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Massive MIMO

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Abstract

The use of a large number of antenna elements, known as Massive MIMO, is seen as a key enabling technology in the 5G and Beyond wireless ecosystem. The intelligent use of a multitude of antenna elements unleashes unprecedented flexibility and control on the physical channel of the wireless medium. Through Massive MIMO and other techniques, it is envisioned that the 5G and beyond wireless system will be able to support high throughput, high reliability (low bit-error-rate (BER)), high energy efficiency, low latency, and an Internet-scale number of connected devices.

Massive MIMO and related technologies will be deployed in the mid-band (sub 6 GHz) for coverage, all the way to mmWave bands to support large channel bandwidths. It is envisioned that Massive MIMO will be deployed in different environments: Frequency Division Duplex (FDD), (Time Division Duplex (TDD), indoor/outdoor, small cell, macro cell, and other heterogeneous networks (HetNet) configurations. Accurate and useful channel estimation remains a challenge in the efficient adoption of Massive MIMO techniques, and different performance-complexity tradeoffs may be supported by different Massive MIMO architectures such as digital, analog, and/or digital/analog hybrid. Carrier frequency offset (CFO), which arises due to the relative motion between the transmitter and receiver, is another important topic. Recently, maximum likelihood (ML) methods of CFO estimation have been proposed, that achieve very low root mean square (RMS) estimation errors, with a large scope for parallel processing and well suited for application with turbo codes.

Massive MIMO opens up a whole new dimension of parameters where the wireless applications or other network layers may control or influence the operation and performance of the physical wireless channel. To fully reap the benefits of such flexibility, the latest advances in artificial intelligence (AI) and machine learning (ML) techniques will be leveraged to monitor and optimize the Massive MIMO sub-system. As such, a cross-layer open interface can facilitate exposing the programmability of Massive MIMO through techniques such as network slicing (NS) and network function virtualization (NFV). Finally, security needs to be integrated into the design of the system so the new functionality and performance of Massive MIMO can be utilized in a reliable manner.

Keywords:

5G, Massive MIMO, beamforming, mmWave, HetNet, energy efficiency, channel estimation, CFO estimation, hybrid architecture, beam optimization, average signal-to-noise ratio per bit.

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INGR ROADMAP

1. Introduction

The 5G and beyond wireless system is envisioned to provide unprecedented throughput, minimal latency, massive connectivity, which will enable entirely new kinds of applications such as virtual reality (VR), vehicular communications, industrial robotic control, tactile-based telemedicine, etc. The use of a large number of antenna elements, or Massive MIMO, is a key enabling technology that provides more control, flexibility, and efficiency in the use of the physical channels of the wireless medium.

Massive MIMO technologies will need to be deployed in mid-band to high-band (e.g., mmWave), indoors to outdoors (HetNets), the physical implementation will encompass different architectures (digital, analog, hybrid). A Massive MIMO system opens up tremendous flexibility and offers many "control knobs" in the way the physical wireless channel is used, and it is envisioned that the latest advancements in artificial intelligence (AI) and machine learning (ML) will be leveraged heavily to monitor, control, and optimize these settings.

1.1. 2022 Edition Update

The IEEE Future Networks Massive MIMO Working Group held its first Massive MIMO Workshop on 8-10 November 2021, and a summary of the discussions and lessons learned are given in Section 3.1. Channel estimation challenges and techniques are discussed in Section 5.3. Privacy considerations are added in Section 4.3 and Section 9. Low carbon footprint considerations are added in Section 6.3 and Section 17. Section 21 has been updated and in particular, a new subsection 21.3 on MU-MMIMO vs SU-MMIMO has been added. Section 22 on Intelligent Reflecting Surface has been significantly updated (a new Figure 5 is added that illustrates RIS-assisted communication). A new section on Cell-Free Massive MIMO is added as Section 23.

2. Working Group Vision

The future of 5G and beyond will likely encompass infrastructure with hundreds or more antenna elements and user equipment with many antennas, where the multiple-antenna systems are leveraged to provide reliable connections with superior spectral and energy efficiency. In coming years, it is envisioned that Massive MIMO systems will be a key enabling technology for cellular systems, with major impact and implications for the vehicular industry, device/sensor manufacturers, standardization groups, governments, and consumer electronics.

With the intelligent operation and deployment of multiple-antenna systems, the improvement of hardware devices with the decrease of the price, the development of future wireless networks will be significantly accelerated. In 10 years, future wireless networks could provide a larger capacity than that of the current system and also improve the QoS significantly. As a result, Massive MIMO can support the high data traffic generated by massive broadband wireless applications, such as multimedia, three-dimensional video games, e-health, and Vehicle-to-everything (V2X) communications.

2.1. Scope of Working Group Effort

The Massive MIMO Working Group will be based on the following frameworks:

- Framework for a large number of active users with massive connectivity
- Framework for high spectral efficiency and energy efficiency with high-user density and emerging applications with a strong need for QoS guarantees
- Big Data Management
- Cost-effective, reliable, and scalable implementation for Massive MIMO
- Machine-type communications and low complexity transceiver design
- PHY design for mmWave massive MIMO systems
- Analog and digital hybrid precoding design
- Secure communications for massive MIMO systems
- The integrating of machine learning into massive MIMO systems

The Working Group considers Massive MIMO both as a fundamental wireless communication technology and also as a component in a larger radio access ecosystem. Where applicable, connections to existing network architecture are highlighted, e.g., with respect to 3GPP or O-RAN functionality or interface specifications. Under the different network architectures, these are the envisioned applications and services: Energy and Utilities, Industry and Manufacturing, Public Safety, Healthcare, Public Transport, Media and Entertainment, Automotive, Financial Services, Agriculture, and Tactile Applications.

Under the scope of Massive MIMO, some of the challenges are the application of artificial intelligence (AI) and machine learning (ML) techniques, the selection of time division duplex or frequency division duplex modes, and the efficient modulation for massive MIMO systems. The following topics may not be addressed fully within the 2021 Edition of the roadmap effort: The specific hardware implementation choices of Massive MIMO, the application of Massive MIMO to cloud computing networks and mobile edge computing networks, and the combination of Massive MIMO with non-orthogonal multiple access techniques.

2.2. Linkages and Stakeholders

Various stakeholders of the Massive MIMO roadmap include end-users, application developers, service providers (e.g., telecom, cable operators, and content providers), equipment manufacturers, component suppliers (e.g., silicon, III-V integrated circuits, and antennas), technology innovators (e.g., academics and inventors), governments and standards bodies, such as the IEEE Standards Association (IEEE-SA), Third Generation Partnership Project (3GPP), International Telecommunication Union (ITU), automotive manufacturers, healthcare, and other industries. As the different technology blocks and modules are interrelated and interlinked in the 5G and Beyond ecosystem, the Massive MIMO Working Group will be seeking inputs and exchanging information with representatives from component manufacturers, suppliers, integrators, network operators, service providers, and end-users, as well as the R&D community, which includes universities, national labs, and industry consortia.

To enable the full benefits of Massive MIMO systems, it is envisioned the following standards are needed:

- The standard for PHY and MAC
- The standards which support the huge data of massive users and high mobility
- The standards for connected devices
- The standards support Multiple RATs
- The standards for achieving low time delay

In addition, in the Massive MIMO 5G and Beyond ecosystem, the other enablers and key applications are Robotics, AI technologies, AR/VR, smart applications, and industry-level controls. Massive MIMO would also impose requirements on adjacent systems, and the following systems and areas may need further innovation to support the demands of a future Massive MIMO system: Physical/Mobile Networking and Computing Facilities, Fronthaul and Backhaul Networks, capacity, performance, and spectrum access.

The Massive MIMO ecosystem is depicted in Figure 1 below. This roadmap document will review some of the key technology drivers and/or performance metrics of interest for Massive MIMO systems, including energy efficiency, channel estimation, mobility, efficient hardware implementation, interference management, as well as single- and multi-user signal processing. The Working Group envisions a standardized, interoperable, and open interface for the Massive MIMO systems to communicate with the core network for better load balancing, scheduling, and caching while ensuring minimal latency. Moreover, the Massive MIMO systems will in turn expose an open and full-featured interface so that the mobile users may customize the AI-enabled beamforming operations, leverage task-specific wireless applications such as intelligent reflecting surface, Massive MIMO radar, or support newly enabled network architecture such as cell-free and user-centric Massive MIMO. These open interfaces will allow for end-to-end, cross-layer optimization to maximize the system performance and user experience of future communication networks.

The Working Group envisions Massive MIMO systems will be deployed over a diverse set of network configurations as well as frequency ranges. Massive MIMO technology will be applicable in traditional macro cellular networks, denser micro or small-cell environments, and more. In general, Massive MIMO applies to a heterogeneous mix of network types. Similarly, Massive MIMO may first be deployed in the currently more common sub-6 GHz wireless frequency bands, with the trend being clear that millimeter-wave or even high-frequency bands will be scenarios of interest for the upcoming Massive MIMO deployments.

With the newly enabled capabilities and flexibility of Massive MIMO, this roadmap document will also discuss the emerging regulations and compliance considerations. In addition, Massive MIMO and its interaction with the rest of the communication network introduces a new set of security considerations—these are further explored in the Security and other Working Groups.

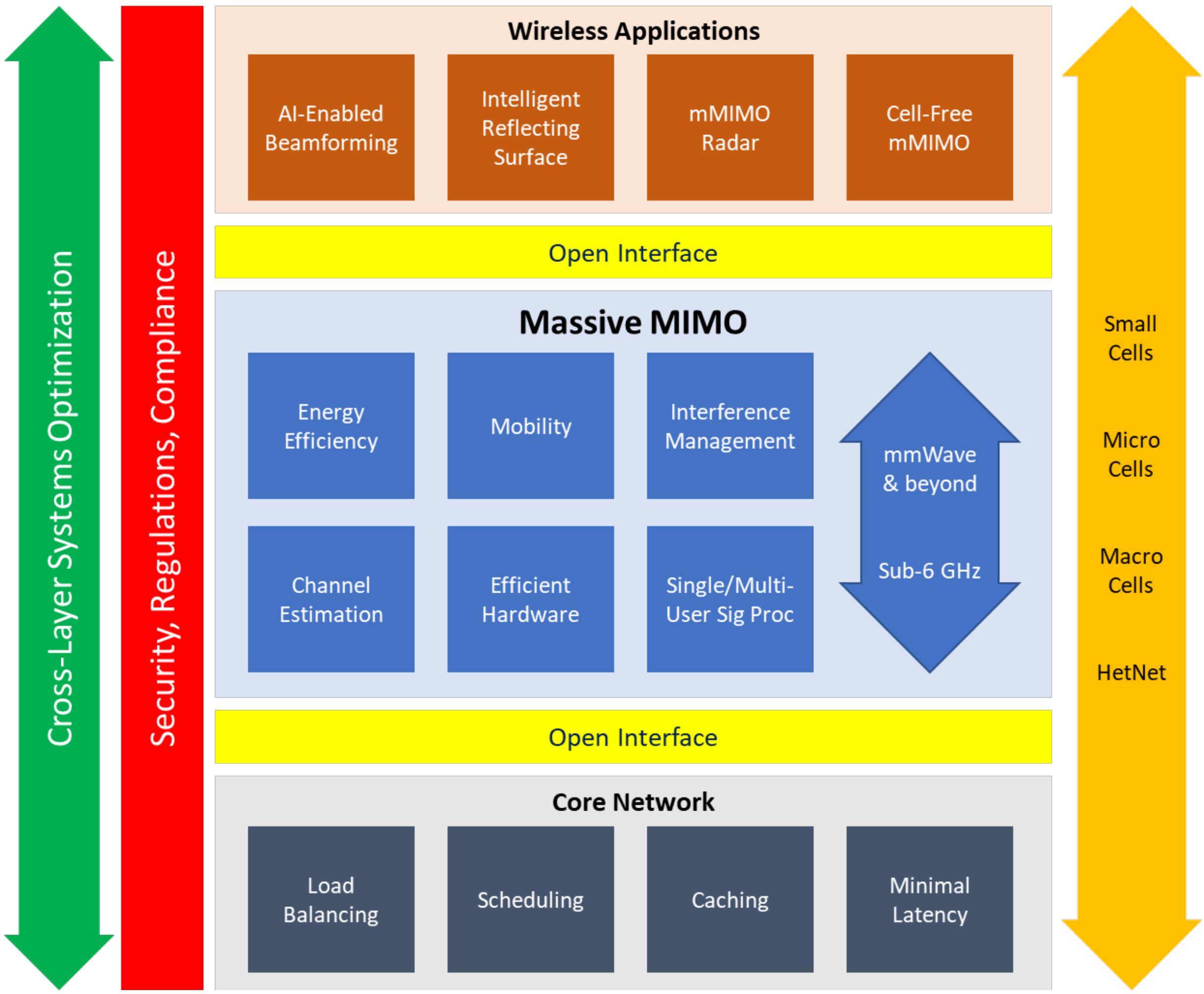

Figure 1. Massive MIMO Ecosystem

3. Today's Landscape

Today, the active development of Massive MIMO theoretical techniques by academics, research labs, and industry participants is underway. Furthermore, a selected number of lab trials, by universities and industry, have shown and validated the superior performance of Massive MIMO. In the coming years, some of the challenges for Massive MIMO to support the 5G & Beyond ecosystem include:

- Large number of active users with massive connectivity
- 5G and beyond networks can advance and integrate the existing network infrastructures
- Address high-spectral efficiency and energy efficiency with high-user density and emerging applications having the strong need of QoS guarantees
- Big Data Management
- Cost-effective, reliable, and scalable implementation for Massive MIMO
- Support for machine-type communications, low complexity transceiver design
- PHY design which is attractive for mmWave massive MIMO systems

- Analog and digital hybrid precoding design
- Intelligent beam-based network management
- Application of artificial intelligence (AI) and machine learning (ML) techniques

While traditionally the 3GPP organization has various standards governing the specifications of cellular infrastructure equipment, the interaction of Massive MIMO and other networking layers remains an open space. To fully exploit the benefits of Massive MIMO, it is envisioned that intelligent beam management may interact or be customizable by particular applications through techniques such as network function virtualization (NFV) and network slicing (NS).

3.1. 2021 Massive MIMO Workshop

The IEEE Future Networks Massive MIMO Working Group held its first Massive MIMO Workshop on 8-10 November 2021 (https://futurenetworks.ieee.org/conferences/future-network-massive-mimo-workshop). The IEEE Future Networks Massive MIMO Workshop aims to bring together researchers, practitioners, as well as technology decision-makers to form a vision on the use of multi-antenna and related techniques in wireless communications over the upcoming decade and beyond. The Workshop focuses on the latest developments in Massive MIMO challenges and opportunities—from fundamental research, experimental results, system architecture, to engineering applications.

The Workshop had 6 keynote presentations, 2 panel sessions, as well as invited and accepted presentations, from both academia and industry speakers. Based on the presentations and the discussions at the Workshop, the Massive MIMO community identified as the key topics as we transition 5G rollouts into early research on 6G:

- Very large antenna arrays.
- Terahertz communications.
- Open radio access network (Open RAN).
- Joint sensing and communications.
- Reconfigurable intelligent surface (RIS).
- Energy efficiency and sustainability.
- Security.
- Artificial intelligence (AI) and machine learning (ML).

Technical insights, discussions, and lessons learned from the Massive MIMO Workshop are summarized in the subsections below.

3.1.1. Very Large Antenna Arrays

Future Massive MIMO systems may have very large antenna arrays: e.g., with many thousands of antenna elements spanning the facades of building structures. With such an array geometry, new considerations arise in its effective beamforming operation, e.g., near-field effects. Moreover, such very large antenna arrays may be used to control the reflection and propagation of radio frequency waves in the form of reconfigurable intelligent surface (RIS). The effective control of such a large number of antenna elements also present opportunities for the application of artificial intelligence (AI) and machine learning (ML) for intelligent control and operation in Massive MIMO systems.

3.1.2. Open Radio Access Network (Open RAN)

Two primary goals of Open RAN are to stimulate innovation and reduce costs in telecommunications networks by introducing competition in an open ecosystem. Since initial trials and deployments, the industry has also come to the view that harmonization among different standards and specifications is crucial to realize the new paradigm's full potential. The Massive MIMO Workshop covered different aspects of Open RAN concepts and implementations: e.g., O-RAN Open Fronthaul analysis, radio intelligent controller (RIC), as well as the application of AI/ML under the Open RAN architecture.

3.1.3. Energy Efficiency, Security, and Deployment

At the Future Networks Panel discussions session, the panelists discussed the possibility that energy efficiency will become more important than the traditional spectral efficiency metrics (e.g., maximizing throughput in the given bandwidth). For example, a 6G system operating at Terahertz, has access to such large bandwidths that their spectral efficiency may no longer be a bottleneck. Rather, the system may see the primary design constraint becoming energy efficiency – and the related deployment concerns such as heat dissipation, size, and weight. While the detailed specifications of the 6G Massive MIMO System is very much an active research effort, the panelists shared the view that energy efficiency, security, and deployment considerations should be integral parts of the end-to-end system design.

3.1.4. Architectural, Spectral, and Algorithmic Challenges

Several sessions were dedicated to new advances in massive MIMO to address the architectural, spectral, and algorithmic challenges in 5G and Beyond 5G (B5G) networks. On the architecture front, the keynote talk by Prof. Rodrigo de Lamare (PUC-Rio, Brazil) focused on the role of cell-free architectures in providing higher rates in future networks. Such systems require the development of more efficient precoding and resource allocation techniques. Another talk by Prof. Ertuğrul Başar (Koç University, Turkey) focused on the rising concept of reconfigurable intelligent surface (RIS)-empowered communications towards 6G wireless networks. These surfaces have the potential to enable low-cost, lightweight, compact transceiver designs.

The need to explore other frequencies and optimize the use of the existing but limited spectrum was captured in the following two talks. Prof. Josep Jornet (Northeastern University) gave an expository lecture on moving toward the Terahertz band for 6G and specific challenges and solutions on this region of the spectrum. Prof. M. R. Bhavani Shankar (U of Luxembourg) highlighted the emerging concept of joint massive MIMO radar communications to share the spectrum using large apertures. These ideas are no longer in infancy and active efforts are underway to build prototypes.

Finally, various applications of massive MIMO in future networks require intense algorithmic efforts. Dr. Ahmet Elbir (Düzce University, Turkey) presented several deep-learning-based architectures for massive MIMO system design, signal detection, channel estimation, and hybrid beamforming. There are various model-based techniques for the design of communication systems but model-free approaches such as deep learning (DL) provide more robustness, adaptability, and lower computational complexity. Prof. Jean Armstrong (Monash University, Australia) highlighted algorithms for localization at visible light frequencies in the context of massive MIMO wireless communications. The combination of VLP and massive MIMO has the potential to advance many practical applications.

4. Future State (2032)

With the rapid development of wireless networks to keep up with demands, the IEEE would like to put forward a long-term vision. In 10 to 20 years, we envision there will be 100 - 1000 controllable antenna elements per person. In the coming decades, through intelligent control of the physical layer, we see wireless evolving from an interference-limited medium to a truly multi-user fabric where traffic is managed using networking-like scheduling and routing techniques. This large-scale Massive MIMO will transform the current person-to-person communications to a world where there will be pervasive device-to-device communications. This readily available communication capacity will enable the next generation of distributed signal processing, machine learning, and other intelligent algorithms. Some of the hardware needs are:

1. Efficient and intelligent hardware/physical layer
2. Support for large-scale parallel processing
3. RF amplifiers to handle constellation sizes in excess of 1000

4.1. mmWave Massive MIMO for HetNets

The bandwidth of a wireless channel is one of the most significant factors in determining the achievable throughput. In 5G and Beyond systems, it is envisioned that carrier frequencies of 10's of GHz (or known as mmWave bands) will be used to accommodate high-bandwidth channels. At mmWave frequencies, however, the propagation path-loss is considerable, it is envisioned a mix of macro cells and small cells will be needed to deliver high capacity and maintain coverage. Therefore, Massive MIMO systems will need to operate in mid- to high-bands, and heterogeneous networks (HetNets).

4.2. MAC-PHY Cross-Layer Design for Massive MIMO in Future Wireless Systems

Massive MIMO systems enable tremendous flexibility in the beamforming operations and other control over the physical wireless channels. Depending on the requirements of the MAC and network layers and the ultimate application, the Massive MIMO subsystems may need to be optimized for reliability, throughput, energy efficiency, or a combination of objectives. Cross-layer design and inter-layer control and open APIs are paramount for applications to take advantage of the flexibility of Massive MIMO systems.

4.3. Secure and private communications in Massive MIMO wireless systems

Massive MIMO introduces new pilot signals, physical-layer schemes, and wireless protocols. While these signals and control mechanisms work together to provide a tremendous increase in achievable capacity, they also increase system complexity and introduce new modules and protocols that need to be secured against malicious agents. In addition, privacy is another pressing issue. Privacy-aware architecture and protocol design, in particular in the setting of joint communication and sensing, are required during the information exchange among base stations for collaborative tasks

4.4. The application of artificial intelligence and machine learning into Massive MIMO wireless systems

Massive MIMO opens up a whole new dimension of control and performance adjustment in the operation of wireless networks. In fact, using the multiple antenna elements for intelligent transmitting and sensing, Massive MIMO transformed the radio access network (RAN) from a passive network layer to an active decision-making network layer. It is a daunting challenge setting, monitoring, and fine-tuning all the “control knobs” enabled by Massive MIMO. It is envisioned that the latest advances in artificial intelligence (AI) and machine learning (ML) will be heavily leveraged in the operation and optimization of Massive MIMO networks.

4.5. Enabling massive connectivity with massive MIMO

Instead of using the multitude of antenna elements to provide superior throughput to a few users, another synergy of the Massive MIMO and 5G and Beyond ecosystem is that the multiple antennas can be used to provide narrow-band connectivity to a large number of users in an energy-efficient manner.

4.6. Autonomous Massive MIMO for a Variety of Applications

Massive MIMO can be adjusted autonomously for a variety of applications. This can maximize throughput for enhanced mobile broadband (eMBB), optimize coverage for massive Machine Type Communications (mMTC), as well as enhance reliability for Ultra-Reliable Low-Latency Communications (URLLC).

5. Needs, Challenges, and Enablers and Potential Solutions

5.1. Summary

Accomplishing this envisioned future comes with many needs and challenges. When the number of elements in an antenna is increased to a significant scale, the receiver design becomes very complex. That being said, there is a need for more efficient components that would require less power and offer a smaller footprint. Hardware designers should take advantage of the proliferation of faster analog to digital converters to simplify the RF frontend. In addition, real-time implementation of digital signal processing algorithms may offer relief to maintain the tight latency requirements.

5.2. mmWave Massive MIMO for HetNet

The emerging unprecedented increase of devices causes high data traffic due to the massive broadband wireless applications, such as multimedia, three-dimensional video games, e-health, and V2X communications. The emerging unprecedented increase of devices causes high data traffic. This high data traffic is also exacerbated by massive broadband wireless applications, such as multimedia, three-dimensional video games, e-health, and V2X communications. Therefore, future wireless networks need to provide a larger capacity than that of the current system and also improve the QoS significantly. Currently, a promising network architecture is the heterogeneous networks (HetNets), which leverage both the high-powered stations and low-powered ones to better suit a diversity of communication needs. Additionally, massive MIMO can fit into HetNets for further improvement in terms of the number of supported devices and spectral efficiency. However, the need for the incorporation of massive MIMO into HetNets may be compromised with technical difficulties. In this part, we briefly summarized the need and some key enabling technologies to leverage high bandwidth, and the deployment of Massive MIMO in a HetNet that encompasses outdoor, indoor, macro-, and small cells.

The need for massive MIMO to be effectively incorporated into HetNet should meet the following needs.

5.2.1. Cell Association and Mobility Management

It is well-known that HetNets, especially ultra-dense deployed HetNets, consist of a large number of stations. Small Base Stations (BS), in particular, are responsible for a smaller region, hence when users move around, the need for handover as well as the association may become inevitably complicated. To support a smooth and highly efficient cell association mechanism in Massive MIMO-enabled HetNets, a variety of elements should be taken into consideration. For example, the association protocol and the tracking algorithms should be tightly coupled and optimized for efficiency and security.

5.2.2. Big Data Management with QoS Constraints

The amount of data that needs to be processed during communication could be large, and in future systems, the diverse requirements, from data rate and latency to reliability should all be considered. With such QoS constraints and the amount of data, an efficient management system is needed.

5.2.3. Low-Cost Channel State Information Acquisition and Beamforming

For a faster connection and higher spectrum utilization, the acquisition of channel state information (CSI) plays an important role. This is not only for massive MIMO but also for traditional MIMO. Without an accurate CSI, the benefits from MIMO-related techniques would vanish. This is especially true in HetNet Massive MIMO, where the number of users and BSs are large. An efficient algorithm or protocol for the CSI acquisition is key here.

5.2.4. Resource Management

In the resource-constrained HetNets, appropriately allocating limited resources to users and BSs is an interesting topic. An efficient resource management algorithm should not only consider user fairness but also account dynamically for different requirements. Resource management can have different forms, either centralized, decentralized, or hybrid. If the power source is one of the constrained resources (e.g., battery power for remote sensors), then end-to-end energy efficiency should be one of the key design considerations.

5.3. Channel Estimation

5.3.1. Sparse Adaptive Filtering Algorithms for Channel Estimation in Massive MIMO Systems

Massive MIMO systems normally comprises of a large antenna array to meet the high data rate as per 5G communication standards. Time-division duplex (TDD) can be useful for uplink (UL) and downlink (DL) channels for bidirectional data transfer in massive MIMO systems. To design DL precoders and UL detectors efficiently, the base station should have adequate prior knowledge of the duplex channel. Thus, the estimation of CSI is crucial in modeling a massive MIMO system. But extraction of CSI becomes more challenging as there is a gradual increase in number of antennas. Sparse adaptive filtering algorithms are computationally efficient and quite useful for channel estimation. These models are applicable to multiuser MIMO (MU-MIMO) systems with a large number of channel coefficients. Channel state information (CSI) obtained through channel coefficients of the UL channel, also can be used to estimate the CSI of DL due to channel reciprocity. Convex combination with the introduction of norm penalty in adaptive algorithms develops efficient sparse channel estimation models for massive MIMO communication systems. The UL and DL performance of the system can be analyzed in terms of bit error rate (BER), mean square error (MSE), and channel capacity calculated from estimated CSI.

6. Networking Planning and Operation

Network planning and operation is another need for taking full advantage of HetNets. The cost of tower management and spectrum drives carriers towards a more manageable operation procedure. This need has different aspects. On one hand, location selection is important even without Massive MIMO in HetNets for the reduction of interference and better signal reception. On the other hand, with Massive MIMO in mind, how do you transform an existing HetNet to embrace this new cooperation?

Challenges for the above needs are listed as follows, possible solutions and ongoing research efforts are also included.

6.1. Guarantee of Coverage

There are strong requirements to guarantee coverage for every user device at anytime and anywhere, under the condition that the users travel at very high speeds. To meet these requirements, standards need to be developed and deployment needs to be optimized (e.g., cell placement, automatic configuration, etc.) for networks of a variety of service area sizes, ranging from PANs to LANs, MANs, and RANs, as well as support the users with different levels of mobility.

6.2. Real-Time Support

Furthermore, the future system should aim to provide real-time support in many applications with a large number of user devices. Moreover, future applications require hard deadline delay constraints in which the data must be received by the receiver within the predetermined time slot. This will require the development of standards to support the huge data of a massive number of users, as well as many emerging applications, including monitoring application and latency-sensitive control data with the strong need of QoS guarantees (i.e., a hard deadline constraint).

6.3. Implementation Cost and Low Carbon Footprint

The other need is to reduce the cost of implementation. The critical challenge is how to jointly and optimally perform channel estimation and beamforming considering the number of RF chains and pilot contamination for the multiuser multi-cell Massive MIMO system operating over the frequency selective channel. The number of RF chains directly influences the implementation costs. Moreover, since scalability is one distinct feature for massive MIMO, the reduction of the cost of scalable devices is the key; with the scalable massive devices, not only the low cost, but also the environmental sustainability, in particular the low carbon footprint (energy consumption, e-waste), need to be modeled together with the economic costs and then be optimized.

6.4. Spectral Efficiency

The other need is to improve the spectral efficiency and energy efficiency of the future wireless network. This is accomplished through developing the standards for networks that address high spectral efficiency and energy efficiency with high-user density thereby forever growing data service, including social networking, gaming, advertisement, and emergency communications.

6.5. Network Integration

Finally, the 5G and beyond network should integrate the existing network infrastructures and the new ones to be a unified system. For this to occur, there is a need to develop the optimized framework for the placement and planning of certain networks where the 5G and beyond network can advance and integrate the existing network infrastructures.

7. MAC-PHY Cross-Layer Design for Massive MIMO in Future Wireless Systems

Another aspect of Massive MIMO in future wireless systems is cross-layer design and optimization. The emerging trends and evolving techniques are investigated. Traditionally, single-layer optimization is more dominant in both the research and industrial domain, where the end-to-end transmission is divided into sub-problems. Even though this approach might be attractive in terms of implementation and complexity, it cannot tackle the essential or better-performance promises. Cross-layer design, which involves the effort of more than one layer, not only provides better performance, but also a good design perspective. The need presented in this section fits well with Massive MIMO, which relies on multiple design efforts. Specifically, the following needs should be carefully addressed for the feasibility and successful delivery of Massive MIMO.

7.1. Physical Design

We must carefully design the transmit signal waveforms that influence system performance and link-level capacity with respect to channel, timing, and CFO estimation, signaling, beamforming, and realizable multiplexing gains. In addition, we should develop the new modulation techniques/waveforms by relaxing the orthogonality and synchronization constraints that are attractive for mmWave Massive MIMO systems. In order to bridge the gap between theory and practice, the operating signal-to-noise ratio per bit (Eb/N0) of the communication system needs to be specified, rather than the received signal strength. The scope for large-scale parallel processing in the channel means that CFO and timing estimation algorithms need to be addressed. Fundamental concepts in the discrete-time implementation of digitally modulated signals like pulse shaping, bandpass sampling, matched filtering, etc. need to be revisited.

7.2. MAC protocol designs

MAC protocol designs, which include multiple access strategies, user scheduling, resource allocation, deal with a large number of active users. Furthermore, the future system would overcome a large amount of signaling (CSI feedback) for every user due to the huge dimension of channel vectors.

7.3. Fronthaul design

To further improve on existing wired fronthaul infrastructure, a novel connectivity design may be considered to provide wireless fronthaul solutions for high-speed, high-capacity, plug-and-play, low-latency, flexible, and cost-effective fronthaul technologies.

7.4. Backhaul design

The challenges are how to engineer a cost-effective, reliable, and scalable wireless backhaul network. Moreover, the design for the future dense HetNet would support different types of traffic and allow the cooperation/coordination between different BSs.

8. Efficient Receiver Architecture Design

Although faster analog to digital converters helps simplify the receiver frontend, as we add more antennas to the base station there is the need to develop efficient architecture to minimize system complexity. Efficiency may include considerations on cost efficiency (i.e., reduce complexity), spectral efficiency (i.e., maximize signal fidelity), and energy efficiency (i.e., minimize power consumption). These new receiver designs must satisfy the more challenging requirements of wireless networks, including low-complexity, more efficient detection techniques to maintain high throughput while minimizing interference, a high level of security by using embedded coding, and high secrecy performance for a very dense wireless network. These approaches can effectively detect and eliminate active eavesdropping threats. With these needs in mind, the challenges, however, are significant. The cross-layer requires more advanced considerations to address the above needs. For a comprehensive study of this envisioned sophisticated wireless network the following challenges should be investigated.

8.1. Physical Layer Design

Traditional physical layer design considerations are usually waveform, modulation, and demodulation. For Massive MIMO, if the design follows this way, it can become very complicated, especially combining with other layers. The challenge here is to propose an efficient standard to exchange one layer's information with the other one. For example, how to effectively collect channel information, deliver it to the MAC layer, then form a good resource allocation access technique.

8.2. MAC design

As previously stated, PHY and MAC should be considered simultaneously. Massive MIMO, in mmWave particularly, has some differences compared with the traditional below 6-GHz spectrum. For example, with a narrower beam pattern, the interference from other users or BSs will be lower than that of a wider beam. MAC scheduling should fully take advantage of this, not only to consider the user location, but also the BSs locations.

8.3. Fronthaul and backhaul design

The overhead resulting from this inter-layer design will be huge. To enable a lower latency as well as a better QoS experience, it is required to reduce the overhead. Meanwhile, challenges arise with a new scheme: architectural design. We envision that the fronthaul and backhaul can be incorporated into a cloud/edge hybrid structure, with remote radio head (RRH) servers, X2 interfaces, and network slices. The standard would define the wireless fronthaul solutions for high-speed, high-capacity, plug-and-play, low-latency, flexible and cost-effective fronthaul technologies.

8.4. Security in Cross-layer

To address this, the standard should consider the following problems. 1) To enable the security with inter-layer communication, for the exchanged parameters and protocols. 2) Special encryption mechanisms for this shared wireless medium. 3) The security protocol also should be efficient and flexible.

9. Secure and private communications in Massive MIMO wireless systems

In this topic, we focus on the application of physical layer security and privacy-preserving to achieve secure and private communications in Massive MIMO systems. Due to the open and broadcasting nature of wireless communications, confidential information that is required to be transmitted is vulnerable to eavesdropping. Malicious users may intercept the confidential information transmitted to the desired users. As an alternative to the traditional cryptographic techniques, physical-layer security and privacy-preserving techniques exploit the physical characteristics (e.g., multipath fading, propagation delay, etc.) of wireless channels to achieve secure and private communications. Thus, it is of great importance to investigate the application of security-/privacy-aware physical-layer to improve the security and privacy of Massive MIMO systems. There are several needs and challenges to achieve this application: 1) The design of precoding schemes; 2) Cooperative secure transmission; 3) Pilot contamination; 4) Hardware impairments; 5) Energy efficiency design. The details for these challenges are presented as follows.

9.1. The design of precoding schemes

An optimal design of the precoding scheme can significantly improve the achievable performance of Massive MIMO systems. The design of future Massive MIMO systems should take spectrum efficiency, energy efficiency, user fairness, latency requirement, user connectivity, and operational cost into consideration. It is of great importance to design optimal precoding schemes to achieve these objectives. Moreover, how to exploit multi-objective optimization theories to simultaneously optimize multiple objectives is important.

9.2. Cooperative secure transmission & local processing/training

The secrecy rate of Massive MIMO systems with physical-layer security is significantly influenced by the channel fading. It is impractical to constantly increase transmission power to improve the secrecy rate. Alternatively, the exploitation of cooperative relay techniques, artificial noise-aided techniques, and cooperative jamming techniques has the potential to overcome the influence of channel fading.

Aside from the cooperation among devices, the ability to do local signal/data processing and training, instead of the central approach, would enhance the privacy and security.

9.3. Pilot contamination

Future wireless communication systems need to serve a massive number of users. It is impractical to use orthogonal pilots to estimate the channels due to the limited communication resource. However, the application of non-orthogonal pilots will result in severe pilot contamination and deteriorate the achievable secrecy rate. In order to resolve this issue, the design of blind channel estimation methods and precoding schemes is important. Moreover, how to design efficient methods with good performance, low complexity and limited cooperative ability need more intensive investigations. However, before venturing into this area, it may be a good idea to exploit pilot orthogonality in space, time, and frequency.

9.4. Hardware impairments

To achieve practical application of physical layer security into Massive MIMO systems, the effect of hardware impairments on the performance should be considered. The challenges are how to quantize the effect of phase noise, per-antenna power constraints, mutual coupling, and hybrid analog/digital precoding architectures on the achievable performance. Amplifier distortion also needs to be minimized by using Class A mode of operation and low transmit power, so that efficiency does not become a critical factor. This would be a useful feature in mobile handsets, where power is a constraint.

9.5. Energy efficiency design

Although the increase of the number of antennas can improve the secrecy rate of massive MIMO systems, the operational cost and the consumed energy will be increased. Future wireless communication systems should be sustainable and economical. Thus, how to achieve energy efficiency design is important. The challenges to achieving this goal are how to design energy-efficient transmission strategies, energy-efficient signal processing methods, energy-efficient modulation schemes, energy-efficient cooperative strategies, etc. For more in-depth discussions on energy-efficient design, the readers may refer to the IEEE International Network Generations Roadmap (INGR) – Energy Efficiency Chapter.

10. Academia and Industry Engagement

To enable secure communication, efforts from both academics and industry need to be promoted. The developed schemes and algorithms have been successfully applied in today's system. However, in terms of Massive MIMO, as stated above, the hardware and efficiency should be taken into consideration. We summarize the following challenges.

10.1. Efficient Design

The design of a secure future Massive MIMO system should take into account spectrum efficiency, energy efficiency, user fairness, latency requirements, user connectivity, and operational costs. These factors should be at the core of the security-related design. The challenge is how to combine all or part of the factors.

10.2. Relay and artificial noise aided techniques

Future systems should consider the exploitation of cooperative relay techniques, artificial noise-aided techniques, and cooperative jamming techniques. As an emerging scheme, relay nodes take more weight in the system; cooperative relaying, specifically, is an approach to increase the communication range and reliability. The physical layer security issue here has the challenge of power allocation, relay selection, and cross-layer design.

10.3. Blind channel estimation and precoding

How does one design blind channel estimation methods and precoding schemes? Eavesdroppers, generally speaking, have two types. One is called passive and the other is active. The difference is the former is more "silent", and the hard part is how to determine if a user is an eavesdropper if it is in passive mode. Blind channel estimation might be a possible solution, but the challenges of its use are still huge. For example, in Massive MIMO, the beam steer can only cover a selected area, hence the possibility of an eavesdropper existing in the area is higher.

10.4. Hardware impairment

How does one quantize the effect of phase noise, per-antenna power constraints, and mutual coupling and hybrid analog/digital precoding architectures on the achievable performance? Due to the complex nature of Massive MIMO signal processing, hardware-related considerations should be taken. For example, the power constraints, especially for mmWave band, where the reported power amplifier has an efficiency of around 10%, hence heating issues might arise. Furthermore, phase noise and the currently popular analog/digital precoding architecture should be incorporated as well. Even though these are hot research topics, the consideration of security is hardly being discussed.

10.5. Energy efficient signal processing

How does one design energy-efficient transmission strategies, energy-efficient signal processing methods, energy-efficient modulation schemes, energy-efficient cooperative strategies? Energy efficiency design is a more important metric in the future wireless system to support the IoT devices, especially when the battery replacement is a hard procedure.

11. The application of artificial intelligence and machine learning into Massive MIMO wireless systems

Applying machine learning in Massive MIMO certainly has some advantages. The ever-emerging machine-learning-related research is ongoing and much of the well-developed tools can boost its application here in Massive MIMO. We briefly list some design considerations specifically for Massive MIMO. In this topic, we introduce learning mechanisms in which we investigate the application of machine learning to realize Massive MIMO with low implementation complexity and little prior information. The significant needs include 1) resource allocation based on machine learning; 2) channel estimation based on machine learning; 3) signal detection based on machine learning; 4) Interference management based on machine learning; 5) Physical layer design based on machine learning. The challenges are presented as follows.

11.1. Resource allocation based on machine learning

The application of machine learning into resource allocation has the potential to achieve low complexity implementation and decrease operational costs. The development of resource allocation based on machine learning would improve spectral efficiency and energy efficiency, increase the number of users, and decrease energy consumption as well as the time delay. Advanced machine learning methods would also be developed for resource allocation.

How does one develop resource allocation based on machine learning to improve spectral efficiency, the energy efficiency, the number of users, and decrease the energy consumption and time delay? That kind of resource allocation requires accurate modeling and a sufficient amount of test data. Besides, it is also important to evaluate its performance.

11.2. Channel estimation based on machine learning

To achieve an efficient estimation of the channel, the challenges are how to appropriately establish, efficiently train and adjust the deep neural networks and how to develop unsupervised learning methods.

11.3. Signal detection based on machine learning

Different from the conventional linear and non-linear detection methods, the challenges of designing signal detection based on machine learning are overcoming the issues of overfitting and underfitting when training the deep neuron networks due to complicated channel distortion and interference.

11.4. Interference management based on machine learning

To efficiently manage the inter-cell or inner-cell interference, the challenges are how to determine the number of interference sources, the interference levels, and how to overcome interference by using machine learning.

11.5. Physical layer design based on machine learning

To achieve low complexity design of the physical layer, the challenges are how to design modulation and demodulation, precoding scheme based on machine learning.

11.6. Detailed design considerations

How to appropriately establish, efficiently train, and adjust the deep neural networks and how to develop unsupervised learning methods. This detailed consideration here poses some challenges in selecting the best-fit tools, the programming language, the supervised and unsupervised selection.

11.7. Overcome overfitting and underfitting

This problem is not only happening in Massive MIMO-related applications but also is the design factor for all other applications. Thus, the feeding data should be carefully designed, the number of deep learning networks should be chosen appropriately.

11.8. System modeling

How to determine the number of interference sources, the interference levels, and how to overcome interference by using machine learning? The aim should be to model every setting but should select those that are the most relevant to performance improvements.

11.9. Modeling of modulation and demodulation

How to design modulation and demodulation, precoding scheme based on machine learning. Massive MIMO has a lot of data for users and operators to process. Selecting the appropriate design factor, which includes modulation demodulation, might be a hard one.

12. Enabling massive connectivity with massive MIMO

Beyond 5G systems require more device connections. Massive MIMO, as an important enabler for future wireless systems, will evolve to meet this need. Yet, challenges exist since this new technique depends on a few elements.

12.1. Low complexity channel estimation

Accurate channel state information is of vital importance since the performance gain mainly comes from precoding and modulation, which requires prior channel information. In addition, low complexity channel acquisition is the key to reducing system overhead.

12.2. Support for machine-type devices

Machine-type communication is the mainstream in IoT; machine-to-machine communication is different from current machine-to-person or person-to-person communication since the former has sporadic yet diverse traffic patterns. Thus, Massive MIMO should accommodate this low-power and high-reliability nature.

12.3. Hybrid precoding design

Precoding is the technique that generates power in a specific direction. For MIMO with a small number of antennas, each antenna has a dedicated RF unit. However, in Massive MIMO systems, multiple antennas may share the same RF chain to reduce power consumption. So, the precoding involves both the analog and digital parts. The challenge comes from the complexity of this combined structure.

12.4. Communication integration with M2M and cloud/edge network

Machine-type devices may have limited power and computation resources; thus, their collected data will be sent to either a remote cloud center or local edge nodes. Massive MIMO should act as the middle layer for information transmission. This pattern should be facilitated for this need.

12.5. Interference coordination and management.

Massive MIMO has the advantage of generating narrow beams to reduce the interference level. However, with more devices connected, interference coordination and management will play a more important role. To achieve this, the sender may need to acquire the prior information of the devices.

13. Challenges with Massive MIMO, Machine-Type, and Massive Connectivity

We list a few challenges that might prevent the successful application of massive MIMO in machine-type and massive connectivity, including, 1) a simple channel acquisition method; 2) The new MAC protocols that support more devices; 3) Diverse requirements from machine-type communications; 4) Hybrid precoding in an energy-efficient way; 5) Other related standards that can help unite existing devices.

13.1. A simple channel acquisition method

This challenge is not unique in massive connectivity applications but should be more obvious here. With more and more devices connected in the same area, to support their communication needs, the BSs should at least have a rough idea about the connected devices' channel. Otherwise, the advantage could quickly vanish. A simple channel acquisition method should take the least effort, and prevent the high overhead that it might incur.

13.2. New MAC protocols that support more users

For various networks with a larger number of devices, MAC coordination is of utmost importance. An efficient MAC protocol should take the advantage of Massive MIMO, specifically, the lower inter-user interference thanks to the narrower beam. Thus, the new MAC protocol should be designed to sense the neighboring user but allow them to transmit simultaneously.

13.3. Diverse requirements from machine-type communications

Machine-type devices become more and more popular at home, in industry, automation, etc. They involve sporadic, yet very diverse, communication needs. For example, while the industrial ones require low latency and high reliability, home devices are more sporadic but should be responsive. The standard should support these communication needs in terms of energy and spectral efficiency.

13.4. Hybrid precoding design

To support Massive MIMO in machine-type devices, the hybrid precoding design is a preferable choice, due to its simple structure and energy-efficient feature. This is critical for low-power and low-complexity transceiver design, especially in a low-cost device. Due to a large number of antennas, the standard should define the cost-effective way to form the narrow beam.

13.5. Related standards

Currently, there is a lack of standards in the industry; each company has its own protocol and design preferences. This becomes a barrier not only from an economic viewpoint but also in the technical aspects. For example, interference should be carefully coordinated in a communication system with massive devices. In addition, the standardization process should include interference management, interference reduction, and suppression.

14. Autonomous massive MIMO for a Variety of Applications

Beyond 5G systems require an ever-divergent set of performance targets. The eMBB throughput could go beyond terabytes per second, with spectral efficiency at petabytes per second per MHz. The reliability for URLLC could go beyond 5 nines to 7 nines (99.99999%) or higher.

14.1. Throughput optimized Massive MIMO

Throughput optimized Massive MIMO could aim for high throughput with restricted coverage. This could be accomplished with sharp and refined beamforming, high modulation schemes, and a data rate prioritized scheduler.

14.2. Reliability and latency optimized Massive MIMO

Ultra-reliability and low-latency optimized Massive MIMO could aim for high reliability and connection robustness through spatial diversity, multiple-access radio, and edge computing. This could effectively combat multiple path-fading and connection blockage.

14.3. Extended coverage optimized Massive MIMO

Extended coverage optimized Massive MIMO could emphasize the sharpness and outreach of the beams through boosted power or repetition. Thus, it can support extensive coverage for sensors or other low-data rates, low-power, latency-tolerant applications.

14.4. Autonomous Massive MIMO for various applications

We are moving from a connection-based network towards service and information-centric network. Thus, sophisticated Massive MIMO will be autonomously optimized for various use cases based on the user requirement to achieve optimized throughput, reliability, and latency or coverage. Soft-defined and autonomously controlled Massive MIMO is essential to achieve this goal.

15. Internet-of-Things (IoT) / Machine-Type Communications

Future networks need to support machine types of communications or the Internet of every Things. This means a massive number of connections, energy efficiency, with a wide range of reliability and latency requirements. Internet of Things can range from Machine-type communications with massive simple low-cost devices to ultra-reliable-low-latency Industrial IoT to Vehicle-to-Things (V2X) communications with ultra-fast speed. Internet of Things is different from current machine-to-person or person-to-person communication since the former has sporadic yet diverse traffic patterns. Thus, Massive MIMO should accommodate its versatile and high-reliability nature.

16. Scalability

The wide range of IoTs requires that Massive MIMO be scalable not only in the number of simultaneous connections but also in achievable performance and service level assurance. For example, the number of simultaneous connections can range from single to millions per radiation point. The latency varies from μs to days, and the reliability from 90% to 99.999999%. The connected devices could be stationary sensors in a winery to ultra-speed rockets in space.

17. Energy Efficiency and Low Carbon Footprint

Massive MIMO base stations with a large number of transmitters and receivers could consume a large amount of energy. The load on the public infrastructure will be a significant burden. To reduce power consumption and sustain a low carbon footprint, there must be stringent requirements on the device power figures. How to handle the impaired devices and when to dispose are issues to be investigated as well, as massive MIMO may be utilized despite of hardware impairment or low-quality devices. There is a need to engage academia and industry for novel chip and more efficient receiver designs. In addition, a sustainable design with dynamic power and sleepy control is essential. This will also reduce interference and improve system efficiency. Machine-Type Communication (MTC) or IoT devices could be low power, with expected long battery life. Massive MIMO should accommodate this low-power and high-reliability nature. It may be noted that energy efficiency is a requirement for all telecommunication systems, not just Massive MIMO. Since future telecommunication systems are expected to be driven by software, running on programmable hardware, the software algorithms also need to be efficient. It may be necessary to specify the operating average signal-to-noise ratio (SNR) per bit since it has been shown in [1] that the minimum average SNR per bit for error-free transmission over fading channels is identical to that of the additive white Gaussian noise (AWGN) channel and is equal to -1.6 dB. Thus, the telecommunication systems need to operate as close to -1.6 dB as possible in order to achieve energy efficiency.

18. Signaling Efficiency

IoT traffic patterns could be sporadic. Thus, signaling traffic could be dominant in data transmission. Massive MIMO signaling overhead should be minimized with less MAC/PHY overhead and more efficient radio channel measurement/reporting. The overall service overhead should also be optimized to improve packet transmission efficiency.

19. Mobility

Future Massive MIMO needs to support mobile users traveling at 100 mph or higher speeds with seamless handover among beams and sites. IoT devices are moving much faster than human beings. High reliability and low latency require an intelligent Massive MIMO beam management system to have a fast and accurate beam selection, steering, and switching.

20. Intelligent Edge Network

IoT devices will have limited power, computation, and storage resources. Thus, data storage and analyses should be carried out in an edge network either locally or be remotely accessible. A Massive MIMO network should be able to intelligently direct and route to proper nodes for storage and computation.

21. Signal Processing and Massive MIMO

The signal processing for massive MIMO will be a challenging one as the antenna beam width becomes smaller. The antenna beam width is inversely proportional to the antenna size. As we work toward the ultimate goal of 1000 antenna elements, the antenna beam width will become smaller. With smaller beams and shorter distances between the base station and the user, beam pointing accuracy will be very important. Equally important will be the ability to form multiple beams and process the information in the scheduled timeframe.

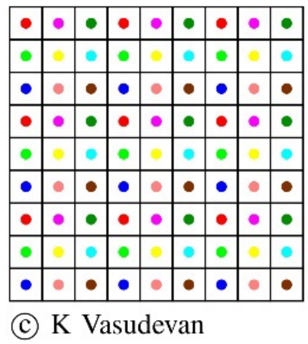

Figure 2. Massive MIMO array: Spatial multiplexing mode.

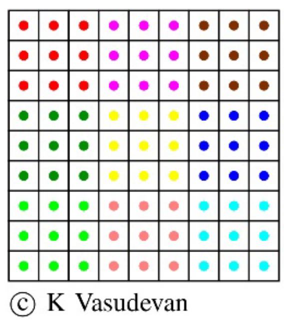

Figure 3. Massive MIMO array: Beamforming mode.

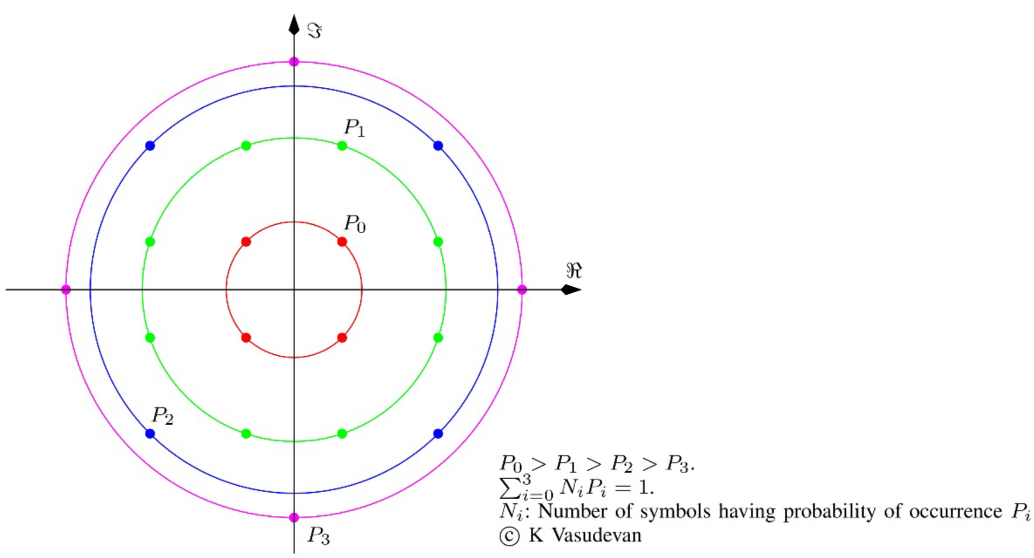

Figure 4. Constellation shaping.

21.1. Signal Processing for Single User Massive MIMO

21.1.1. Single user massive MIMO (SU-MMIMO)

SU-MMIMO [1] [2] [3] has a much higher spectral efficiency (bits per transmission) per user in the uplink and downlink compared to multi-user Massive MIMO. High spectral efficiency per user is essential in applications such as driverless cars, remote proctoring of exams, remote surgeries, and so on. Note that high-spectral efficiency translates to high-data rates. An antenna array is available to both the base station and the user. This is unlike multiuser Massive MIMO, where only the base station is equipped with an antenna array and each user has only a single antenna. Different colors in Figure 2 and Figure 3 denote antenna elements using distinct carrier frequencies. Antenna elements with different colors transmit independent data. In the "single-user" mode, the antenna elements having the same color are spaced far apart to ensure independent fading and transmit independent data. In the beamforming mode, antenna elements having the same color transmit the same data, with a delay.

21.1.2. Channel estimation

In a single-user Massive MIMO system, the number of channels to be estimated [4] [5] [6] [7] can get very large when there is a large number of antenna elements. To alleviate this problem, the antennas can be divided into smaller partitions, with each set using a different carrier frequency. Thus, the number of channels to be estimated in each set is only the number of antenna elements in each partition.

21.1.3. Synchronization

Efficient carrier and timing and start-of-frame (SoF) synchronization algorithms need to be used [4] [5] [6] [7], that have a large scope for parallel processing.

21.1.4. Beamforming

Results in directivity at the cost of spectral efficiency, since the same signal, is transmitted through all the antenna elements instead of transmitting independent signals. Hence, beamforming needs to be used judiciously. Locating user equipment (UE) using a combination of beam sweeping and deep neural network (DNN) is discussed [8]. It was found that the location accuracy is sensitive to small perturbations in the training signal. This could be due to the neural networks being inherently non-linear. Instead of using beam sweeping, the possibility of using successively smaller (narrower) beamwidth along with a linear estimation of direction of arrival (DOA) to locate UE could also be investigated. Linear systems typically exhibit graceful degradation in the presence of noise.

21.1.5. mmWave Massive MIMO

It is possible that mmWave (100-200 GHz) with large antenna arrays can be used for indoor wireless, say within a large room, so that there are no issues of propagation through walls, etc. Reflectors can be used to get a "rich scattering" channel. As an example, a 4-state, rate-½ turbo coded QPSK (small constellation) can be used to get good bit-error-rate (BER) performance. High spectral efficiency can be ensured by transmitting independent QPSK signals through each antenna element. For outdoors, we continue to use ~6 GHz frequencies, a small number of antennas, and large constellations, say 1024-QAM to get high spectral efficiency. Constellation shaping [9] (see also Figure 4) can be used to reduce the transmit power by as much as 1.53 dB (maximum possible shape gain) per device. If a shape gain of 1 dB can be achieved per device, it would result in significant power saving for a billion devices. Large constellations result in a high peak-to-average power ratio (PAPR), which needs to be handled by the RF power amplifiers. Since mmWave generates a lot of heat, the transmit power levels need to be proportionately reduced, resulting in smaller cell sizes.

21.1.6. Efficiency

More efficient methods for implementing filter bank multicarrier (FBMC) need to be investigated. It may be necessary to specify the operating average signal-to-noise ratio per bit (E_b/N_0) for all telecommunication systems, instead of specifying only the received signal strength. This would ensure a match between theory (university) and practice (industry). It has been shown that the minimum average SNR per bit for error-free transmission over fading channels is identical to that of the AWGN channel and is equal to -1.6 dB.

21.2. Signal Processing for Multi-User Massive MIMO

Multi-user massive MIMO will continue to play a major role in 5G and beyond as it was in previous wireless networks. But in the case of a massive number of antenna elements, the physical aperture will impose other constraints on the system. Some of the constraints will be easily overcome but others will present challenges that will require research and development. In general, it would be necessary to involve researchers from academia to help investigate solutions. We can also borrow ideas from the phased array radar technology because this is a mature and well-understood industry.

21.3. MU-MMIMO vs SU-MMIMO

The comparison between single-user massive MIMO (SU-MMIMO) and multi-user massive MIMO (MU-MMIMO) is given in Table 1 [10] [11].

Table 1: Comparison of MU-MMIMO with SU-MMIMO

MU-MMIMO	SU-MMIMO
Beamforming is possible in downlink	Beamforming is possible in uplink & downlink
Spatial multiplexing not possible	Spatial multiplexing possible in uplink & downlink
Low spectral efficiency per user	High spectral efficiency per user
High directivity in downlink in beamforming mode	High directivity in uplink & downlink in beamforming mode
Consumes large amount of power due to the use of M-ary constellations (see Table 3)	Consumes significantly low power due to the use of QPSK (see Table 3)

The differences between beamforming and spatial multiplexing are given in Table 2 [10] [11].

Table 2: Beamforming vs spatial multiplexing

Beamforming	Spatial Multiplexing
High directivity	Little or no directivity
Line-of-sight communication required	Rich scattering channel required
Low spectral efficiency per user since the same signal is transmitted from each antenna element	High spectral efficiency per user since different signals are transmitted from each antenna element
Spectral efficiency can be improved by increasing the constellation size, resulting in high PAPR	QPSK constellations with PAPR 0 dB can be used
Difficult to turbo/LDPC code large constellations	Easy to turbo/LDPC code QPSK
Large BER at SNR per bit close to 0 dB	Small BER at SNR per bit close to 0 dB

Note that beamforming and spatial multiplexing are conflicting operations, as illustrated in Figure 2 and Figure 3. Table 3 shows the power saving using QPSK with SU-MMIMO vs M-ary with MU-MMIMO. Uncoded signaling is assumed and all constellations have a minimum Euclidean distance of 2, which results in a similar symbol error rate (SER) [9] . The symbol coordinates of the QAM constellations are of the form $[\pm 1 \pm j]$, $[\pm 1 \pm 3j]$, $[\pm 3 \pm j]$ and so on. The average power of the constellation is computed assuming all symbols are equally likely and is given by [9]

$$P_{\text{av}} = \frac{1}{M} \sum_{i=1}^{M} |\tilde{a}_i|^2 \, P_i \qquad (1)$$

where $\tilde{a}_i$ is a complex number denoting the two-dimensional coordinates of the i^{th} symbol in the M −ary constellation. From Table 3, observe that the power savings with SU-MMIMO using QPSK for a spectral efficiency of 10 bits/transmission is

$$P_{\text{sav}} = 10 \, \log_{10}\left(\frac{682}{10}\right) = 18.3 \text{ dB}. \qquad (2)$$

For higher spectral efficiencies, it may not be feasible to use M −ary signaling.

Table 3: Comparison of QPSK with SU-MMIMO and M-ary with MU-MMIMO

Spectral efficiency (bits/transmission)	QPSK		M −ary	
	Transmit antennas N_t	Total average transmit power	M −ary QAM	$N_t = 1$ Average transmit power
4	2	4	16-QAM	10
6	3	6	64-QAM	42
8	4	8	256-QAM	170
10	5	10	1024-QAM	682

Simulation results in "Turbo Coded Single User Massive MIMO" [12] [13] indicate that it is possible to achieve a BER of 2×10^{-6} at an SINR per bit of just 3 dB, with and without precoding, with a 512×512 MIMO system. Re-transmission of data does not significantly improve the performance. Note that the work in "Turbo Coded Single User Massive MIMO" [12] [13] does not require the number of transmit antennas to be equal to the number of receive antennas and demonstrates that the BER does not change significantly with variations in the number of transmit and receive antennas. This gives flexibility for a trade-off between the upper bound on the SINR per bit and spectral efficiency. Note also that precoding requires the channel to be time-invariant or at least wide sense stationary (WSS) over two consecutive time slots (transmit and receive). In Single User Massive MIMO, parallel concatenated turbo code is used [1] [2] [3] [7] [10] [11] [12] [13]. The performance of serially concatenated turbo code could be investigated. The effect of correlations in the channel covariance matrix could also be studied.

22. Intelligent Reflecting Surface

Intelligent Reflecting Surface (IRS) [14] that is also known as Reconfigurable Intelligent Surface (RIS) or software-controlled metasurface is envisioned to play a very important role in the next-generation wireless communication systems due to its novel characteristic of manipulating the electromagnetic (EM) waves [15] and its powerful enabling capability of facilitating reconfigurable and flexible radio systems and environment for (but not only limited to) the Massive MIMO technology to be assisted and deployed. There are several aspects of the roadmap concerning the IRS-enabled/aided massive MIMO as follows.

22.1. Channel Estimation

Theoretically speaking, IRS employs a large number of sub-half wavelength antenna elements [16] and some micro-controllers to perform the manipulation of EM wave through controlling the reflection phase shift and the amplitude of the incident signals in a real-time manner, so that the wireless propagation channel can be collaboratively reshaped to facilitate the wanted signal transmission to combat with the undesired fading and/or interferences [17]. However, timely acquiring the correct channel state information is still challenging due to the large number of channel coefficients that are associated with massive passive reflecting elements, which is critical for improving the passive beamforming gain.

22.2. Channel Models and Spectrum

The channel models of IRS/RIS-enabled/assisted wireless communications are one of the most important things to study when building the system models of the application scenarios of interest. For different application scenarios such as static, mobile, or hybrid (static & mobile) in urban high-rise/dense urban/urban/suburban environments, the channel models are various and need careful investigations. There have been several publications in the literature about the channel models of IRS/RIS-assisted wireless communications, such as the path loss modeling and experimental measurement at C-band, X-band [18], and mmWave frequency bands [19]. Moreover, authors in [20] have proposed a non-stationary 3-D wideband channel model for IRS-assisted high-altitude platform (HAP)-MIMO communication systems. It can be predicted that when the carrier frequency moves to THz bands, the channel models with IRS/RIS involved can be more complicated since scattering and other THz-related channel propagation effects such as scattering, diffraction, cannot be ignored [21].

22.3. Distributed IRS/RIS Communications

Some emerging research works on IRS/RIS communications have considered application scenarios that are aided by multiple distributed IRSs/RISs that are independently serving its close-by associated users so that the overall system gain, and quality of service can be improved [22]. In the situation of distributed IRS communications for Massive MIMO, multiple IRSs are spatially distributed (located) to serve wireless users with the optimization target of the energy efficiency possibly through dynamically controlling the on-off status of each IRS as well as the reflection coefficients matrices of the IRS.

22.4. Cooperative Beamforming in IRS/RIS Communications

One of the most critical challenges to be confronted by 5G and beyond system design and deployment lies in energy efficiency as today's world is facing some potential issues and concerns related to energy [23]. Cooperative beamforming gains between IRSs/RISs or between RISs and access points (APs) can be obtained to further improve the overall system performance from conventional multiple-IRS/RIS systems. A design example at WiGig 60 GHz mmWave bands is given as follows:

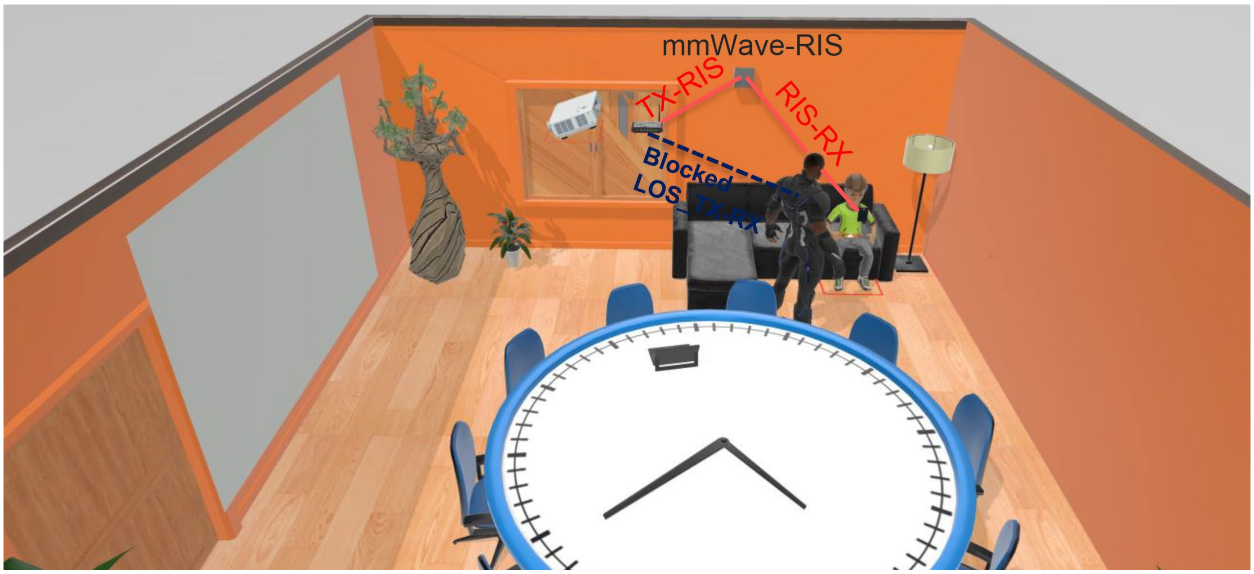

Figure 5. 3D transparent view of RIS-assisted mmWave communication with a realistic environment and human blockage ©Y. Huo.

As illustrated in the specific design case, when the router/AP is blocked by the human users indoors, another artificial reflection link is re-established. As a result, path loss (with atmospheric attenuation and real RIS refl. coeff.) of 60 GHz is 11.8 dB lower (better) than the best NLOS link (situation without RIS). And the RIS is composed of 80 * 80 unit cells, occupying a total hardware area < 0.14 m * 0.14 m. Therefore, the artificial reflection link outperforms 'natural' reflection where the attenuation depends on building materials and roughness factor. Plasterboard material is used in the simulation.

On the other hand, when and how the beamforming will be performed between the router and RISs totally depends on the real-time channel status and decision-making taken by the algorithm. In the meantime, more channel training overheads may be necessary to estimate more channel coefficients over the inter-RIS multiple-reflection link and Massive MIMO links. However, more advanced algorithms based on artificial intelligence (AI) may help to mitigate the issue.

22.5. Machine Learning Aided IRS/RIS Communications

Machine learning techniques can be very powerful tools to further improve the performance of IRS-aided massive MIMO communications. Some earlier research has suggested that taking advantage of supervised learning tools to predict channel coefficients and the IRS matrices can help configure passive surfaces without requiring massive channel estimation. This can be accomplished while still being able to reduce the beam training overhead. This strategy may need to consume significant resources to collect large datasets and train the neural network models. Furthermore, deep reinforcement learning frameworks can also serve as another enabling strategy for making online learning feasible for the standalone IRS to operate and learn how to predict the IRS reflection matrices based on minimal beam training overhead.

22.6. Integrated Sensing and Communications Based on IRS/RIS and Massive MIMO

Integrated Sensing and Communications (ISAC) is a promising component in the future network [24]. In particular, when frequency moves higher to mmWave or THz bands, ISAC on top of massive MIMO and IRS/RIS is envisioned to be a necessary architecture. Consequently, a joint waveform and system design are very critical for an ISAC-capable system architected on massive MIMO and IRS/RIS. Such a system is supposed to localize/sense the target/user, deliver the data in a more energy-efficient way with low latency and low hardware expense.

22.7. Applications Enabled and Enhanced by IRS/RIS-Aided Massive MIMO Communications

There are many types of very promising applications for the beyond 5G communications that can be facilitated and/or enabled by adopting IRS aided massive MIMO communications, such as follows:

1) Unmanned aerial vehicle (UAV) communications assisted by IRS/RIS [25];
2) Integrated space-air-sea-terrestrial (SAST) communications, including satellites to UAVs, satellites to maritime/ground vehicles [26], satellites to satellites, UAVs to UAVs, and maritime/ground vehicles;
3) IRS/RIS aided Massive MIMO combined with deep learning and computer vision techniques to enable the indoor/outdoor localization, tracking, and "through-wall" visualization techniques;
4) Link, coverage and QoS performance enhancement at rural areas [27];
5) Combining IRS/RIS with 5G and beyond user equipment (UE) design [23].

23. Massive MIMO Radar

23.1. Introduction

There has been recent excitement in the signal processing and communication society in employing manifold antennas to the order of hundreds of elements in each antenna at base stations, improving: capacity, capability, and quality of service to many users of the communication channel. Therefore, in general, this approach could improve the currently employed MIMO communication systems. In this context, it is pertinent to note that the defense radar industry already employs and maintains phased arrays consisting of thousands of elements. These radars have existed since the 1970s, performing important national security missions to keep the homeland safe from airborne, terrestrial, and space-based threats. Advances in hardware technology in the past 30 years have allowed for modern military phased array radars to have massive apertures consisting of thousands of elements and are constantly improving their performance.

23.2. Definition

Although deployed radars are large phased arrays, the true potential of such arrays has not been completely harnessed and is currently underutilized. This is because the radar industry typically looks for smart solutions to challenges from diverse researchers and energetic scientists in academia and professional societies. These massive aperture radars remain relatively unexamined because existing signal processing techniques focus largely on small arrays, oftentimes, linear and sparse. Massive aperture arrays offer a goldmine of technical opportunities and unsolved challenges to signal processing scientists and engineers alike. Current research on Massive MIMO radars focuses on ascertaining a very high number of virtual spatial antenna channels that satisfy the radar system performance requirements, without any a priori knowledge of the statistics of undesired signals. These results are largely asymptotic with respect to the number of transmitting and receiving antennas.

23.3. Future Vision

These massive radar apertures now allow the complete aperture to be subdivided into smaller, overlapping, joint, or disjoint sub-apertures, each perhaps having a different role in the system such as tracking, searching, etc. Data from these elements or subarrays may be used for different radar modes such as detection, tracking, machine learning-enabled automatic target classification, air/ground moving target identification (A/G MTI), and space-time adaptive processing (STAP). Part of the array or a group of sub-apertures may allow for a single or multiple MIMO radar capability by transmitting multiple waveforms from these sub-apertures or element levels along with hybrid beamforming, interference nulling, electronic jamming, and electronic protection countermeasure capabilities without sacrificing beamwidth and angular resolution. All of this and more without over-utilizing the temporal and spectral resources.

Parts of these arrays or sub-arrays may transmit and receive multiple polarizations, i.e., polarization diverse, offering unique capabilities for algorithm and system development research. When multiple such arrays are geographically disparate, they would only improve bi-static and multi-static and networked radar system capabilities for surveillance and early warning. Lastly, the massive aperture allows for a combined radar and communication dual functionality, permitting communication data to be embedded in radar transmissions, or alternatively using the communication infrastructure for radar purposes.

With the space race heating up with major corporate players as well as start-ups deploying satellites with Massive MIMO apertures in low earth orbit (LEO), geostationary orbit (GEO), and medium earth orbit (MEO) with reusable rocket technology, is only a matter of time before these space-based resources may be tasked for space-based communication and space-based radar applications. In order to prepare for these unique challenges, it is imperative to collectively get the scientific, academic, industry, and government interests to explore collaborative and innovative solutions to such practical problems.

24. Cell-Free Massive MIMO

24.1. Motivation

Current cellular networks (namely 4G & 5G) architecture is based upon Network Centric approach where each user is connected to a cell, which presents the following challenges:

- Intercell interference on cell edge.
- Poor signal quality at cell boundaries.
- Cell edge users are comparatively far from their serving cells, which results in unfavorable channel conditions.

24.2. Previous Research

Many solutions have been explored. MIMO techniques can improve the SINR for cell-edge users by employing spatial beamforming. In addition, different coordination techniques have been considered, e.g., Inter-Cell interference cancelation (ICIC), Coordinated Multi-Point transmission and reception (CoMP), Joint Transmission (JT), and Coordinated Beamforming. Cell-free Massive MIMO is an enhanced form of coordination among the access antennas over different geographic locations.

24.3. Cell-Free Approach

Instead of centralized cell-based servers, Cell-Free Massive MIMO systems use a large number of distributed, cost- and power-efficient access point antennas. There are no separate cells in the network. Rather, each user is served by all nearby access point antennas. These distributed access antennas are coordinated via a network controller. Therefore, no matter where the user is geographically located in the network, the user is served by a collection of coordinated access antennas, and no user will experience the cell edge conditions. Cell-free Massive MIMO is a technique that can eliminate the cell edge problems, increase coverage, and offer consistently high throughput for the users regardless of if they are close to or far away from an individual access antenna.

25. Systems Design

Currently, the exploitation of multiple antennas is primarily confined to the wireless physical layer. In particular, the capabilities afforded by Massive MIMO are not exposed as a controllable interface to various applications utilizing the services provided by the network. Such applications are not aware of Massive MIMO-enabled opportunities, such as requesting to steer an RF beam to a certain user at a given time.

We envision when large-scale (100-1000 controllable antenna elements) Massive MIMO systems are deployed, it will provide ample controllability for the network applications to tailor the wireless physical layer capabilities for their respective needs. The network will evolve to provide well-defined application programming interfaces (APIs) for the network applications to gain visibility into the status of the Massive MIMO system, as well as to directly control certain parameters of the Massive MIMO operation, e.g., setting power levels, beamforming beam widths, beam shapes, and beam scheduling policies. This Massive MIMO API may be integrated with and jointly optimized with other functionality in the communications network. For example, an end-to-end network slice may be commissioned with given Quality-of-Service targets that are jointly designed with the intended Massive MIMO capabilities.

26. Regulatory & Compliance

Considerations for using Unlicensed Spectrum:

1. Select the best frequency band for an industrial wireless network
2. Compatibility of the selected band with industrial wireless radios

3. Each unlicensed band support for mesh network/wireless radios

Considerations for leverage Dynamic Spectrum Sharing:

1. Share the spectrum between two technologies instead of splitting the mid-band spectrum/ Use of the same spectrum bands for different radio access networks
2. Consideration of the impact of the spectrum on users' experience via network management

The mobile wireless industry continues to make great strides in the research, development, standardization, and deployment of 5G technologies. The evolution and revolution in wireless continue with new standardized technical features at 3GPP as the mobile wireless industry connects more people and things in new markets.

3GPP is in its final stage of completing Release 16 while simultaneously engaging in detailed discussions and decisions on Release 17. In Release 16, the current 5G NR capabilities are enhanced from Release 15, improving the operational efficiency of the radio-access technology. In parallel, Release 16 introduces new capabilities extending NR towards new verticals. Some key features of NR Release 16 are:

- Support for Integrated Access/Backhaul (IAB) extending NR to support also the wireless backhaul, thereby enabling, for example, rapid deployment of NR cells and new ways to provide NR coverage in areas with sparse fiber density.
- Support for NR operation in unlicensed spectrum, both in form of license assisted access where an NR carrier in unlicensed spectrum complement and operates jointly with a carrier (NR or LTE) in licensed spectrum, and stand-alone operation.
- Enhanced support for V2X, URLLC, and Industrial IoT, thereby extending/enhancing the applicability of NR to new usage scenarios including factory automation and the transport industry.

Decisions by 3GPP were made on Release 17 in December of 2019 to improve network capacity, latency, coverage, power efficiency, and mobility. In Release 17 addition to general enhancements of current features, several new Release 17 features have been outlined including:

- Extending the operation of NR to spectrum above 52.6 GHz to 71 GHz
- Introducing Reduced Capability NR devices (NR-Light, i.e., enabling services with a UE complexity/capability trade-off in-between the conventional high-quality eMBB services and the low-complexity services enabled LTE-MTC and NB-IoT).
- Enhanced Dynamic Spectrum Sharing
- Multi-Sim devices
- More advanced Side-link communications
- Small data capabilities
- Enabling broadcast/multicast services within NR
- Support for non-terrestrial networks (i.e., a satellite component of NR)

In an urban environment, 5G will rely on dense networks with reduced cell sizes, which may share the same band with other services operating in different territories. 5G can perfectly use the spectrum sharing schemes developed in the last fifteen years, getting additional spectrum when and where needed.

A robust pipeline of low-, mid-, and high-band spectrum will be required to ensure that 5G reaches its full potential in the United States. The Federal Communications Commission (FCC) has been aggressive in free additional spectrum for wireless use, but more work is left to be done. Companies are engaging with the FCC and the National Telecommunications and Information Administration (NTIA) to promote flexible spectrum policies and continue the effort to identify and unleash much-needed spectrum for 5G use.

Over the past few years, the U.S. government has made 5G spectrum access a top priority, launching numerous proceedings to free additional spectrum and propel 5G deployments forward.

On the low-band front, the FCC repurposed 70 MHz of 600 MHz spectrum for mobile use through the broadcast incentive auction. The Mid-band spectrum has also been a key focus. The FCC aims to auction 70 MHz of priority access licenses in the 3.5 GHz band in June 2020, and it continues to weigh options for making the C-band spectrum at 3.7-4.2 GHz available for 5G in the near term. For its part, NTIA has announced that it is studying the feasibility of allowing commercial operations in the 3.45-3.5 GHz band. Finally, on the high-band side, the FCC continues to auction large swaths of millimeter wave spectrum, recently completing two consecutive auctions of the 28 GHz and 24 GHz bands.

Future auctions will release more spectrum into the commercial marketplace. The FCC and NTIA will need to continuously evaluate their spectrum policies to ensure that enough spectrum is available for 5G to deliver the ultra-high-speed, low-latency, reliable networks consumers are expecting. Companies can help shape smart spectrum policies from the start by engaging with the agencies early and often. Communicating technological needs and limitations will help policymakers develop better-informed spectrum frameworks for the 5G future.

Global technical standards and spectrum harmonization for wireless services are vital for 5G's success. Regional and national decisions on spectrum band allocations and technical and licensing conditions will affect the ability to fully deploy 5G domestically and abroad. These decisions will also impact the ability of players in the 5G ecosystem to leverage economies of scale.

27. Safety

3GPP defined new bands such as n77 and n78 (3200 MHz to 4200 MHz) that raise health concerns, in particular with regard to increased electromagnetic radiation resulting from higher frequencies combined with beamforming. Consequently, the 5G rollout is slowing down in several countries until it is proven that the radiation is below a certain country-specific threshold.

To continue the network rollout, dynamic spectrum sharing between LTE and 5G NR in already used frequency bands could be a good compromise to provide 5G NR but use existing antennas without beamforming. In the case of dynamic spectrum sharing, specific LTE sub-frames are omitted to allow the insertion of 5G NR signal components. Furthermore, dynamic spectrum sharing provides a much less usable spectrum. Because of these facts, dynamic spectrum sharing is not as efficient as a 5G NR rollout based on 3.5 GHz with beamforming antenna arrays in terms of the data that can be achieved. Nevertheless, the radiated power is also increasing, and operators and governments have to ensure that the total radiated power (and electromagnetic pollution) is below a certain threshold.

Over the past two decades, extensive studies on radio signals used by mobile technologies have been undertaken and research continues. The WHO stated in February 2020 that: "To date, and after much research performed, no adverse health effect has been causally linked with exposure to wireless technologies… Provided that the overall exposure remains below international guidelines, no consequences for public health are anticipated."

The following guidelines have been summarized in the literature that can be taken into consideration:

1. mmWave radiation is nonionizing because the photon energy is not nearly sufficient to remove an electron from an atom or a molecule.
2. Power density is not as useful as SAR or temperature for assessing safety in mmWave devices, especially in the near field.
3. The FCC and ICNIRP standards are designed principally to protect against thermal hazards since ionizing radiation is not a concern at mmWave frequencies. See also FCC Report 19-126 [28] on considerations on exposure that goes up to THz.
4. At mmWave frequencies, where most of the energy is absorbed in the few outer millimeters of tissue, even a 1-g averaging volume can seem large.
5. It has been suggested in the literature that performing temperature elevation measurements for the compliance evaluation of mmWave wireless devices operating very close to the human body.
6. The eyes are particularly vulnerable to mmWave radiation-induced heating.
7. mmWave attenuation of most garment materials is negligible.
8. Further measurements of dielectric permittivity on different body sites and different human subjects are warranted to characterize the variability and distribution of properties for the development of accurate human models.
9. Major decisions on public policy or health care should not typically be made based on reports that were not reproduced independently.

28. Conclusions and Recommendations

28.1. Summary of Conclusions

The 5G and beyond wireless system holds great promise for high bandwidth, low latency, ultra-reliability, and the ability to support a massive number of connected devices. A key technology to support this next generation of wireless systems is the use of Massive MIMO systems. When we intelligently exploit a large number of antenna elements, we are able to achieve an unprecedented level of controllability and efficiency in the use of the physical channel of the wireless medium.

It is envisioned that Massive MIMO systems will be deployed from mid-bands (sub-6 GHz), high-bands (10's of GHz), to mmWave bands. The operation of Massive MIMO in different bands may be optimized for different scenarios such as coverage, throughput, reliability, and/or energy efficiency. The use of Massive MIMO will encompass different deployment scenarios such as TDD, FDD, indoor, outdoor, small cell, macro cell, etc., as part of a heterogeneous network (HetNet).

28.2. Working Group Recommendations

- Plan for the deployment of Massive MIMO systems in different configurations: from mid-bands to mmWave, TDD, FDD, indoor/outdoor, small cells, macrocells, etc., as part of a heterogeneous network.
- Support different Massive MIMO hardware implementation architectures: e.g., digital, analog, hybrid.
- Apply artificial intelligence (AI), machine learning (ML), and Big Data techniques in the monitoring, operation, and optimization of Massive MIMO systems.
- Support an open cross-layer interface that allows wireless applications to customize the operation mode of the Massive MIMO sub-system, e.g., to optimize for throughput, reliability, and energy efficiency through techniques such as network slicing and network function virtualization.
- The Massive MIMO radio access network (RAN) is transitioned from being a passive network layer to an intelligent decision-making network component.
- The organization of wireless networks is transitioned from cell-based topology and a dynamic, self-optimizing beam-based wireless ecosystem.
- Single user massive MIMO could be employed to increase spectral efficiency per user.
- It may be necessary to specify the operating average signal-to-noise ratio per bit (E_b/N_0) for all telecommunication systems, instead of specifying only the received signal strength. This would ensure a match between theory (university) and practice (industry).

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30. Acronyms/abbreviations

Term	Definition
1G-4G	First Generation to Fourth Generation
3GPP	Third Generation Partnership Project
5G	Fifth Generation
ACK/NAK	Acknowledgment/negative acknowledgment
AI	Artificial intelligence
API	Application programming interface
B2B	Business to business
B2C	Business to consumer
BER	Bit error rate
BS	Base station
BSS	Business support system
CAPEX	Capital expenditure
CDMA	Code division multiple access
CFO	Carrier frequency offset
CN	Core network
COTS	Commercial off-the-shelf
CP	Control plane
C/U	Control plane / User plane
D2D	Device to device
DevOps	Development and information technology operations
DFT-s-OFDM	Discrete Fourier transform spread orthogonal frequency division multiplexing
DL	Downlink
DNN	Deep neural network
DOA	Direction of arrival
EAP	Edge automation platform
eMBB	Enhanced mobile broadband
eNB	Evolved node B
EPC	Evolved packet core
ETSI	European Telecommunications Standards Institute
FDD	Frequency-division duplex
FDMA	Frequency division multiple access
GHz	Gigahertz
GSMA	GSM (Groupe Speciale Mobile) Association
HetNet	Heterogeneous Network
HIR	Heterogeneous Integration Roadmap
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IMS	IP multi-media subsystem
IoT	Internet of things
IP	Internet protocol
IRDS	International Roadmap for Devices and Systems
ISG	Industrial specification group
ISP	Internet service provider
ITS	Intelligent transport system
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
KPI	Key performance indicator

LAA	Licensed assisted access
LDPC	Low-density parity-check
LTE	Long-term evolution
M2M	Machine to machine
MAC	Medium access control
MANO	Management and orchestration
MEC	Multi-access edge cloud
MIMO	Multiple input, multiple output
ML	Machine learning
mMTC	Massive machine-type communication
mmWave	Millimeter wave
MR	Merged reality
MVNO	Mobile virtual network operators
NaaS	Network as a service
NF	Network function
NFV	Network function virtualization
NGMN	Next generation mobile networks
NGC	Next generation core
NOMA	Non-orthogonal multiple accesses
NR	New radio
NS	Network slicing
NSA	Non-standalone
OEC	Open edge computing
OFDM	Orthogonal frequency-division multiplexing
OMEC	Open mobile edge cloud
OPEX	Operational expenditure
OPNFV	Open platform network virtualization
OSS	Operational support system
OTT	Over the top
PAPR	Peak-to-average power ratio
PGW	Packet gateway
PHY	Physical layer
PoC	Proof of concept
QoS	Quality of service
RAN	Radio access network
RE	Range extension
RSRP	Reference signal received power
SDN	Software defined network
SDO	Standards developing organization or standards development organization
SER	Symbol error rate
SIM	Subscriber identification module
SINR	Signal-to-interference plus noise ratio
SLA	Service level agreements
SON	Self-optimizing network
TDD	Time-division duplex
TDMA	Time division multiple access
TSDSI	Telecommunications Standards Development Society India
TTI	Transmission time interval
UAV	Unmanned aerial vehicle
UE	User equipment
UL	Uplink

UP	User plane
URLLC	Ultra-low reliability low latency connection
V2I	Vehicle to infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything
vEPC	Virtual evolved packet core
VNF	Virtual network function
WRC	World Radiocommunication Conferences
WSS	Wide sense stationary
WG	Working group

31. Contributor Bios

Harish Kumar Sahoo is now working as Professor in the Department of Electronics and Telecommunication Engineering, Veer Surendra Sai University of Technology, Burla, India. He received B.Tech., M.Tech. and Ph.D. degree from Utkal University, National Institute of Technology, Rourkela and Sambalpur University respectively. He is a senior member of IEEE and the chair of student activities IEEE Bhubaneswar Subsection. He has published number of research articles in the journals of IEEE, Elsevier, Springer and Wiley. He is an active reviewer of journal articles from IEEE. His research groups are working on efficient estimation and equalization models for massive MIMO.

Kumar Vijay Mishra obtained a Ph.D. in electrical engineering and M.S. in mathematics from The University of Iowa in 2015, M.S. in electrical engineering from Colorado State University in 2012, and B. Tech. summa cum laude (Gold Medal, Honors) in electronics and communication engineering from the National Institute of Technology, Hamirpur (NITH), India in 2003. He is currently Senior Fellow at the United States Army Research Laboratory (ARL), Adelphi. He is the recipient of several awards and fellowships. He is the lead/corresponding editor of the upcoming book Signal Processing for Joint Radar-Communications (Wiley-IEEE Press).

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Yang Miao received the M.Sc. and Ph.D. degrees from the Radio Propagation Laboratory, Mobile Communications Research Group, Tokyo Institute of Technology, Japan, in 2012 and 2015, respectively. From 2010 to 2015, she was a Research Assistant with the Takada Laboratory, Tokyo Institute of Technology. From 2015 to 2018, she was a PostDoctoral Researcher with the Institute of Information and Communication Technologies, Electronics, and Applied Mathematics, Universite Catholique de Louvain, Louvain-la-Neuve, Belgium, and IMEC, Wireless, Acoustics, Environment, and the Expert Systems Laboratory, Ghent University, Ghent, Belgium. From 2017 to 2018, she was a part-time Senior Antenna Engineer with Jaguar Radio Wave Corporation, Shenzhen, China. From 2018 to 2019, she was a Research Assistant Professor with the Southern University of Science and Technology, Shenzhen, China. Since Aug. 2019, she has been an Assistant Professor with the Radio Systems Group, University of Twente, The Netherlands. From Nov. 2021, she is also affiliated in part-time with KULeuven as a Marie Curie Individual Fellow. Her current research focuses on Joint Communication and Sensing, incorporating mobility and human factors and machine learning.

Webert Montlouis received his BS, MS, and Ph.D. degrees in Electrical Engineering from Northeastern University, Boston MA. He joined the System Architecture, Design, and Integration Directorate (SADID), a division of the Raytheon Company. There, he developed radar systems architecture, Concept of Operations (CONOPS), and performance analysis for phased array radar systems. He has worked as a Senior Member of Technical Staff for many research and development companies. He has also worked as Technical Consultant for many consulting firms primarily specializing in developing ASIC and FPGA for communication systems. He served as the General Co-Chair of the IEEE Future Networks 1st Massive MIMO workshop. He is the Co-Chair of the IEEE Future Networks Massive MIMO working group. Dr. Montlouis has been with Johns Hopkins University where he is a faculty in the electrical and computer department and he has served as senior staff and chief scientist at JHU Applied Physics Laboratory.

Dr. Montlouis' research interests are in the areas of multichannel system architecture and associated signal processing which include radar systems architecture and design, communications, adaptive antenna array signal processing, robust tracking and localization, wireless communications, multichannel sensing architecture for biomedical signal processing, and quantum information science. He is a Fellow of the IEEE and he is affiliated with the communications, signal processing, and Aerospace and Electronic Systems societies.

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