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MmWave massive MIMO small cells for 5G and beyond mobile networks: An overview

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***Abstract*—Promising technologies are being investigated to integrate them into the fifth generation (5G) and beyond mobile network systems. The main goal of these technologies is to evolve cellular networks that will significantly stress forward the limit of legacy network systems through all dimensions performance metrics. Some of the most potential key enabler technologies are millimeter waves (mmWave), massive multiple-input multiple-output (MIMO) and small cells (SC) systems. These sets of technologies will dramatically increase the network throughput, enhance the spectral and energy efficiency, increase the network capacity and improve the network coverage by using the joint capabilities of the huge available bandwidth in mmWave frequencies while achieving high multiplexing gains through the extreme antenna arrays gains and achieving full coverage network by network densification through small cells. In this paper we present a detailed overview of millimeter wave, massive MIMO, small cells, channel estimation, beamforming technology, signal processing techniques in mmWave, beyond 5G systems, challenges and future research trends.**

***Keywords*—5G, mmWave, massive MIMO, small cells, beamforming, signal processing techniques, 6G.**

I. Introduction

The launching of the commercial service for the fifth generation (5G) mobile network systems has been initiated since 2018 in many countries. 5G is the pillar that will enable revolutionary applications not only in the telecommunication market but also, including industrial, automotive, medical, and even defense. The numbers of connected devices to the internet are on exponential increase, and emerging technologies such as smart cities, smart homes, internet of things (IoT) are about to be a reality [1]. Consequently, the high demand of mobile data is assumed to increase in a factor of 1000 per device in coming years [2]. Current communication systems are about to reach the Shanon limit, for this, the research community has identified three ways to get several orders of magnitude throughput gain.Firstly, extreme densification of infrastructure. Secondly, Large quantity of new bandwidth and finally, by integrating many more antennas, allowing throughput gain in the spatial dimension.

In order to face the aforementioned problem, new technologies are emerging to make 5G and beyond networks able to meet the explosive demand of data rate. Millimeter wave (mmWave), massive multiple-input multiple-output (MIMO) and small cells (SCs) technologies are foreseen to be the answer of this high data demand [3]. They are considered as the most promising technologies to leverage performance of 5G and beyond networks. 5G era is foreseen to lead in the next generation that will deliver ultra-high-speed connectivity, higher data rates with more robust reliability, higher spectral efficiency, lower energy consumption and wider coverage with high capacity than the legacy system. Thus, these render 5G systems as the most outperform communication systems. Unlike the previous generation of mobile communication standards in which peak data rate has been steadily increased with wider channel bandwidth, 5G is more than just enhancement in data rate, it is all about the end-to-end ecosystem with deeper innovation for the fully mobile and connected society in the future.

Millimeter waves can provide a bandwidth of up to 252 GHz and the possibility of up to 100 GHz new spectrum for mobile applications [4]. The extreme high bandwidth in mmWaves makes it suitable for various applications in future networks such as front-hauling/back-hauling [5], vehicular networks and forth. On the other hand, massive MIMO technology exploits spatial domain resources to offer diversity gain, multiplexing gain, and power gain [6].

Likewise, small cells will offer thousands of connections and supported high transmission rate to provide variety local services [7]. Besides that, since small cells locate base stations near users,they are automatically one of the main drawbacks of mmWaves which is the high attenuation due to high frequencies with the distance. Moreover, small cells reduce the effect of blocking due to the need of going through walls.

Although, these technologies have a significant effect on the performance of the system, there are however, many

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challenges like blockage sensitivity in mmWave, interference management in massive MIMO and other challenges that have to be tackled while designing such systems. Therefore, considering some technologies like beamforming, and designing suitable signal processing techniques for channel estimation in mmWaves bands-based systems will effectively impact the performance of the system and it is highly important.

The rest of this paper is organized as follow: section II present a detailed description of mmWaves. In section III a brief overview on massive MIMO technologies is explained. Small cells are outlined in section IV. In section V a full review on channel estimation and signal processing techniques are highlighted, followed by beamforming in section VI. An overview on beyond 5G networks are presented in section VII. Challenges and research trends are given in section VIII. Finally, we conclude the paper in section IX.

Notation

Throughout this paper, boldface lower and upper case symbols represent vectors and matrices, respectively.

II. Millimeter Wave

MmWave frequency bands are also denoted as extremely high frequency. They are electromagnetic waves in the range of 30-300 GHz with a wavelength of (1-10 mm) and available bandwidth of up to 252 GHz. It can also avail about 100 GHz new spectrum for mobile applications [4].

MmWave spectrum has been employed in different application such as in radars [8], satellite communication and point to point (PPT) communication application [9] but not for commercial wireless networks. However, mmWave have recently appeared in short range communication [10] and mobile broadband networks [11]. About 28 GHz bandwidth is being identified for mmWave cellular networks while 57-64 GHz oxygen absorption band is excluded, and it is considered a best suited for indoor fixed wireless communication [12]. The extreme high data rate in mmWave bands makes it adequate for different applications such as vehicular network and fronthauling/backhauling. Another advantage of mmWave is its small wavelength which makes it possible to design small antenna that can easily be integrated on chips. The small wavelength will also help massive MIMO technology through involving huge number of antennas due to their small size.

Furthermore, the relatively closer spectral allocation in mmWave bands leads to a more homogeneous propagation unlike the disjointed spectrum in precedent network. Besides that, mmWave communication is foreseen to be a best solution to replace fiber optics backhauling in areas where installation of fiber optics will be difficult [13]. Additionally, narrow beams in mmWaves ease on packing more antenna elements than at microwave bands [10].

Regarding to its unique features, mmWave technology can be categorized into mmWave for wearable device, mmWave communication for virtual reality, mmWave in vehicular network, mmWave for 5G networks, satellite communication and mmWave for imaging tracking and detecting combination [10]. And it is envisioned that mmWave communication will be playing a great role in many areas as well.

Over the last three decades, various studies and measurements have been conducted in order to gain a deep knowledge of the special and temporal characteristics of millimeter wave frequency bands for the sake of developing new methods and techniques that will ease operating over mmWave bands, most of these studies and measurements were done in the 40 GHz band [14], 50 GHz band and 60 GHz band [15]. Recently in the 28 GHz [16], 38 GHz band [17] and 72 GHz band [18], all of these were sub 100 GHz, however, currently the above 100 GHz gained high attention though it lacks measurements.

Despite the high bandwidth that mmWave can provide, it also suffers of atmospheric absorption, blockage effect such as human body blockage [19] and self-blockage caused by on-chip components and human activities [20].

Why mmWave for 5G:

1) Large bandwidth
   With mmWave bands a peak data rate of about 10 Gbits/s can be achieved and this can increase with full duplex capability. This is much higher compared to 1 Gbits/s at low microwave frequencies [21].
2) Short wavelength
   MmWave bands have a very small wavelength compared to currently used microwave bands. This makes them possible to have tiny size components, thus enabling integrating of more antennas in a small sized device, therefore, it will help to miniaturize physically smaller circuits, modules and equipment for 5G mmWave application [10] [22]. Another advantage of short wavelength is the high antenna gains. According to electromagnetic and antennas theories, shorter wavelength of mmWave can obtain proportionally higher antenna gains.
3) Narrow beams
   In mmWave antennas arrays, highly directional steerable narrow beams can be formed to direct the transmit power precisely to the intended users along desired direction.
4) Increased security and interference Immunity
   The highly directional beams and greater resolution render mmWave signal difficult and costly to jam due to its restrict to a relatively small area. In addition to that, narrow beams make mmWave transmission highly immune to interference and noise at the receiver side due to the ability to focus transmit power level of the signal.

III. Massive MIMO

Massive multiple-input multiple-output (MIMO) systems are part of current wireless systems. Prior MIMO systems, there were single-input single-output (SISO) system which was known of its low throughput, thus unable to support large number of users with highly reliability. This has led to the development of new MIMO systems such as the single user

MIMO (SU-MIMO), multi-user MIMO (MU-MIMO) [23], however, these developed new MIMO systems could also not handle the ever-increasing demand of data. On top of that, the ongoing increase of connected devices and introducing of new application such as autonomous vehicles, smart cities, smart homes and more 5G applications, paved the integrating of new MIMO technologies that meet the requirements of 5G systems.

Massive MIMO technology is one of the most promising technologies in 5G and beyond networks systems. It is foreseen to be a powerful solution of massive data and connected devices related issues. Massive MIMO is a continuation of contemporary MIMO technology used in current networks which involves using hundreds or even thousands of antennas at the base station. The extreme use of antenna arrays in massive MIMO systems will leverage focusing energy into smaller regions of space which will provide better spectral efficiency and throughput.

Augmenting the numbers of antennas in a massive MIMO system makes the radiated beams narrow and spatially focused toward the user [24], this increase the throughput for the intended user and mitigate the interference to neighboring users. Fig1 shows a simple network for mmWave massive MIMO small cells.

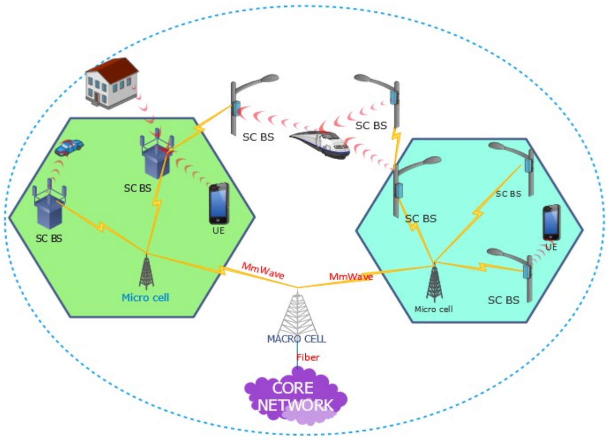

Fig1 MmWave massive MIMO small cells network

In mathematical perspective, we can consider a system that is composed of a transmitter (BS) with **N** transmit antennas and a receiver (UE) with **M** receive antenna. The base station **BS** (Tx) transmits simultaneously to multiple users **UE** (Rx) each with a single antenna. The received signal vector $\mathbf{y} \in C^{M\times 1}$ can be written as :

$$\mathbf{y} = \sqrt{p}\mathbf{H}_{m,n}\mathbf{x}_n + \mathbf{z}_m \quad (1)$$

where $n = \{1,2,....,N\}$ transmit antennas, $m = \{1,2,...M\}$ receive antennas. $\mathbf{x}_n \in C^{N\times 1}$ is the transmit signal vector,$\mathbf{H}_{m,n} \in C^{M\times N}$ is the channel matrix, $\mathbf{z}_m \in C^{M\times 1}$ is the noise and interference vector and p is normalized transmit power.

Furthermore, massive MIMO technology relies on the channel state information (CSI) for signal detection and decoding. The performance of massive MIMO systems depends on the knowledge of the channel, thus when CSI is perfect, the performance of the system grows linearly with the number of transmitted or received antennas, whichever is less [25]. Toward this, massive MIMO systems are mostly foreseen to use Time Division Duplexing (TDD) operations rather than using Frequency Division Duplexing (FDD) because of its complexity and the difficulty in hardware implementation. However, a huge research is ongoing for a possibility usage of FDD operations in massive MIMO systems.

IV. Small cells

Small cells are known as miniature base stations that break up a cell site into much smaller pieces, they encompass Pico cells, Micro cells and Femto cells, they can comprise of indoor/outdoor system. The main goal of small cells is to increase the macro cells edge data capacity, speed and over all network performance. Small cells were firstly added in release 9 of the 3rd Generation Partnership Project (3GPP) LTE spec in 2008 [26] and they are one element of network densification.

In 5G wireless communication systems, mmWave massive MIMO small cells, will play a tremendous role. The deployment of small cells densely, will provide thousands of connections and supported high transmission rate that will facilitate providing variety of local services [27]. These small cells base stations (SCBs) will avail a short range communication to mobile terminals (MTs) to reduce propagation loss of signal transmission [26]. By using mmWave and massive MIMO technologies, small cells can utilize large number of antennas to form directional beams to MT and provide concurrent transmission simultaneously.

Moreover, small cells deployment is considered to be an efficient approach to enhance spectral efficiency [28]. On the other hand, with mmWave and massive MIMO technologies, small cells are foreseen to be used for backhauling, this can be the best replacement of high capacity wired based solutions which require a very costly investment in infrastructure [29]. Similarly, small cells are considered to be a promising solution to replace fiber optic fronthauling in environment that installation of fiber seem to be impossible [30].

However, the increase of the number of small cells and connected devices in the cell, renders them hard to perform traditional signal processing. This has pushed artificial intelligence (AI) technology to involve in signal processing with some of its concepts such as machine learning [31] and deep learning [32] to enhance the wireless system performance. Furthermore, the AI agent can assist with baseband processing functions such as radio management, interference management, and handover control. Moreover, a centralized processing of CSI can allow additional insights into the channel that performs closer to channel capacity and schedulers that provide better fairness and end user experience [33].

V. Channel estimation and Signal processing techniques

Knowledge of the channel is highly important in any communication system. CSI determines the physical layer parameter and schemes used for radio communication in wireless systems [34], it has a substantial effect on radio resource allocation [35]. Accurate CSI is very essential in order to ensure the quality of the mmWave communication.

However signal processing in mmWave communication systems differs from other low frequency systems due to channel model, hardware constraints due to high frequency and bandwidth and the large antenna array that will be used at both transmitter and receiver side. Hardware constraints come up from practical consideration such as power consumption and circuit technology. A suggested signal processing in this is partitioning signal processing operation between analog and digital domain to decrease their resolution or the number of analog to digital converters (ADCs) [36]. This has brought up the development of hybrid beamforming architecture [37], low rate ADC methods [38] and beam space signal processing methods.

On the other hand, mmWave channel model, is different in other low bands channel model due to high sensitivity to blockage, small wavelength and the difference between line of sight and non-line of sight conditions, this leads to exploit mathematical properties of sparsity in channel estimation and equalization as well as precoder/combiner design. Furthermore, involving mmWave in MIMO systems rises a combined implication of hardware constraints, channel model and large array of antennas. The later has a huge impact on the design of mmWave MIMO systems.

Generally, low frequency, signal processing operations are acquired in the baseband while at high frequency, the hardware constraints render it difficult to have radio frequency (RF) chain and data converted for each antenna. Implementing power amplifier (PA), RF chain, associated with each antenna element and all basebands links is very hard at mmWaves [39], the closeness of antenna elements prevents from using a complete RF chain per antenna. Additionally, PA, ADCs are power consumer especially at mmWaves [40].

Moreover, Path loss, scattering and fading are three critical factors that affect the CSI in practical wireless communication. Path loss is related to the transmission distance, scattering appears in wireless systems due to the radiation of electromagnetic wave propagation in the air, while fading appears due to multipath propagation and shadowing is incurred by obstacles. The commonly used algorithm for channel estimations are the least square (LS) algorithm, maximum likelihood (ML) algorithm and Minimum mean square error (MMSE) algorithm. However, the two algorithms do not balance in the computation complexity and estimation accuracy well. LS has low computational complexity without considering the noise influence while MMSE considers noise influence at the cost of computing time [41].

Beside that, several algorithms for CSI estimation have proposed such as the imperialist competitive algorithm-extreme learning machine (IC-ELM) algorithm [49], online CSI estimation (OCEAN) algorithm [42] and a time domain channel estimation [43] algorithms.

To this end, channel estimation has many techniques like beam training and sparse channel estimation in lens based, multiuser channel estimation and sparse channel estimation based on phase shifter or switches. At mmWave channel estimation can be formulated as sparse problem where the hybrid precoder/combiner are the measurement through employing various idea based on adaptive compressed sensing [44] and ideas that rely on traditional random compressed sensing using pseudo random weights in phase array [45].

Signal processing techniques

1) Beam training protocols

   This technique is used in the approach of analog beamforming in MIMO systems, it is used for the purpose of discovering angular directions of the strongest signal between the transmitter and the receiver without explicit channel estimation. The concept of beam training can be explained in three phases: sector level sweep, beam refinement protocol (BRP) and beam tracking.

2) Hybrid precoding

   Hybrid precoding provides a compromised between system performance and hard complexity. The precoding /combining processing is divided between the analog and digital domain, it is also useful for both single user and multiuser cases [43].

3) Precoding and combination and combining with 1-bit ADCs:

   Here CSI is assumed [46]. A simple channel inversion precoding is proven to be optimal when the channel has full row rank. Finally, there are other techniques such as the signal user hybrid precoding with phase shifter or switches, single user hybrid precoding and combining with lens based front-end and multiuser precoding and combining.

VI. Beamforming

MmWave radios are inherently much more capable of focusing beams and acquiring gains through antenna aperture than at microwave radios, this is due to the small size of the antenna aperture which is large electrically.

On the other hand, one of the biggest challenges that mmWave communication faces is the losses of radio propagation. To reduce such issue, beamforming techniques are foreseen to be used to compensate the high losses [47]. The potential of beamforming techniques for dense spatial frequency reuse; pointing narrow beams to the intended users which keeps interference to other users minimal, making multiple concurrent transmission feasible in confined area. These make beamforming promising for mmWave communication [48]. In addition to that, possessing electrically large antenna arrays at both downlink and uplink sides, provides spatial multiplexing in multi path channels as well as in LOS only channels.

Besides that, knowing the interaction between antennas and radio propagation is essential in order to analysis multipath effects on beamforming performance, as it specifies the degree of channel capacity improvement through gain focusing [49]. Toward this, beamforming can be categorized into three categories analog, digital and hybrid beamforming. Fig2 describes beamforming.

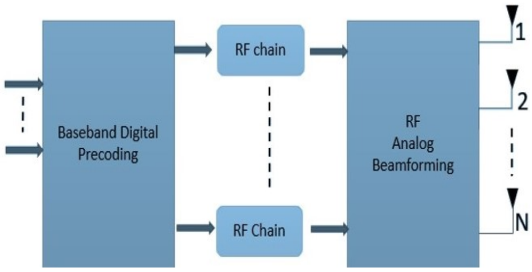

Fig2 Analog & digital beamforming (Hybrid beamforming)

VII. Beyond 5G

The beyond 5G networks or the sixth generation (6G) mobile networks are expected to be a complete wireless network with no limitations. This network is mostly at its begin of development. The transmission speed is foreseen to be on the range of terabits. The demand of massive data will continue, therefore the need of using high frequencies will be a paramount in future networks.Toward this, terahertz (THz) bands are seem to be potential candidate. THz frequency bands ranges between (300GHz to 3 THz). Additionally, new applications will continue to emerge some of these applications are multi-sensory extended reality, space travel, connected robotics, deep-sea sightseeing, tactile internet etc...

Consequently, 6G networks are expected to provide data rate up to 10 Tbps which is 100 times more than 5G networks, latency is expected to be as low as 0.1 ms , ubiquitous connection, spectral efficiency and energy efficiency that will be 100 times more efficient network energy usage compared to 5G networks. The introducing of this new generation mobile network is expected to be in 2030.

VIII. Challenges and Research trends

Despite of the immense benefits of millimeter waves massive MIMO small cells technologies that will bring to the core system performance, there are still many challenges like channel estimation, pilot contamination, precoding, energy efficiency, spectral efficiency and signal detection that need to be widely addressed and tested in real world environment to achieve their promised advantages. On the other hand, more researches in new technologies such massive MIMO, ultra massive MIMO, millimeter waves and terahertz waves need high attention in both academia and industry before getting these technologies implemented in current wireless systems. However, complexity of processing that is inherent to the Massive MIMO millimeter wave communications can be supported by Artificial Intelligence / Machine Learning techniques. A detailed description of each technology and its challenges is given in table I.

TABLE I
Challenges

Technology	Challenge	References
MmWave massive MIMO	Pilot contamination, computational complexity,signal detection algorithms, channel estimation, precoding, hardware impairments, user scheduling and energy efficiency	[24], [50]
Terahertz Ultra MIMO	Fabrication of plasmonic nano array antennas, optimal channel estimation methods, low complex and efficient precoding, accurate beamforming and beam steering.	[51]
Small cells	Signal processing methods	[31]
6G	THz communication, visible communication and holographic radio.	[24]

IX. Conclusion

In this paper we have presented a comprehensive overview that focused on promising technologies that are needed in 5G and beyond mobile systems in order to be able to accommodate the high requirement data. We have first given a full detail of mmWaves and their advantages on 5G networks. Followed by a review on massive MIMO technology which is considered as a promising technology that will play a great role in 5G and beyond networks systems. Subsequently, we presented a brief details on small cells, channel estimation and signal processing techniques, beamforming as well as an overview on beyond 5G networks. We also presented some of the challenges and potential future research trends. Finally, achieving a low complexity and high efficiency mmWave massive MIMO small cells, will absolutely make it one of the most powerful technology that will enhance the performance of 5G and beyond networks.

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