Future challenges with Massive MIMO, Reconfigurable Intelligent Surfaces and Teraherz Communication

Joakim Lönn Stefan Markovic Ekaterina Saltykova

***Abstract*—This report brings up the three following multi-antenna techniques: Massive MIMO, Reconfigurable Intelligent Surfaces and Terahertz Communication. The future implementation of these techniques looks promising. However, there are a lot of implementation challenges to be considered and successful deployment of these technologies requires future research work. This paper covers the main deployment challenges for each multi-antenna technique ans examines possible application scenarios.**

***Index Terms*—Massive MIMO, Reconfigurable Intelligent Surfaces, Terahertz Communication**

I. Introduction

Over the past several decades, there has been an extraordinary technological development in the field of wireless communications. Services for a wide range of applications requiring high speed data transmission are in demand. To solve the problems associated with these services, the development of antenna techniques that can be implemented in 5G and future wireless networks beyond 5G, is crucial. This paper describes three multi-antenna techniques for high speed wireless communication: Massive MIMO , Reconfigurable Intelligent Surfaces, and Terahertz communication. The report is limited to these three methods since they represent the most promising solutions for solving the challenges associated with future wireless communication networks. The current use of the three technologies in emerging wireless networks (5G and 6G) are investigated. Additionally future research directions associated with them are discussed. The focus is made on exploring the practical deployment challenges and potential application scenarios.

A. Massive MIMO

Over a decade ago Massive MIMO (multiple-input multiple-output) was just a 'prospective concept' for future cellular networks. However, since 2018 its implementation and practical application has started. During the past few years major challenges like equipping base stations with multiple antenna arrays used to serve several users simultaneously, finding an appropriate method in signal processing required to achieve a decent spectral efficiency (SE), finding a way to ease limitations due to pilot contamination and etc. have been resolved [1]. Currently, the first 5G products for mmWave communications deploy only analog or hybrid analog-digital beamforming systems. Nonetheless, case studies for developing fully digital Massive MIMO are being carried out. It is only a matter of time before digital technologies will dominate the market and become the most cost and energy efficient implementation solution.

The future ubiquitous deployment of base stations (BSs) with massive antenna arrays reveal a new reality in which spatial processing capabilities can be used in brand new usage scenarios, such as machine-type communications, extended reality (XR), Industrial Internet of Things (IIoT) and etc.

However, current realization of massive MIMO has its own drawbacks, such as inter-cell interference or excessive power consumption and high deployment cost. Therefore, there have been several research studies towards new deployment concepts, which might improve mentioned implementation disadvantages: cell-free massive MIMO and holographic massive MIMO. The following sections will describe their working principles, research challenges and prospective application opportunities.

B. Reconfigurable Intelligent Surfaces

A Reconfigurable Intelligent Surface (RIS) is a multi-antenna technology which can be used to possibly improve future communication systems. A RIS differs in comparison to a normal reflecting surface. A normal reflecting surface has a constant impedance, which causes the signal to reflect in a direction based on the fundamentals of Snell's Law. In short, the incoming signal will be reflected, resulting in a reflected scattered output signal. When the value of the input angle matches the output angle, this is when the reflected scattered signal is the strongest. In RIS, the surface is based on something called Meta-surface. This Meta-surface consists of many small meta-atoms that scatters the incoming signal. However, these meta-atoms can be programmed, changing the phase of the transmitted signal by phase-shifting it. This results in having different phases on each of the reflected scattered signal. The programming of the meta-atoms is done with the RIS-controller, which is based on a programmable device, such as a FPGA. This allows for interesting opportunities when combining all the scattered signals, they can form a directional beam towards a specific receiver. As a result of this technology, there will be a greater SNR at the receiving device. This type of multi-antenna technology can be really powerful if implemented in today's communications, as it would be useful in propagation environments where there is little or no line of sight (LOS). [8] [9]

C. Terahertz communication

Wireless communication systems show a tendency of explosive growth for ultra-high data rates and the development of wireless data rates have doubled every 18 months [12]. Although the data rate in the millimeter wave band can achieve several Gigabits per second (Gbps), it is still not enough to satisfy the requirement of the increasing data traffic in future wireless communications. To tackle the challenge of reaching data rates of several Terabits per second (Tbps), the Terahertz (THz) frequency band should be explored. THz communication can supply large available bandwidth and achieve ultra-high data rate. It is therefore envisioned as the priority choice for scenarios of high-speed transmission [11]. As 5G most likely will be commercialized before the end of 2020, research activities have been underway for 6G. Since 6G is expected to require data rates in excess of 100 Gbps or faster, THz communication is emerging as a likely candidate [13].

The THz range refers to frequencies between 100 GHz and 10 THz, located in the boundary region between the radio spectrum and the optical spectrum. Since the wavelength in THz communication is very small compared to todays 4G microwave frequencies, diffraction and material penetration will incur greater attenuation, thus elevating the importance of propagation along dominant paths, reflection and scattering [13].

II. Implementation Challenges

A. Future Massive MIMO related research directions and challenges associated with them

Currently, there are several promising massive MIMO related research directions. This paper will outline the following two: Cell-Free (CF) Massive MIMO and Holographic Massive MIMO.

a) *Cell-Free Massive MIMO:*

In contrast to conventional cellular network, where each base station (BS) serves users within one cell, this concept is based on distributing a large number of BS antennas (also called access points (APs)) over a large geographical area without strict cell boundaries [2]. APs are equipped with single or numerous antennas and cooperate with each other to serve several user equipments (UE) simultaneously. This is achieved by implying time-division duplex (TDD) operation, combining it with dense distributed network topology [3]. Each AP is connected to central processing unit (CPU) through front-haul network links. Each CPU is coordinating several APs. CF massive MIMO performs coherent user-centric transmission since all APs, which use local channel state information (CSI), perform joint transmission to nearby UEs. APs receive downlink (DL) data and power control coefficients from CPU and send back users data in upper link (UL).

The benefits of CF Massive MIMO technology include its micro-diversity and the capability of reducing inter-cell interference [2], since all the access points are distributed uniformly across the coverage area [4] and coherently interact with each other via high-rate, low-delay front-haul links. In addition to this it was shown [5] that CF Massive MIMO can attain larger energy efficiency (EE) than cellular massive MIMO by employing max-min power control algorithm.

However, this research direction is considered to be comparatively new and there are some issues which remain to be open. For example, the previous research conducted in this area mainly considered slowly moving UEs, i.e with a velocity less than 10 km/h. In high-mobility scenarios shorter symbol-duration may affect the multi-path dispersion which can exceed channel coherent time [3]. This might corrupt the communication. Also, a possible phase-shift should be taken into consideration, which might influence the performance of the CF massive MIMO system. Therefore, precautions should be taken, like developing of relevant transmit precoding and power allocation algorithms.

Another concern is the confidentiality of information shared within CF massive MIMO. Due to the broad density of APs and UEs, and the publicity and standardisation of transmission protocols and pilot sequences, this network is vulnerable for eavesdropper attacks [3]. Hence, to prevent the degradation of security performance a robust attack detection algorithm should be proposed.

One more issue to be noted, in order to make CF massive MIMO applicable in 5G, further work towards compliance with existing standards should be made [2].

b) *Holographic Massive MIMO*:

This concept is based on a new beam forming technique which uses passive electronically steered antennas (PESAs) [6] devised to be exploited in radio-frequencies (RF) range. These antennas are integrated into a limited two-dimensional surface area in a form of spatially continuous aperture [1], also so-called Holographic MIMO Surfaces (HMIMOS) [7]. In terms of power consumption, this surfaces are categorised into two categories: active HMIMOS and passive HMIMOS.

In the first case the surface with multiple antennas is used as a transmitter. In 2017 the startup company 'Pivotal Commware' had introduced this device as a commercial product and called it 'Holographic Beam Forming (HBF)'. Each HBF device is equipped by RF input port and distribution network which controls propagation of RF wave over the device surface. This wave is called 'Reference Wave' which is intended to be transformed into a beam - 'Objective Wave'. In order to transfer the energy from 'Reference Wave' to 'Objective Wave' the 'Hologram' technique is used [6].

In the second case HMIMOS are used as 'wave collector' or 'reflection' surfaces and are called Reconfigurable Intelligent Surfaces (RIS) which we talked about previously. The implementation challenges connected with this technology will be reviewed in the next section.

The benefits of Holographic Beam Forming and HMIMOS include a significant reduction in power consumption, since it is designed in such a way that antenna's pointing operation (directing a beam form to a certain direction) requires negligible power usage. Moreover, comparing to massive MIMO which control system consists of complex and costly components, HBF requires control elements which are much cheaper [6]. This significantly lowers the cost of the maintenance.

Although the practical implementation of Holographic Beam Forming technique has started [7], there still remains a lot to accomplish. Finding approaches to estimate potentially large HMIMO channels, developing algorithms for the energy efficiency (EE) resource allocation and beam forming [7], user's scheduling and etc. are among open research prospective.

B. Challenges with Reconfigurable Intelligent Surfaces

1) Channel estimation: Performing channel estimations, to optimize the SNR in the different propagation environments is certainly a challenge. The receiving device might be in motion which will result in having a dynamic changing environment which makes brings this challenge to a further level. There have been studies, pointing out issues that improvements for estimating the channel is necessary to optimize the phase-shifts caused by the surface. It is mentioned that it could be done by implementing a feedback solution with sensors from the RIS that returns information to the transmitter that would improve and adapt. [9] Solving this challenge is beneficial, as having optimized phase-shifts will result in a better directional beam and further better SNR at the receiving device.

Research has been carried out in order to improve the channel estimation in the uplink from the BS to the RIS. The research explains findings and a concept of how the channel estimation protocol should be carried out. It was discovered that the cascaded channels are sparse, where they propose a solution to solve this by using a technique called compressive sensing. By using this technique together with pilot-based training, the study could result in an improved channel estimation performance. [10] Further improvements to optimize this would be by doing pilots-training from the BS to the RIS and simultaneously, in real-time, do the phase-shifts to achieve the most optimal directional beam and SNR at the receiving user.

C. Challenges with Terahertz communication

The main challenges of THz communication is listed below [14]. The following subsections describes the most critical challenges in more detail.

- The propagation loss is high compared to RF signals.
- The existing channel models for RF frequencies do not apply to THz Communication due to high propagation losses and many other factors.
- High-performance THz transmitters and receivers suitable for developing a communication link are not available yet.
- The power and detection sensitivity of THz Communication are very low compared to the radio frequency (RF) counterparts.

1) A new type of channel: The effects of atmosphere absorption on high frequency signals has long been recognized. At frequencies below 6 GHz, the attenuation of the signal is mainly caused by molecular absorption in free space, which is minimal. At higher frequencies however, the effects of scattering become more severe as the wavelength approaches the size of rain, snow, hail, or dust. The THz band also suffer greater attenuation than the sub 6 GHz bands in free space propagation in clear air. However, the loss compared to sub 6 GHz signals may be as small as 10 dB/km for frequencies up to 300 GHz, making these frequency bands suitable candidates for high speed 6G mobile wireless networks with up to 1000 m size coverage range. Most of the spectrum between 600 and 800 GHz suffers 100 to 200 dB/km attenuation corresponding to 10 to 20 dB over a 100 m distance. Hence, these frequency bands might be used in 6G networks consisting of small cells with a radius of somewhere around 100 m [15].

2) Lack of existing technologies: In the THz band, solid state amplifiers are relatively lacking because the development of appropriate transistors for the circuits is immature. In the current situation, only a few countries can carry out the development of THz amplifiers at the cost of high price and low yield rate. The realization of THz communication systems depends on the breakthrough of THz key solid-state circuits. That is, to develop the solid-state THz system, mixers and multipliers must be deeply studied and explored [12].

III. Application scenarios

In this section the use cases of the techniques are investigated. The main focus is on possible future application scenarios.

A. Cell Free Massive MIMO

One of the feasible ways of CF massive MIMO application lies within the field of machine-type communications such as Internet of Things (IoT), Industrial Internet of Things (IIoT), Smart X, etc. This type of communication requires scalable and continuous connectivity of a large number of devices. Conventional cellular network topology will not be able to maintain this level of communication load, since each cell is capable of serving only limited amount of UEs. Hence, cell free structure combined with massive MIMO will be more appropriate technology to use in this case.

B. Reconfigurable Intelligent Surface

Implementing RIS in the future generation of Wireless Networks is considered possible and very beneficial, due to the fact that RIS almost consists of entirely passive components and does not require any external power supply. The actual placements of the RIS such as, on top of buildings or different ceilings is not considered to be of an issue. Further application scenarios with RIS, is within the massive MIMO area. The RIS would be useful in propagation environments where there is little or no LOS as it is considered to be able to perform at frequency bands above 100 GHz. [9]

Other different scenarios for RIS applications are the following: milimetrewave-, THz communication and IoT. Where these mentioned applications scenarios could make usage of the directional beams reflected from the RIS to improve their wireless communication links. [9]

C. Terahertz communication

Due to the limitations in transmission distance, especially in bad weather conditions, it might be problematic to use THz communication in outdoor applications. However, THz communication may be used for indoor application scenarios such as WPAN, WLAN and indoor cellular networks. In these applications the users are close to the access points and the transmission distance is short. Hence, the path loss is not a problem.

Another possible application scenario for THz communication is wireless data centers. In the current standards, the architecture of the traditional data centers is based on wired connections. However, the cables take up lots of space and their maintenance cost is very high. In brief, the main problems with wired data centers include performance, cost of switching fabrics, maintenance cost and power consumption. To solve the various difficulties associated with traditional wired data centers, researchers have recently raised the concept of wireless data centers. The first paper about wireless data centers was published in 2008 and since then, the research on this subject has been in the ascendant [12].

Worth mentioning, is that space communication also is a possible usage case for Thz communication. Since applications in the space environment do not suffer from the atmosphere attenuation, THz communication can be used to meet the extremely high data rate requirement.

IV. Discussion and conclusions

Out of these three different multi-antenna techniques, there can be a conclusion made that the future looks exciting. All the mentioned technologies have a potential to change the way we use Wireless communication systems. There are opportunities that could make these technologies work together, such as exploiting Massive MIMO with Holographic beamforming or RIS combined with THz communication for better performance in bad propagation environments. However, this needs further research work in order to find relevant technological solutions to the implementation challenges mentioned in this paper.

Regarding THz communication, the main problem is that the atmosphere attenuation weakens the signal. Looking at indoor- or outdoor applications in urban environments, where the distance between the base stations is small, the signal attenuation will not be a major issue. Hence, THz communication is a promising solution for future wireless communication networks in those environments. However, before it can be fully implemented in real application scenarios more research is needed. Specifically, research on hardware is needed before THz communication can be implemented in large scale, and a breakthrough of THz circuits need to be made.

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