An Overview of Research Topics and Challenges for 5G Massive MIMO Antennas

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***Abstract*—An overview of the main research topics for massive multiple input multiple output (MIMO) antenna arrays is presented. Massive MIMO is expected to be one of the pillars of fifth generation (5G) and beyond cellular systems. In fact, with millimeter wave (mmWave) communications, a large number of antenna elements can be used to form large arrays of reasonable sizes. This entails significant challenges that need to be overcome in practical implementations. In this paper, we present an overview of important research topics related to massive MIMIO, and discuss their associated challenges. Furthermore, we present several application areas where massive MIMO antenna arrays could lead to significant performance enhancements.**

I. INTRODUCTION

Massive MIMO (also known as Large-Scale Antenna Systems, Very Large MIMO, and Hyper MIMO) is an exciting concept in wireless communications research that promises to address the massive capacity requirement demanded by 5G systems. In Massive MIMO, the base station is usually equipped with a very large number of antennas, operated fully coherently and adaptively to serve multiple users devices, each equipped with one or more antennas. The extra antennas help focus the transmission and reception of signal energy into smaller regions of space, thus bringing huge improvements in throughput and energy efficiency. With the advent of millimeter wave communications [1], [2], Massive MIMO antenna deployments are becoming practically feasible [3]. This would allow the placement of a large number of antennas in a relatively small area.

Massive MIMO antennas can indeed have a primordial role in several aspects of 5G communications. Some of their interesting configurations are presented in Section II. Their role in backhaul links is described in Section III, and their role in access links is described in Section IV. Several other applications undergoing significant research are presented in Section V, and the role of massive MIMO in these application scenarios, which has not yet received sufficient research attention, is outlined.

II. INVESTIGATION OF ANTENNA CONFIGURATIONS FOR 5G MASSIVE MIMO

Due to their large number, proximity and modes of operation, strict requirements are imposed on the design of the antennas in a massive MIMO system. The array configuration in which the antennas are placed, their individual patterns and mutual coupling all play roles in the performance of the system.

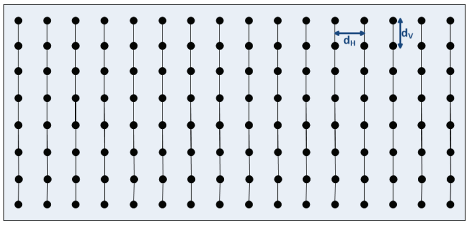

Fig. 1. Planar array.

Thus, antenna configurations for use in Massive MIMO schemes for 5G should be investigated and analyzed. For example, rectangular, circular and cylindrical array configurations could be studied in terms of their element numbers, resulting pattern beamwidth, gain, mutual coupling and their effects on coverage, the received signal strength and the channel capacity. The investigation could be done for one or more of the 6 GHz, 27-28 GHz, and 60-70 GHz bands. Several antenna element types could be used, such as dipoles, horn antenna and printed antennas.

In Fig. 1, a planar antenna array disposition is shown. Planar arrays allow obtaining directive beams that lead to high antenna gains in a desired direction while leading to low sidelobe levels in undesired directions. The antenna gain is closely related to the directivity of the antenna, which is calculated directly from the array factor [4]. Planar antenna arrays are obtained by placing linear arrays one parallel to the other such that the elements form a planar configuration, as depicted in Fig. 1. It was shown in [4] that the array factor of a planar array is equivalent to the multiplication of the array factors of two linear arrays in orthogonal directions.

On the other hand, cylindrical antenna arrays are obtained by stacking circular arrays one above the other such that the elements form linear arrays in the vertical direction, as depicted in Fig. 2. It was shown in [5] that the array factor of a cylindrical array is equivalent to the multiplication of the array factor of a linear array on the z-axis by that of a circular array in the $x - y$ plane. Thus use of circular arrays provides 360 degrees symmetry whereas their stacking in the vertical direction provides increased gain and directivity.

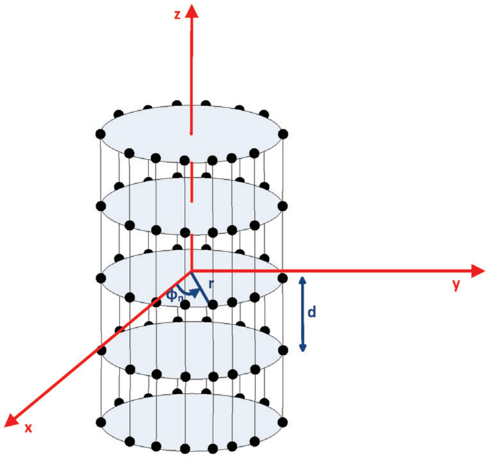

Fig. 2. Cylindrical array.

A method that transforms a circular array to a virtual linear array was proposed in [6]. It allows to join the benefits of 360 degrees symmetry in circular arrays with the flexibility of adjusting the array factor through varying the excitation coefficients in linear arrays. The approach of [6] was applied in [7] on the stacked circles forming cylindrical arrays to enhance the directivity in the direction of the desired elevation angle. This transformation needs a large number of elements on the circular array. At the time it was proposed, and later when it was considered for cylindrical arrays, the number of antenna elements required to implement it was too large for practical systems. However, with the advent of 5G millimeter wave communications, stacking very large numbers of small antenna elements to form huge arrays with reasonable dimensions gained practical viability and increasing research interest, as demonstrated by the exceptional interest in massive MIMO systems, e.g., [3]. Thus, cylindrical arrays and planar arrays with large number of elements would be interesting to build and investigate their performance in mmWave massive MIMO scenarios. Furthermore, the complexity of the feeding network of massive MIMO arrays is challenge not to be overlooked, especially at mmWave frequencies, and with the beam-steering required to serve multiple users simultaneously.

III. MASSIVE MIMO FOR BACKHAUL COMMUNICATIONS

Massive MIMO can be used to ensure reliable high rate communications between two cellular base stations (BSs). This can be considered as a replacement to wired fiber optic communications or microwave links, or even as a backup communication link in case these connections exist [8], [9]. Since the BS locations are known, it is possible to direct the antenna beams of the highly directive massive MIMO arrays at each of the BSs towards each other. The large antenna gains of the transmit and receive arrays would lead to high data rate backhaul communications capable of coping with the stringent requirements of 5G cellular systems.

It should be noted that these backhaul connections do not necessarily have to link two BSs of the same type, e.g., two macro BSs. They can be used for connecting two micro, pico, or any type of small cell BSs (SCBSs) together. In addition, they can be used in a heterogeneous network (HetNet) framework to connect different types of BSs [9]. For example, several SCBSs can communicate over a macro BS using massive MIMO arrays.

Considering the case of a cylindrical array, which consists of several circular arrays stacked on top of each other, provides interesting insights: due to the 360 degrees symmetry of circular arrays, the beam of each circular array at a macro BS can be used to point to an SCBS in any direction. Hence, a macro BS having a cylindrical array consisting of 10 circular arrays could for example communicate with 9 SCBSs and 1 macro BS (1 circular array for each), or communicate with 5 SCBSs and 5 other macro BSs (using 1 circular array for each). It could also communicate with 5 SCBSs (using 1 circular array for each) and 1 other macro BS (using a cylindrical consisting of the 5 remaining circular arrays). One could envisage all kinds of hierarchical combinations for backhaul communications between femto, pico, micro, and macro BSs. Thus, the dynamic selection of the number of antenna elements for each transmission direction, the transmit power for each element, and the structure of the hierarchical backhaul network leave the door wide open for a broad range of optimization problems.

In addition to the cylindrical array example considered above, suitable for a BS at the cell center, other geometries offer different advantages depending on the scenario considered. For example, three planar arrays, disposed along a triangular configuration, can cover 3-sectored cells (each with its own planar array). The role played by a circular array in the previous cylindrical array example can be played by a linear array forming the planar array in this example.

IV. MASSIVE MIMO FOR USER ACCESS

Massive MIMO can also be used for communication between BSs and users in 5G networks. The presence of a large number of antennas at the BSs allows the BS to implement efficient beamforming techniques, steering the beam of the antenna array towards each user. With high directive beams and low sidelobe levels, each user will have a nearly interference-free communication link with the BS. This would be expected to allow 5G cellular systems to reach very high data rates even in the presence of multiple users connected to the network. This performance can be enhanced further by the use of the multiple antennas present at the mobile devices [10]. In addition, when large number of antennas become available at mobile devices, massive MIMO techniques can be applied at both the BSs and user devices [11], which would lead to even more gains.

Consequently, interesting optimization problems can be formulated to optimize the radio resource management (RRM) in 5G networks in the presence of massive MIMO. Different scenarios can include: single cell cases, multiple cell scenarios with intercell interference mitigation and/or management, RRM optimization in HetNets, scenarios with distributed base stations, relays, and scenarios with device-to-device (D2D) communications [12].

Furthermore, one could formulate the optimization problems with massive MIMO for indoor femtocells, in the presence of mmWave-based WiFi access points (802.11ad) [13], and in scenarios with cellular/WiFi coexistence. For example, a HetNet scenario with possible offloading of users to IEEE 802.11ad access points would constitute an interesting case for investigation.

In addition, massive MIMO techniques could have an essential role in energy efficiency. Thus, they can be investigated in terms of their role in ensuring green communication networks. For example, when the network traffic is low (e.g. at night), a single macrocell equipped with a massive MIMO array can serve a wide coverage area with dispersed users, while putting all (or most of) the SCBSs in that are into sleep mode.

Nevertheless, several practical challenges will face the implementation of massive MIMO techniques in 5G. Examples of challenges faced:

- Inaccurate location estimation: accurate location of the best signal path between BS and users is needed in order to perform efficient beamforming.
- Inaccurate channel state information (CSI) feedback/feedback overhead: The CSI feedback between users and BSs might suffer from inaccuracies. In addition, in case the channels between the different antennas at the BS and those at the user devices are significantly different, large feedback overhead might be required.
- Dynamic beam steering in the case of fast moving users: users moving at high speeds could be hard to track, and the feedback required might end up being too slow at the given speed, which would affect the MIMO performance.
- More than one user located along the same transmission direction: In this case, the beams pointing to the different users might overlap. A possible solution would be to dedicate orthogonal subchannels for the users having overlapping beams.

The impact of the above inaccuracies and challenges on the system performance should be evaluated and assessed in research activities related to massive MIMO.

V. DIFFERENT APPLICATIONS OF MASSIVE MIMO

Several applications of massive MIMO in hot research areas can be investigated and analyzed. Some of these areas are described in this section.

A. Internet of Things

With the Internet of Things (IoT) and machine-to-machine (M2M) communications (also called machine-type communications, MTC, in 3GPP standards), 5G networks need to serve the large numbers and devices deployed as part of IoT. These are mostly sensor devices requiring low data rates, but their huge amounts pose challenging problems to network connectivity. Furthermore, their traffic should not overlap with the “traditional”network traffic. A typical scenario consists of a large number of smart power meters transmitting their data in real time or near real time over the network. Massive MIMO techniques could play a significant role in ensuring appropriate RRM in such scenarios.

B. Vehicular Networks

In the scenario of vehicular networks, different vehicles can be equipped with massive MIMO arrays to perform efficient vehicle-to-vehicle (V2V) communications in an intelligent transportation system (ITS). This communication can also occur between a vehicle and the infrastructure (V2I), be it the ITS infrastructure or cellular infrastructure (with the 5G BSs). The use of massive MIMO will allow a faster exchange of large amounts of data between vehicles, while reducing interference to neighboring vehicles.

C. Railroad Networks

In Railroad networks, trains follow a known track at a known speed according to known schedules. Thus, BSs covering railroad tracks could benefit from massive MIMO techniques to transmit at high data rates for trains moving at very high speeds. In addition, the train structure consisting of several interconnected wagons allows the installation of very large number of antennas on the train roof, thus forming a large MIMO array. In addition, each wagon can be equipped with its own access point, acting as a moving femtocell or moving SCBS, and using the antennas on top of the wagon to communicate with the macro BSs along the train track. In addition, it can communicate with the mobile devices inside the wagon using an indoor antenna. This allows avoiding the penetration loss across the metallic train structure, while providing communications at high data rates. Accurate CSI feedback and dealing with the Doppler effect are important challenges to be overcome in this scenario.

D. Public Safety Networks

In public safety networks, massive MIMO arrays can be used to transmit information securely and reliably to a large number of public safety personnel at an incident site. A fire department vehicle can use it to communicate with firefighters inside a building, a police vehicle can use it to communicate with the policemen breaking into a hostage situation area, a helicopter transmitting to ground teams in a disaster situation, etc. This allows the transmission of fast and reliable data to the public safety personnel at an incident site, which leads to a more efficient performance.

E. Multimedia Communications

Massive MIMO antennas have also applications in multimedia communications. In fact, one could also consider the quality of service (QoS) and quality of experience (QoE) during real-time video streaming or voice over IP (VoIP) in the network. The role of massive MIMO arrays in enhancing the

QoS/QoE of a large number of users connected to the network would an interesting topic to investigate. In fact, a cross-layer optimization problem can be considered, with scalable video coded (SVC) sequences at the application layer, and efficient beamforming and RRM at the physical and MAC layers. Real-time implementations of video streaming of high quality videos could have important implications in public safety scenarios. For example, real-time videos could be transmitted to/by the public safety personnel at a disaster site.

F. Security Applications

The large antenna arrays used in massive MIMO have their benefits in security applications. In fact, in [14], [15], methods to exchange secret keys with massive MIMO are investigated in the presence of pilot contamination attack (PCA), mostly common in time division duplex (TDD) systems.

They also have their role in physical layer security techniques, where communications are secured without relying on the overhead of traditional application layer encryption techniques. Instead, physical layer security relies on signal processing, channel coding, and other physical layer techniques [16].

With a large number of antennas present at the transmitter, beamforming can be performed to place a null in the direction of a potential eavesdropper, thus eliminating, or significantly reducing its capability to detect the secret key transmission or later on the encrypted messages, or even the unencrypted messages in case of a physical layer security scenario. The main beam can be directed towards the legitimate receiver, whereas sidelobes or nulls can be directed towards the eavesdropper thus minimizing the received data at the eavesdropper. Under these scenarios, the receiver can also steer its main beam in the direction of the transmitter, thus maximizing its received signal.

In addition, massive MIMO arrays could be useful for simultaneous data transmission (not necessarily encrypted) to a legitimate receiver while jamming an eavesdropper at the same time. In fact, part of the antenna elements at the transmitter can be used to transmit a jamming signal in the direction of the eavesdropper. The remaining antenna elements can transmit the secret key information and then the encrypted data messages to the destination, as shown in Fig. 3. A relatively small number of elements can be sufficient to jam the eavesdropper by sinking the leaked signal in jamming noise. When an eavesdropper is jammed, its ability to detect the useful signal becomes very limited.

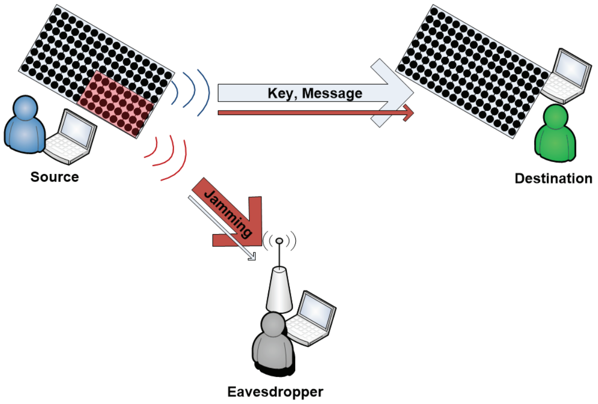

Fig. 3. Communications using massive MIMO with a subset of the antennas used for jamming the eavesdropper.

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