5G Millimeter-Wave Mobile Broadband: Performance and Challenges

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I. ABSTRACT

With the rapid expansion in mobile data demand, the fifth generation (5G) mobile network would take advantage of the vast amount of spectrum available in the millimetre wave (mmWave) bands to considerably enhance communication capacity. In terms of high propagation loss, directivity, and susceptibility to blocking, mmWave communications differ significantly from conventional communication technologies. These characteristics of mmWave communications provide several problems in fully realising their promise. Integrated circuits and system design, interference management, spatial reuse, anti-blockage, and dynamics control are only a few of the topics covered. The goal is to support the explosive demands for mobile broadband service. To fulfil the requirements, we developed various 5G technologies, including milli meter-Wave, massive multi-input multiple outputs, microcells and UDN. Despite the merit of large contiguous spectrum in mm-wave range, cellular type of communication with mm-wave technology has been considered as challenging. We also go through how mmWave communications might be used in the 5G network, including small cell access, cellular access, and wireless backhaul. Finally, we discuss relevant open research issues including software-defined network architecture, measurements of network state information, efficient control mechanisms, and heterogeneous networking, which should be further investigated to facilitate the deployment of mmWave communication systems in the future 5G networks.

II. INTRODUCTION

With the fast development of electronic devices and computer science, various emerging applications (e.g., Virtual Reality, Augmented Reality, Big Data, Artificial Intelligence, 3D media, ultrahigh definition transmission video, etc.) have entered our society and created a significant growth in the data volume of wireless networks. Meanwhile, mobile networks have become indispensable to our society as a key service for personal computing devices. Unprecedented traffic volumes, enormous area spectral efficiency, and extremely high throughput per device are some of the primary characteristics of future mobile networks (5G and beyond) (multiple Gbps). For instance, it is predicted that the world monthly traffic of smartphones will be about 50 petabytes in 2021 [1], which is about 12 times of the traffic in 2016. To meet these requirements, the research and deployment for the future mobile networks [2]– [4] have already been launched. Since 2013, the national level 5G research organizations and projects have been set up one after the other to achieve the 2020 technical targets. In 2015, ITU-R officially named 5G systems as IMT-2020 and released recommendation on its framework and overall objectives. Currently, Phase-1 of 5G is being standardized in 3GPP. It's worth noting that 5G isn't just meant to grow and accommodate a wide range of scenarios and applications that will last beyond today's networks key performance metrics such as spectral and energy efficiencies, data rates, reliability, latency, and mobility support, among, but also to support a broad variety of new application scenarios, including:

1) Enhanced Mobile BroadBand (eMBB) is targeted for mobile broadband services that require extraordinary data rates
2) Massive Machine Type Communications (mMTC) is the basis for connectivity in Internet of Things (IoT)
3) Ultra Reliable Low Latency Communication (URLLC) is needed for applications which have stringent latency and reliability requirements.

The following eight key performance indicators (KPIs) are expected to be provided by IMT-2020 [4]: higher than 10 Gbit/s peak data rate, userexperienced data rate of 100 Mbit/s, 3x spectrum efficiency, and cell edge rates of greater than 100 Mbps, 10Mbit/s/km2 area traffic capacity, 100x network energy efficiency, 1ms over-the-air latency, support for 500 km/h mobility, and 106/km2 connection density [2]. The multiplicative improvements are measured with respect to IMT-Advanced.

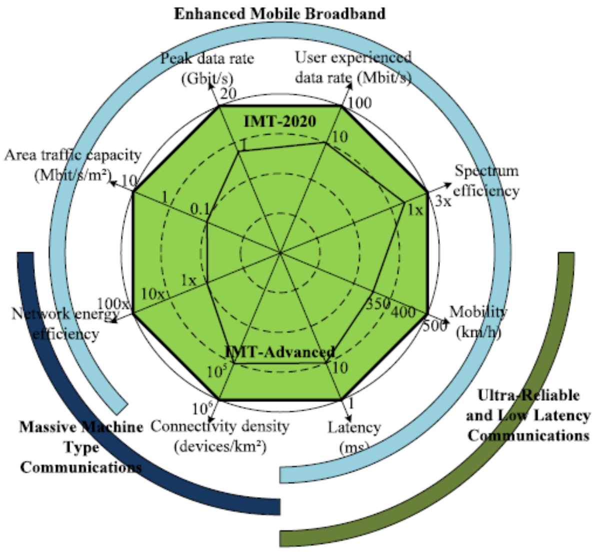

Fig. 1 illustrates potential usage scenarios and capabilities of IMT-2020 [4].

Also, to meet the explosive user data demand projected for 2020, the consensus among researchers in both academia and industry is that the “three big 5G technologies” can support next-generation mobile networks. They will jointly provide the 1000x capacity increase envisaged for 5G relative to 4G systems. These future networks are expected to enhance key performance characteristics such as spectral and energy efficiency, data throughput, dependability, latency, and mobility support, among others, in addition to increasing capacity. The "main three" 5G technological enablers that are expected to pull this off are:

- Ultra-dense networks, UDNs
- Millimeter-wave (mmWave)
- Multiple-output (MIMO) antenna arrays

The expected capacity gains from these technologies are due to the combined impact of high frequency reuse, large additional spectrum, and spectral efficiency enhancement, respectively [4]. SCs will be deployed in UDNs based on the network's ideal cell density threshold and the intersite distance (ISD) of 50–200 metres. The multi-gigahertz contiguous bandwidth in the 30–300 GHz mmWave spectrum and the 0.1–10 THz bands [5, 6] will support multi-gigabits-per-second data rates. At 70 GHz, for example, the number of antennas. mmWave communications Bandwidth growth is a successful way to accommodate the rapid rise in data speeds. Bandwidth shortages prompted the discovery of the rich millimetre wave (mm-Wave) frequency spectrum extending from 3 to 300 GHz [9]. Massive Multiple-Input Multiple-Output (MIMO) is a technology that has evolved from the most recent MIMO technology [10]. The Massive MIMO system makes use of antenna arrays with hundreds of antennae, which are frequency slots that serve thousands of user terminals at the same time. Massive MIMO technology's fundamental aim is to extract all of MIMO's advantages but on a broader scale [11].

III. Progress of Standardization Activities on 5G

The deployment and standardization activities of 5G networks are rapidly increasing. Standardization of 5G technology is broken into two phases. The goal of this phased standardization approach is to complete initial specifications to allow deployments in the 2020 timeframe. Phase 1 will be completed by September 2018 in Release 15. Phase 2 will incorporate more functions to extend the capabilities of 5G to enable more services, scenarios, and considerably higher frequency bands as time goes on (e.g., above 40 GHz). Phase 2 will be completed around the end of 2019 in Release 16. The focus on eMBB and URLLC use cases, non-standalone functioning of the New Radio, and interworking back to the existing EPC (enhanced packet core) through the eNodeB acting as the anchor cell were all major decisions made during the Release 14 study phase. Release 17 (Rel-17) of the 3GPP is a significant milestone in the standardisation of 5G new radios (NR). Massive MIMO, support for the 52.6–71 GHz frequency band, multicast/broadcast support, and advancements in terms of integrated access and backhaul, industrial IoT/URLLC, 5G NR sidelink, and dynamic spectrum sharing are also targets in Rel-17. Despite these efforts, 5G is still in its infancy, and many operators have yet to announce commercial 5G service launches [3]. Beyond 5G (B5G)/sixth generation (6G) networks are being conceptualised in parallel to maintain wireless communication networks' competitive edge. The number of Internet-connected devices worldwide is estimated to surpass 50 billion by 2020, with wireless data traffic for new IoT services expected to reach 5016 exabytes per month [4,5]. The omnipresent connectivity and spectrum needs are predicted to be met by B5G/6G networks with technological advantages and demanding disruptive capabilities in 2030 and beyond.

IV. Network Architecture of 5G

A mutually beneficial relationship exists among these three technologies. As a result, the massive MIMO mmWave paradigm for UDNs has emerged as an important research topic for future cellular networks. For reasons of interoperability, the coexistence of mmWave/terahertz SCs and the legacy microwave (mWave) cellular networks is being explored for 5G. The central and local server operation in the 5G network architecture method enables consumers with faster content and low latency apps. A mobile network's two primary parts are the 'Radio Access Network' and the 'Core Network.' Small cells, antennas, masts, specific building networks, and residential systems are all part of the Radio Access Network, which connects smartphone users and cellular devices to the central network itself. Small cells are an important aspect of 5G networks, especially for the newest millimetre wave frequencies (mmWave), which have a relatively short range of transmission. Small cells are arranged in clusters to offer continuous connectivity where consumers want it, supplementing a large-area macro network [34]. MIMO antennas, which contain many components or connections, can be used by 5G Macro Cells to concurrently send, and receive more data. Consumers benefit since more people may connect to the network at the same time while maintaining excellent performance. The spatial dimension of the antennas in the base station 3G and 4G is same, even though MIMO antennas employ many antenna components, which is referred to as "mega MIMO." The core network is the cellular network that exchanges and controls telephone voice, data, and internet connections. The 'heart network' has been updated for 5G to increase connectivity with the internet and cloud-based networks, as well as to include distributed servers that improve reaction time (reducing latency). Many of 5G's novel characteristics, such as network slicing and network features, may be handled by a variety of applications and services.

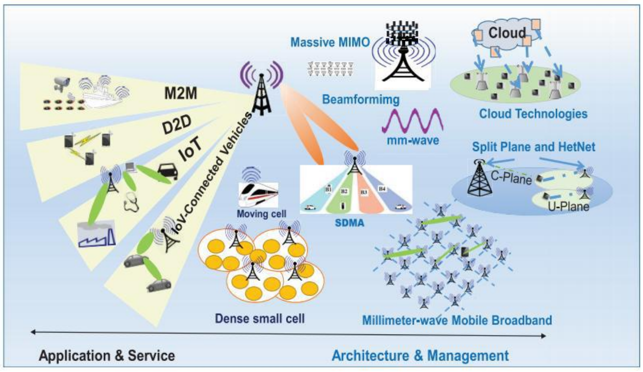

Fig. 2 Schematic diagram of 5G wireless networks

Ultra-Dense Networks (Small Cell Deployment)

mmWave networks can also be made very dense to overcome blockages and can benefit from the current trend of moving cellular systems to a more heterogeneous infrastructure that includes small cells and relays, when combined with the usage of adaptive steerable arrays. Femto and pico cells, which are small cells having a range of 10-200 m, enable for higher frequency reuse rates. In fact, the mmWave's atmospheric absorption nature will effectively strengthen each cell's isolation by further attenuating background interference from more distant base stations.

Massive MIMO

Massive MIMO is a major enabling technology for next-generation networks that combines antennas at both the transmitter and receiver to enable exceptional spectrum and energy efficiency with simple processing. mmWave networks must use electronically steerable directional antennas with high gain to provide a high signal-to-noise-ratio (SNR) consistently throughout a cell, which means they must pre-code or beam-form data on massive antenna arrays. Because of the small wavelength, feasible arrays will be able to hold orders of magnitude more elements than existing arrays. This will give sufficient gain to overcome path-loss and ensure a high SNR output.

Millimeter Wave and Terahertz Band

For wireless communication, frequencies greater than the millimeter-wave range (30 GHz–300 GHz) could be employed. The Terahertz band spans the frequency range of 300 GHz to 3 THz. Apart from having a larger spectrum, the THz band has several advantages, including interference-free deployment, scalability, increased security, greenfield spectrum availability, low power consumption, a front-haul boost for wireless networks, reduced antenna sizes, and focused beams. Imaging, spectroscopy, holographic telepresence, industry 4.0, and enormous scale communications would all benefit from THz technologies.

Combined Two-Tier Network

These three technologies have a mutually beneficial relationship. As a result, for future cellular networks, the massive MIMO mmWave paradigm for UDNs has emerged as a key research area. The coexistence of mmWave/terahertz SCs with legacy microwave (mWave) cellular networks is being investigated for 5G for interoperability concerns. The mWave BSs offer coverage and signalling for the macrocells (MCs), while the mmWave Small Cells (SCs) act as hotspots for consumers with high data rate demands, as well as broadband or bandwidth-hungry applications. This network layout, on the other hand, is a gold mine of advantages as well as a rich source of obstacles. Due to the density of SCs and the unusual propagation properties at mmWave frequencies, this is especially true for the SC tier.

The strong interference from dense SCs, the high noise power coming from wide mmWave bandwidth, and the low received signal strength in mmWave massive MIMO arrays due to smaller antenna apertures create additional issues in this tier. Due to the increased losses and noise level at mmWave, the SINR (Signal to Interference & Noise Ratio) in the mmWave SC tier seems to be lower than that in the mmWave MC tier. If all other factors remain constant, the SINR decreases as the amount of mmWave bandwidth used increases. The capacity of the network continues to expand, although not at the same rate as the bandwidth.

V. Future Research Directions

Due to higher path loss, increased noise, and other extra losses, such as wall/penetration and indoor losses (for indoor users) and absorption losses (for the 57–63 GHz bands), the SINR in mmWave systems is deteriorated in the 2-tier architecture. Even though the SCs have a significantly wider bandwidth than the MCs, it is not uncommon for the SCs to function worse than the MCs in scenarios with very low received signals (or even complete outage). Despite its fantastic spectrum possibilities, higher-frequency (i.e., mmWave and terahertz) linkages are highly opportunistic and potentially unreliable due to this circumstance, in addition to their significant sensitivity to obstruction. The following are some possible solutions for overcoming the SINR bottleneck in mmWave systems.

Signal Power Enhancement

The received signal strength can be improved by increasing the transmit powers of the mmWave SCs. The capacity of mmWave SCs grows when the transmit power is increased. In the outdoor setting, the capacity improvement with increasing transmit power is large. Indoor UEs, on the other hand, have a terrible performance. Furthermore, due to the following limits, among others, the SC transmit powers cannot be increased indiscriminately: Regulations limit the amount of power that can be sent. Excessive power, in addition to amplifying the signal, will raise the level of interference. More transmit power increases the network's energy consumption, which is undesirable in 5G networks. As a result, achieving the best transmit power is a crucial design goal.

Interference Mitigation

Interference from other BSs is reduced by beamforming to target UEs. Through its transmit and receive beamforming gains, this will help improve the signal level. This, however, necessitates pencil-like beams, whose performance is strongly reliant on beam steering, beam tracking, and beam alignment efficiency, as well as other complexity issues. Despite the higher antenna gain in the directional instance, network performance with a directional antenna is worse than with an omnidirectional antenna. This is because we used static beamforming, which only served a portion of the users (those within the beams' coverage zone). Dynamic beamforming, in which the locations of the users are continuously scanned and tracked, is the answer in radial SCs with users spread randomly in all directions. Narrower beams and larger gains can be used to obtain better performance in this instance. However, due to beam tracking requirements, this would result in a far higher level of complexity. The SINR bottleneck will be broken by a balance in transmit power and adequate (dynamic) beamforming gains, as shown above. As a result, the performance of indoor users serviced by outdoor mmWave SC networks will improve, and the performance of outdoor users will improve much more. Furthermore, when the mmWave frequency grows, up to the terahertz regions, the ISD must drop in proportion. Only a coverage range (or ISD) of 10 m may now be considered realistic for terahertz spectrum application in cellular systems, as opposed to 200 m for mmWave systems.

As a result, the next step in the research will be to incorporate dynamic beamforming, software defined architecture and investigate network performance because of this innovation. The research can also be expanded to higher terahertz bands, where even greater bandwidths are available.

VI. Conclusion

The 5G mmWave specification operates within the 24 GHz and 300 GHz-high frequency range of electromagnetic spectrum and can support more users due to more capacity availability and provide faster data transmission speeds, higher bandwidth, and low network latency. The network performance of mmWave 5G makes it a comparable alternative to fiber-based wired communication, thus opening new opportunities for wireless broadband services for commercial and residential applications. This is due to its economic advantages and ease of deployment over fiber. The objective is to combine hyper-densified small cells (SCs) (otherwise called ultra-dense networks, UDNs), abundant bandwidth in the millimeter-wave (mmWave) and terahertz bands and massive multiple-input multiple-output (MIMO) antenna arrays to coexist in the network architecture and evaluate the performance and challenges of this network and make comparisons. The result is that the joint impact of all the components in the network will provide 1000x capacity increase envisaged for 5G relative to 4G systems. The expected capacity gains from these technologies are due to the combined impact of high frequency reuse, large additional spectrum, and spectral efficiency enhancement, respectively. The only drawback of this architecture is when the performance for outdoor and indoor users are compared, there is reduction in the SINR of indoor users as mmWaves are electromagnetic waves with higher frequencies and cannot travel long distances and are more susceptible to noise and physical obstructions (wall and indoor absorption losses, rain and vegetation attenuation etc.) This challenge can be overcome when design and operating parameters of 5G networks (bandwidth, transmit power, beamforming configuration, and so on) are carefully examined to optimize the performance such that the spectrum potential in the mmWave and terahertz regions can be fully exploited while maintaining a balance in complexity and cost.

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