaterials [11,17] can be utilized to develop plasmonic nano-antennas for frequencies between 60 GHz and 1 THz. In [14], the propagation properties of SPP waves on metamaterials as low as 10 GHz were presented. While SPP waves can propagate on metamaterials at such frequencies, their confinement factor γ is usually under 10, and, thus, the miniaturization gains are lower than at frequencies above 1 THz. In addition, conventional metamaterials are not tunable. However, novel Software Defined Metamaterials (SDMs) have been recently proposed in [18]. The fundamental idea in SDMs is to combine conventional metamaterials with nanoscale communication networks to dynamically control the properties of the metamaterial by switching the state of its building blocks. Such approach could be utilized to change the effective permittivity or conductivity of the metamaterial and, thus, modify the confinement factor in real-time.

2.2. Integration of many antennas

Despite a high radiation efficiency, the effective area of plasmonic nano-antennas is very small. Nevertheless, this small size enables the creation of very dense nano-antenna arrays in a very small footprint. A conceptual plasmonic nano-antenna array is illustrated in Fig. 1. In addition to the size of the antennas, the total number of elements depends on the minimum required separation between the antennas and the maximum allowable footprint for the array. We define the minimum separation between the nano-antennas as the distance at which there is no significant mutual coupling between them. It can be shown that the mutual coupling between plasmonic nano-antennas drops quickly when the separation between the two nano-elements approaches the plasmonic wavelength λ_{spp}. Therefore, the plasmonic confinement factor γ plays a key role on the number of elements that can be integrated in a fixed footprint.

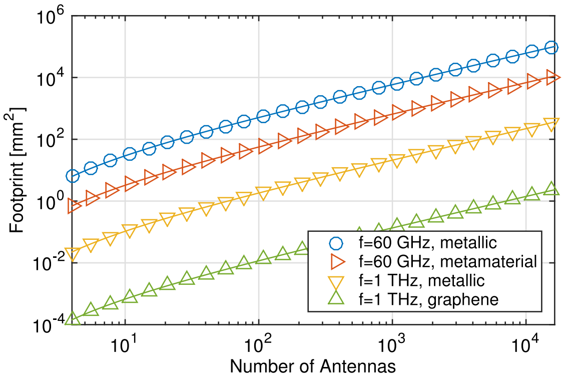

Fig. 2. Footprint of metallic and plasmonic antenna arrays as a function of the number of elements.

Without loss of generality, the footprint $\mathcal{S}$ of a uniform square planar plasmonic nano-antenna array with N elements per side is given by $\mathcal{S} = (N\lambda/\gamma)^2$. In Fig. 2, the footprint is shown as a function of the total number of antennas for four different scenarios: (1) a metallic antenna array at 60 GHz; (2) a metamaterial-based plasmonic nano-antenna array at 60 GHz; (3) a metallic antenna array at 1 THz; and, (4) a graphene-based plasmonic nano-antenna array at 1 THz. We consider a confinement factor $\gamma = 4$ for metamaterials [14] and $\gamma = 25$ for graphene [16]. As shown in Fig. 2, when operating at 60 GHz, the use of metamaterials can help to reduce the footprint by more than one order of magnitude. For example, 1024 plasmonic nano-antennas would occupy 10 cm^2, whereas the same number of metallic antennas would require 100 cm^2. This array would be too large to be embeddable in conventional mobile communication devices. For frequencies 1 THz and above, the very high confinement factor of graphene brings major reductions in the array footprint. For example, when operating at 1 THz, 1024 metallic antennas can be packed in a 1 cm^2 footprint, whereas less than 1 mm^2 would be needed to integrate the same number of plasmonic nano-antennas. The very small size of the plasmonic nano-antenna arrays allows its integration in all sort of communication devices. These results further highlight the benefits of utilizing plasmonic materials to design antennas and antenna arrays.

2.3. Feeding and control of the antennas

To operate the array, we need to be able to generate and control the amplitude or at least the time delay/phase of the SPP wave at each nano-antenna. For the time being, several alternatives to generate the plasmonic signals at THz-band frequencies have been considered. For frequencies under 1 THz, standard Silicon (Si) Complementary Metal–Oxide–Semiconductor (CMOS) technology [19], Silicon Germanium (SiGe) technology [20] and III–V semiconductor technologies such as Gallium Nitride (GaN), Gallium Arsenide (GaAs), and Indium Phosphide (InP) [21] can be utilized to generate a high-frequency electrical signal. By means of a plasmonic grating structure, a SPP wave could be then launched to the metamaterial-based antennas [22].

For frequencies above 1 THz, different mechanisms to excite SPP waves can be considered. These can be classified either as optical or electrical pumping techniques. In terms of optical pumping, Quantum Cascade Lasers (QCLs) [23,24] combined with grating structures can be configured to excite SPP waves. However, although QCLs can provide high-power THz signals, their performance quickly degrades at room temperature. Infra-red lasers and photoconductive antennas can also be utilized to excite SPP waves. However, the need for an external laser limits the feasibility of this approach in practical setups. For electrical pumping, sub-micrometric High-Electron Mobility Transistors (HEMTs) based on compound semiconductors materials as well as graphene can be utilized to excite SPP waves [25,26]. While the individual power of each HEMT is expectedly very low, their very small size and possibility to operate at room motivate their further exploration.

The distribution of the plasmonic signal through the nano-antenna array depends on the excitation mechanism. When relying on optical pumping, a single laser could be utilized to simultaneously excite SPP waves on all the nano-antennas, due to the relatively large aperture of the required lasers. While this would simplify the feeding of the nano-antennas, it would also limit the applications of the array, as all the elements would be fed with the same time-delay or phase. For the case of electrical pumping, we can consider different approaches. On the one hand, following a conventional scheme, we could utilize a single or small group of HEMT-based nano-transceivers to generate the required signals and then rely on a plasmonic waveguide [27] and plasmonic delay/phase controllers [28] to distribute the signals with the adequate phase to the different nano-antennas. However, given the low power generated by a single nano-transceiver (a few microwatts [25]) and the limited propagation length of SPP waves (only a few wavelengths [10]), the performance of the nano-antenna array would be compromised. Alternatively, the very small size of individual plasmonic sources allows them to be integrated with each nano-antenna, thus, enabling the equivalent of a fully-digital architecture. This does not only increase the total radiated power, but can potentially simplify the control of the nano-antenna array needed to support UM MIMO communication.

3. Ultra-massive MIMO communication

The possibility to create very large controllable nano-antenna arrays enables UM MIMO communication systems in the THz band. The objective of UM MIMO is to maximize the utilization of the THz band over long distances, by overcoming the two main phenomena that affect the propagation of THz signals, namely, the spreading loss and the molecular absorption loss. Next, we describe the working modes of UM MIMO and present initial performance estimates.

3.1. Dynamic UM MIMO

By dynamically adapting the amplitude and time-delay/phase of the plasmonic signals at each nano-antenna, different UM MIMO operation modes are defined, ranging from UM beamforming to UM spatial multiplexing.

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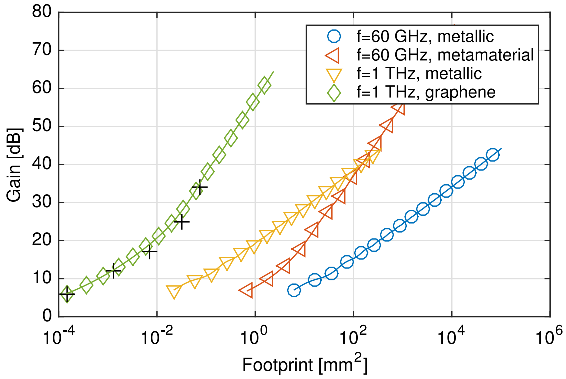


Fig. 3. Gain of metallic and plasmonic nano-antenna arrays at different frequencies as a function of their footprint ('+' refers to points validated by means of simulation).

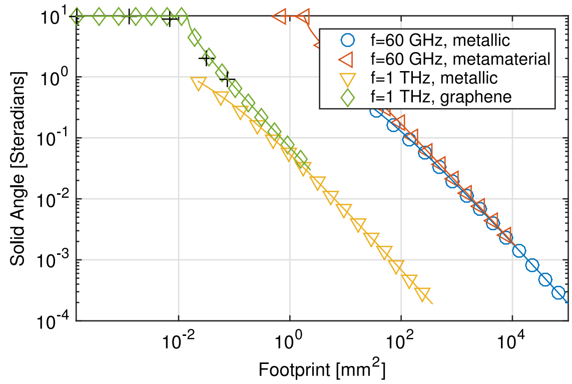


Fig. 4. Beam solid angle of metallic and plasmonic nano-antenna arrays as a function of their footprint ('+' refers to points validated by means of simulation).

3.1.1. UM beamforming

In this case, all the nano-antennas are fed with the same plasmonic signal, as in conventional beamforming. The main advantage from UM MIMO comes from the much larger number of nano-antennas that can be integrated in one array. However, there are two main differences with conventional arrays. On the one hand, the possibility to integrate a plasmonic signal source within each nano-antenna results in a higher output power, independently of the separation of the antennas or the time-delay/phase between them. In traditional architectures, either a single signal is distributed among all the elements or an "array-of-sub-arrays" architecture is used, in which each sub-array is actively powered. As a result, the gain of the plasmonic nano-antenna array is higher. However, on the other hand, the fact that nano-antennas are placed much closer to each other, reduces the beamforming abilities of the array.

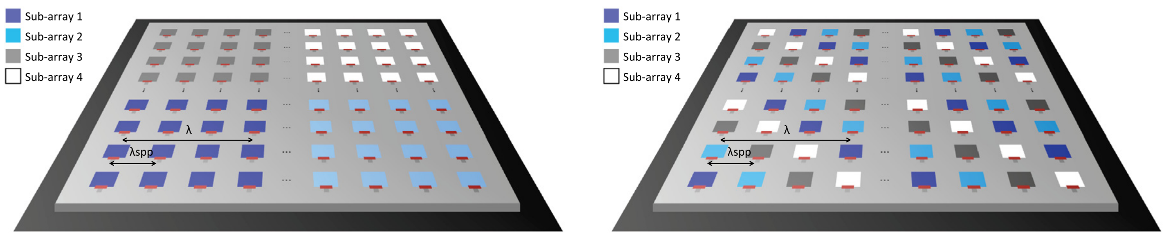
Without loss of generality, let us consider a uniform square planar plasmonic nano-antenna array with a single beam in the broadside direction. In Fig. 3, the array gain in the pointing direction is shown for different array technologies as a function of the array footprint. The results have been obtained by analyzing the array factor and nano-antenna response of a time-delay array under the assumption of negligible mutual coupling. For graphene-based plasmonic nano-antenna arrays, the results for the smaller footprints with up to 128 elements in transmission and in reception have been validated by means of simulations with COMSOL multi-physics. The validated points are represented with "+" in the figure. From the figure, at 60 GHz, the gain of a 100 mm^2 metamaterial-based plasmonic nano-antenna array can be up to 40 dB, i.e., almost 25 dB higher than that of a metallic antenna array with the same footprint. At 1 THz, the gain of a 1 mm^2 graphene-based plasmonic nano-antenna array is up to 55 dB, or almost 35 dB more than that of a conventional metallic antenna array with the same footprint. It is relevant to note that this higher gain is achieved not only because of the higher number of nano-antennas, but also due to the fact that each nano-antennas is actively powered by a nano-transceiver. This can also be seen from the array beam solid angle, as we discuss next.

In Fig. 4, the beam solid angle in the pointing direction is illustrated for different arrays as a function of their footprint. While the use of plasmonic materials enables the integration of a very large number of antennas in a very small footprint, such arrays will not exhibit beamforming capabilities unless they extend over at least half free-space wavelength. This is due to the spatial correlation between nano-antennas which are less than $\lambda/2$ apart. While this could motivate the decision to spread the nano-antennas over λ, without taking advantage of the plasmonic confinement, there are many new opportunities enabled by densely integrating them, such as the possibility to create interleaved sub-arrays for spatial multiplexing.

In order to illustrate the impact of UM beamforming, we consider a specific numerical example. In particular, we focus on the absorption-defined transmission window at 1 THz, which has approximately 120 GHz of bandwidth at 10 m. From [29], the total path-loss at 1 THz exceeds 115 dB over 10 m. If we consider that the transmission power is 0 dBm and the noise power at the receiver is −80 dBm, it can be easily shown that a 1024 × 1024 UM beamforming scheme, with 40 dB of gain in transmission and in reception, can support wireless data links of almost 2 Tbps at 10 m. However, it is relevant to note that the available bandwidth in the THz band shrinks as the transmission distance is increased and, thus, trying to increase the capacity by simply adding more antennas is not the best that can be done. Instead of that, it might be more effective to simultaneously transmit over multiple windows, as we will discuss in Section 3.2.

3.1.2. UM spatial multiplexing

Very large antenna arrays can be virtually divided to support multiple broader and lower-gain beams in different directions. As in conventional MIMO or massive MIMO, those beams can be utilized to exploit spatial diversity and increase the capacity of a single-user link or to create independent separate links between different users. Moreover, the possibility to independently control the signal at each nano-antenna by means of the aforementioned plasmonic nano-transceivers, enables innovative ways to group the array elements which can increase the number of simultaneous beams while



(a) Non-interleaved. (b) Interleaved.

Fig. 5. Plasmonic nano-antenna virtual sub-arrays.

maintaining relatively narrow beams. For example, instead of dividing the array in separate sub-arrays, the sub-arrays can be physically interleaved (see Fig. 5). As a result, the separation between elements in each virtual sub-array can be increased without affecting the physical footprint of the system. As discussed in the previous section, in order to perform beamforming, the array elements need to extend an area of at least half wavelength but no longer than one full wavelength, to prevent the presence of grating lobes. In the case of a non-interleaved sub-array (Fig. 5(a)), the achievable gain per beam would be compromised not only because each sub-array has fewer active elements, but also because they are too close to exhibit beamforming capabilities. Alternatively, by interleaving the sub-array elements (Fig. 5(b)), the separation between elements can be increased to $\lambda/2$ and thus, beamforming gain is obtained.

In Fig. 6, the gain per beam is shown as a function of the number of beams for both separate sub-arrays and interleaved sub-arrays, when considering a graphene-based plasmonic nano-antenna array with 1024 elements at 1 THz. On the one hand, the 1024 nano-antennas can be utilized to create a single beam. This case corresponds to the UM beamforming. On the other hand, each nano-antenna is utilized to transmit create a separate beam. In between, square planar sub-arrays are created by grouping the plasmonic nano-antennas. For example, a total of 64 sub-arrays with 16 elements each can be created. The gain of each beam can be in the order of 12 dB if non-interleaved sub-arrays are utilized, and can be increased to 22 dB per beam by interleaving the sub-arrays. These results highlight the benefits of sub-array interleaving and motivate the development of new array pattern synthesis methodologies.

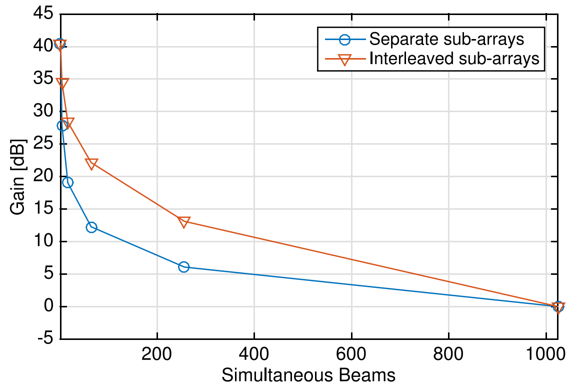


Fig. 6. Gain per beam as a function of the number of beams, with and without sub-array interleaving ($N = 128$ active plasmonic nano-antennas, $\gamma = 25$).

3.2. Multi-band UM MIMO

Until this point, we have considered that the array is designed to operate at a specific frequency window. However, for distances beyond a few meters, the THz band exhibits multiple absorption-defined transmission windows. To maximize the utilization of the THz channel and enable the targeted Tbps links, more than one window might be needed [1].

Multi-band UM MIMO enables the simultaneous utilization of different transmission windows by leveraging the capabilities of plasmonic nano-antenna arrays. The fundamental idea is to virtually divide one nano-antenna array into multiple sub-arrays and to tune each sub-array to operate at a different center frequency. Each transmission window is effectively narrowband, i.e., its bandwidth is much smaller than its center frequency. This simplifies the design of each nano-antenna as well as the dynamic control of the nano-antenna array.

There are several unique capabilities of plasmonic nano-antenna arrays which enable multi-band UM MIMO communication. On the one hand, as discussed in Section 2.1, the frequency response of an individual plasmonic nano-antenna can be electronically tuned. Therefore, the response of individual elements in the array can be dynamically and independently modified. On the other hand, the required spacing between antenna elements can be adapted by choosing the right elements to contribute to the array. For example, the elements should be chosen so that their separation is approximately $\lambda/2$ at the targeted frequency band. The very high density of elements, whose separation is much shorter than the free-space wavelength, provides the required "granularity" to create the required spacing at the desired frequency. Moreover, "virtual" sub-arrays at different frequencies can be interleaved as previously discussed. All these opportunities introduce many challenges and motivate further analyses of the proposed schemes.

Ultimately, the possibility to create very dense nano-antenna arrays, with individually tunable and controllable elements, introduces many opportunities to the design of dynamic and multi-band UM MIMO schemes which can make the most of the THz band. Nonetheless, this brings many additional challenges, which we summarize next.

4. Challenges for UM MIMO systems

4.1. Fabrication of plasmonic nano-antenna arrays

The complexity in the fabrication of the THz antenna arrays depends on their underlying technologies. For metallic antennas, the main challenge is posed by the design of the array feeding and control network. The development of an array-of-sub-arrays architecture and the balancing between the operations done in the analog domain or in the digital domain, similar to what is done in mm-wave communication systems [7], are necessary steps towards building the first THz arrays. The problem becomes more challenging when metamaterials or nanomaterials are utilized to build plasmonic nano-antenna arrays. For metamaterials, the first step is to identify the nano-block that will be utilized to build the material. In [14], an array of sub-wavelength copper-based patches was utilized as the support for SPP waves at frequencies as low as 10 GHz, but other building blocks such as split ring resonators could be utilized instead [11]. In addition, the signal excitation, control and distribution network will have to be interleaved with the metamaterial design [18].

When it comes to graphene, the possibility to create the plasmonic signal source, time-delay/phase controller and antenna out of the same material simplifies the fabrication of the array. For the time being, graphene can be obtained by various methods, but only micro-mechanical exfoliation and chemical vapor deposition can consistently produce high-quality samples. Once the graphene layer is obtained, the array needs to be defined on it. For the time being, chemical and plasma etching techniques can be used to cut the required structures out of graphene. However, to define thousands of antennas and their feeding network, more accurate techniques are needed. For example, novel lithographical methods based on the use of ion beams [30] to "outline" the array can enable transformative ways to define arrays and their control network.

4.2. UM MIMO channel modeling

The performance of UM MIMO communication depends on the behavior of the THz-band channel. For the time being, THz-band channel models for line-of-sight, non-line-of-sight and multi-path propagation conditions have already been developed [29]. Currently, we are working on the first UM MIMO channel model that takes into account the peculiarities of the very large arrays in transmission and in reception as well as the THz-band channel propagation effects [31]. More specifically, in relation to the arrays, our analysis captures the mutual coupling between neighboring nano-antennas and the performance of the required signal distribution network and time delay/phase controllers. In terms of the channel, the analysis takes into account the impact of the spreading loss, the molecular absorption loss, and the very high reflection loss at THz frequencies in realistic three-dimensional scenarios.

In addition to the complete channel characterization, novel mechanisms to efficiently estimate thousands of parallel channels for real-time dynamic operation of the arrays need to be developed. Spatial correlation between neighboring plasmonic nano-antennas, whose separation is much smaller than the free-space wavelength, can be leveraged to simplify the complexity of the problem. In addition, new types of pilot signals tailored to the channel characteristics need to be developed. Moreover, channel prediction techniques could also be utilized to reduce the channel estimation overhead [32]. These should also be able to estimate in real-time the available transmission bandwidth, which plays a key role in the definition of efficient physical layer solutions.

Both channel characterization and real-time channel estimation become more challenging in the case of multi-band UM MIMO. The main reason is that separate transmission windows can exhibit significantly different propagation characteristics, not only in terms of path-loss and transmission bandwidth, but also in terms of coherence bandwidth and delay spread. For this, hybrid mechanisms that take into account the correlation between carriers in the same window but independently analyze separate windows are needed.

4.3. Physical layer design

One of the main challenges at the physical layer is the design of optimal control algorithms able to fully exploit the capabilities of very large nano-antenna arrays to maximize the utilization of the THz-band channel. The ability to control the frequency at which each element operates, the gain and time-delay/phase at each element, and the possibility to dynamically create interleaved groups of virtual sub-arrays, introduce many degrees of freedom for the design and operation of a UM MIMO communication system. On the one hand, this can be modeled as a resource allocation problem with different optimization goals based on the UM MIMO mode, i.e., dynamic beamforming and spatial multiplexing or multi-band communication. On the other hand, practical algorithms are needed to find and implement such optimal solution in real-time and in practical scenarios.

In addition, the unique distance-dependent bandwidth provided by the THz-band channel motivates the development of distance-aware modulation techniques [33,34]. These can operate either in a single transmission window or over multiple separate bands. In the case of multi-band UM MIMO, new coding strategies that spread the redundant information across different transmission windows can be developed to increase the robustness of long-distance THz links. Ultimately, the combination of the UM MIMO modes with dynamic modulation and coding schemes will lead to the maximal utilization of the THz band.

4.4. Link layer and above

New networking protocols are needed to fully exploit the capabilities of UM MIMO communication systems. At the link layer, synchronization becomes one of the main challenges due to the transmission at very high-data rates with very narrow beams and in the presence of phase noise at the THz oscillators. New time and frequency synchronization methods able to minimize the synchronization delay are needed to maximize the channel utilization. Another factor affecting the achievable throughput at the link layer is the delay associated to the process of beam-steering. This depends on the technology utilized to build the UM MIMO arrays. For metallic arrays, this is mainly related to the performance of the time-delay/phase shifters. In case of plasmonic nano-antenna arrays, the bandwidth at which SPP wave phase can be modulated is in the order of 10% of the carrier signal, i.e., several hundreds of GHz in the THz band. This enables very fast beam-steering arrays.

One more element to consider at the link layer is the impact of multi-user interference. On the one hand, the use of very narrow beams in transmission and in reception results in very low average interference. On the other hand, however, the fact that the very high gain beams are frequently steering can result into very high values of instantaneous interference. The impact of such transient interference needs to be analyzed and mechanisms to overcome it should be designed accordingly.

Similarly, at the network layer, the requirement for high-gain directional antennas simultaneously in transmission and in reception increases the complexity of frequent tasks such as broadcasting and relaying. In terms of broadcasting, the possibility to dynamically steer the beam at very high speeds and the fact that information is transmitted very fast, i.e., hundreds of Gbps or Tbps, enables new fast broadcasting schemes. New optimal relaying policies that take into account the very large arrays, the THz-band channel behavior, and the overhead in terms of synchronization at each hop need to be developed. While the unique distance-dependent available bandwidth further motivates the use of shorter links, the overhead associated to the process of beam steering and the relay costs dictate otherwise. Therefore, an optimal relaying distance can be defined. All these will also depend on the specific application, i.e., whether UM MIMO is for Device-to-Device (D2D) applications or for example in small-cell deployments. Ultimately, all these challenges at each underlying layer need to be jointly addressed in a cross-layer fashion to guarantee end-to-end reliable transport in THz-band communication networks.

5. Conclusions

Terahertz-band communication is envisioned as a key wireless technology to satisfy the need for ultra-high data-rates in the next five to ten years. UM MIMO communication has been proposed as a way to overcome the very high propagation loss at THz-band frequencies while fully exploiting the very large bandwidth in the THz band and, thus, enabling wireless Tbps links between compact devices over several tens of meters. In this paper, we have described the enabling technology for UM MIMO systems, namely, the use of plasmonic nano-antennas and nano-transceivers as the building block for plasmonic nano-antenna arrays. For frequencies in the 0.06–1 THz range, metamaterial-based nano-antennas can be utilized to create plasmonic nano-antenna arrays with hundreds of elements in a few square centimeters both in transmission and in reception. For example, 144×144 UM MIMO at 60 GHz is possible with 1 cm^2 arrays. At higher frequencies (1–10 THz), graphene-based plasmonic nano-antenna arrays with thousands of elements can be embedded in a few square millimeters. For instance, a 1024×1024 UM MIMO system at 1 THz is realizable with arrays that occupy just 1 mm^2. Ultimately, the higher the frequency the larger the number of antennas, but the more challenging it becomes to operate the array. We have also introduced the different working modes of UM MIMO, namely, UM beamforming, UM spatial multiplexing and multi-band UM MIMO. Finally, we have highlighted the major challenges and potential solutions in terms of communication and networking protocols for UM MIMO systems, thus defining a roadmap for the development of this paradigm.

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