Telecommunications Networking

Technologies for 5G Networks: Challenges and Opportunities

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Extensive mobile data traffic has led researchers and designers to begin developing fifth-generation (5G) networks. This article reviews potential technologies for 5G and concludes that radical changes to the network paradigm will be necessary.

The significant growth in wireless broadband traffic has had a major impact on future mobile network architectures. Such architectures will need to deal with increasing demands, including

- high traffic volume (massive capacity), involving increases on the order of several magnitudes—the future requirement is a 1,000× increase in data traffic for 2020 and beyond;
- increased indoor and small cell/hotspot traffic, which will make up the majority of mobile traffic volume—today, roughly 70 percent of mobile traffic happens indoors; in the future, indoor data traffic and hotspot areas could exceed this figure;
- higher numbers of connected devices (massive connectivity) stemming from the Internet of Things (IoT), which will support massive machine-to-machine (M2M) communications and applications; and
- improved energy consumption—5G must be a green network to reduce its carbon footprint.[1]

Mobile communication has evolved from voice-only services into a complex, interconnected environment with multiple services built on a system that supports myriad applications and provides high-speed access to a massive number of subscribers and machines.[2]

Here, we examine potential technologies that could define the 5G standard in the next few years. We look at possible challenges and try to answer important questions that should be interesting to researchers in this field.

5G: Evolution or Revolution?

Future emerging technologies and the changes that they require will determine whether 5G is merely an evolution of the existing network or revolutionary. Massive multiple-input, multiple-output (M-MIMO), beamforming, device-to-device (D2D) communications, small cell deployment, and other technologies have already been adopted in recent 4G releases and need only be modified for 5G adoption. Thus, to support these technologies, the network could merely evolve from 4G, and all current mobile devices would be supported. However, the millimeter wave band will necessitate many revolutionary technologies due to its different propagation characteristics and hardware constraints. A significant change will be required on the network node and architecture levels, and this change will extend to mobile devices; current devices will need to be modified or upgraded to support this 5G revolution because the millimeter wave signal is incompatible with these devices' frequency.[3] However, this change will bring with it higher data speeds, more reliable networks, and more applications.

The answer to the question of evolution or revolution will thus depend highly on the changes that shape 5G,[4] which could be any of the following:

- minor changes at the base station or network architecture level (network evolution);
- major changes at the base station level (component changes), such as a new transmission waveform;
- major changes at the network level (architectural changes), such as the introduction of new base station types, applications, and functions; or
- major changes at the base station and network levels (radical changes), such as adopting the millimeter-wave.

We now look at some of the technologies that will shape 5G networks.

Potential 5G Technologies

Wireless research activity is already considering many technologies for a future wireless system. High-speed data and low-latency demands will be the theme for the future 5G environment. Five key research areas will have the largest impact on progressing 5G: dense small cell deployment, M-MIMO, D2D, M2M, and millimeter-wave communications (see Figure 1). In addition, new waveforms, advanced coordinated multipoint (CoMP), carrier aggregation, multiple radio access technology (M-RAT), efficient coding techniques, network virtualization, and the emergence of cloud radio access networks (C-RAN) will also have a significant impact on 5G networks.[4,5] We've classified these technologies into four categories according to their impact on 5G network performance: *capacity and speed*, *latency*, *spectral efficiency*, and *massive connectivity and the IoT*.

Figure 1. 5G multitier network architecture. The next generation of network technologies includes macrocells (bands <3 GHz); small cells (millimeter-wave); femtocells and Wi-Fi (millimeter-wave); massive multiple-input, multiple-output (M-MIMO) with beamforming; and device-to-device (D2D) and machine-to-machine (M2M) communications. Solid arrows indicate wireless (fronthaul) links, whereas the dashed arrows indicate backhaul links.

Network Capacity and Data Speed Improvement

To meet dramatic traffic growth over the next decade, 5G mobile networks are expected to achieve higher capacity increases compared to 4G networks, with considerably higher-speed data rates. This objective can be accomplished with dense small cell deployment, utilization of the millimeter-wave band, and M-MIMO and beamforming.

Dense small cell deployment. Dense small cell deployment is necessary to offload macrocells and improve signal power. Small cells can be employed indoors or outdoors and offer a simple, cost-effective solution to network capacity issues resulting from the massive growth in mobile traffic. Small cells must be deployed with a limited cell radius to help reuse the spectrum (increase spectral efficiency) and increase the network capacity (as the network resources increase).

One problem here is the significant increase in the handoff rate. Users' continuous movement from one small cell coverage area into another will create too many or unnecessary handovers. Mobile stations must move to and from many hotspots, which can lead to an increase in handover failure and call drops. This problem will be a point of concern as small cell deployment becomes denser.

This issue can be addressed as follows. To minimize the handoff rate in future 5G heterogenous networks, control/user plane (C/U plane) splitting can be used. Basically, C/U plane splitting enables mobile terminals to receive system information, issue access requests to a base station, and get assigned radio resources for high-rate data transmission at a different base station. Signaling and data services can be provided by specialized base stations or implemented as separate and independent services into the same physical equipment. In the case of heterogeneous networks, a possible approach is to have the macro base station provide the signaling service for the whole area in a licensed, low-frequency band (legacy < 3 GHz), while the millimeter-wave small cells (phantom cells) specialize in data resources for high-rate transmission with a light control overhead and appropriate air interface. This would further reduce control signaling due to high handovers between small cells and macrocells, or among small cells.[6]

A second potential challenge is intercell interference. The dense deployment of small cells will increase interference from nearby cells. Moreover, the uncontrolled deployment of small cells could lead to uncontrolled cell shape, in which network operators have little control over the small cell's location.

Millimeter-wave frequency band. The overwhelming majority of communication systems are already operating in the microwave band (MW) below 3 GHz, due to its favorable propagation characteristics. This makes the MW band too scarce. 5G can address such bandwidth scarcity as follows.

When higher network capacity and connectivity is required, additional spectrum is also required. Moreover, mobile networks have improved quality of service (QoS) by utilizing additional spectrum (higher frequencies and wider bandwidth). Therefore, 5G will likely also utilize higher spectrum, such as by using the millimeter-wave band due to its substantial available bandwidth.[2]

Additional spectrum for 5G networks is vital to satisfy 5G demands. Extra spectrum at the 6-GHz band became available at the World Radio Communications (WRC) conference in 2015 (see www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx); however, this addition will fulfill only part of the 5G need. Substantial amounts of spectrum can be made available if the millimeter-wave band is utilized to fulfill all the requirements of 5G.

As per the US Federal Communications Commission (FCC), many bands within the millimeter-wave band seem promising and can be candidates for future 5G mobile systems, including the local multipoint distribution service (LMDS) band from 28–30 GHz, the license-free band at 60 GHz, and 12.9 GHz located from 71–76 GHz, 81–86 GHz, and 92–95 GHz in the E-band (see Figure 2).[4,7]

Figure 2. The millimeter-wave band as a candidate spectrum for 5G networks. Considerable bandwidth is available at various frequencies within the millimeter-wave band. LMDS: local multipoint distribution service.

Thus, 5G systems are expected to use millimeter-wave bands from 20–90 GHz, due to the availability of a wide chunk of unused bandwidth. This step is revolutionary because millimeter-waves have very different propagation conditions, atmospheric absorption, and hardware constraints compared to MW. These challenges could be compensated for using beamforming and a larger antenna array. It is widely accepted that the millimeter-wave band must be used with a limited cell radius (< 100 m) to minimize high path loss. Fortunately, this action fits well with the trend of dense small cell deployment.[7,8]

High path loss compared to MW bands below 3 GHz is one primary challenge in a millimeter-wave band 5G system. Generally, path loss is given by

$$L_{FS} = 32.4 + 20 \log_{10} f + 20 \log_{10} R, \qquad (1)$$

where L_{FS} is the free space path loss in decibels (dB), f is the carrier frequency in GHz, and R is the distance between the transmitter and receiver in meters.[9] This means there will be approximately 23 and 31 dB of extra path loss when moving the operating frequency from 2 GHz to 28 GHz and 70 GHz, respectively. So, millimeter-wave can be used with highly directional antennas in line-of-site (LOS) transmissions, because its non-LOS (reflected) signal is very weak. Furthermore, shrinking the cell coverage area will further reduce path loss by reducing the required signal path. Therefore, the losses for 28 GHz and 73 GHz are minimized by 10 dB compared to the 2 GHz for distances up to 100 m (see Table 1).

Table 1. Relative path loss for specific frequencies and distances.*

Carrier frequency (GHz)	1 km path loss (dB)	100 m path loss (dB)
2.0	98.46237	78.46237
28.0	121.3849	101.3849
73.0	129.7082	109.7082

*$L_{FS} = 32.4 + 20 \log_{10} f + 20 \log_{10} R$

A second challenge is signal attenuation at high frequency bands. This is a serious issue because it limits signal propagation. Millimeter-wave energy is absorbed by oxygen and water vapor. The oxygen molecule absorbs electromagnetic energy at around 60 GHz; therefore, the free-licensed band from 57–64 GHz has high oxygen absorption with attenuation of approximately 15 dB/km. Furthermore, water vapor absorbs electromagnetic energy at 164–200 GHz with even higher attenuation.[4,7]

A third challenge is that millimeter-wave signals penetrate solid materials with very high losses (if they can penetrate such materials at all), which makes them too sensitive to blockages such as buildings.[10] High levels of attenuation could limit the use of millimeter-wave communication from outdoor cells to only outdoor receivers. Indoor coverage would thus be provided by indoor millimeter-wave small cells or Wi-Fi solutions.

Massive MIMO and beamforming. M-MIMO is considered when a network is equipped with a large number of antennas at its base stations that can accommodate many co-channel users at a time. *Beamforming* is the concentration of power in a certain direction with a limited beam width but a large gain.

Beamforming and M-MIMO are key enabling technologies for 5G systems. M-MIMO can significantly improve signal strength, which could result in much higher cell throughput and better cell-edge performance than traditional 4G systems.[11]

One challenge with M-MIMO is pilot contamination[4] from nearby cells as the number of antennas increases. Researchers must optimize pilot orthogonality without consuming network resources.

Second, due to the "massive" number of antennas used, accurate channel estimation is a challenging issue even with time division duplexing (TDD) due to huge costs and complexity. A more sophisticated algorithm is necessary to enable accurate channel estimation in frequency division duplexing (FDD) and to reduce signaling overhead.

Finally, the physical size of M-MIMO is a point of concern because it requires a very large-scale architecture.[12] It will thus face pushback from the public and property owners regarding potential environmental issues. Moreover, larger-sized towers will create extra technical challenges, which will cause further pushback. However, a successful marriage that could address the physical size issue is to pair M-MIMO with the millimeter-wave band.[13] A realistic array size will become possible that facilitates M-MIMO installation.

Latency Reduction

Latency is the time it takes a signal to complete a single, full transaction. Besides achieving high data rates, latency reduction becomes vital to enable energy savings and long battery lifetimes. Current 4G latency is about 15 ms based on the 1-ms subframe. This latency is considered perfect for current applications; however, 5G will introduce technologies such as tactile Internet, two-way real-time gaming, cloud-based applications, and augmented reality that cannot be supported at current latencies (see Figure 3). Therefore, 5G should support latencies lower than 1 ms, which will have a major impact on design choices at all layers.[5]

Figure 3. Data speed vs. latency. According to the required services and applications, this figure shows a tradeoff between latency and data speed, and the potential of next-generation networks to support their demands. UHD: ultra-high definition.

One of the ways to reduce latency is through dense small cells (as discussed) and D2D communications, as follows: If two devices are in close proximity, their communications can be handled via D2D communication without consuming network resources. D2D can handle local traffic efficiently. It is an important option for applications that require low latency. D2D has already been studied as a 4G technology (release 12) in the Third-Generation Partnership Project (3GPP), and its adoption is driven by its importance for safety and disaster applications and low-latency applications.[4]

In this area, the challenges are efficient proximity detection, network integration, and native support in future 5G networks.

Spectral Efficiency Improvement

Spectral efficiency improvement is vital in 5G to deliver ultra-fast data speeds to more smartphones and tablets than ever before. Spectral efficiency (bit/sec/Hz) can be increased by increasing the modulation order, through D2D communications (as discussed), M-MIMO, and the adoption of new efficient transmission waveforms, as discussed next.

Orthogonal frequency division multiplexing (OFDM) is a powerful and inherent way to address the problem of intersymbol interference (ISI). Instead of sending information on a single carrier, OFDM uses multiple carriers to transmit simultaneous subframes after dividing the main stream and modulating each subframe on a different subcarrier frequency, which helps combat multipath and ISI.

There are several possible challenges. 5G waveforms should establish a set of requirements, such as high spectral efficiency, low latency, and limited cost and complexity. 5G systems will have several strategies to fulfill these requirements, such as dense small cell deployments and use of the millimeter-wave band, which will be directly influenced by the modulation format used at the physical layer.[14]

Will OFDM be the dominant theme in 5G? OFDM is not exempt from drawbacks, and its adoption by 5G should not be taken for granted. The main disadvantage of OFDM is its high peak-to-average-power ratio (PAPR), which decreases power amplifier efficiency. Also, cyclic-prefix (CP) insertion decreases spectral efficiency.

New schemes can be further utilized to improve spectral efficiency; those schemes include

- nonorthogonal multiple access (NOMA), which can ensure that multiple users share a wireless medium and experience the same diversity as orthogonal multiple access techniques;
- filter bank multicarrier (FBMC), in which signals on each subcarrier are shaped by a well-designed filter to suppress signal side lobes and limit its band; and
- sparse coded multiple access (SCMA), in which different data are directly mapped to code words of different codebooks, where each code represents a spread transmission layer.

As an example, with successive interference cancelling (SIC) receivers, NOMA has improved throughput in macrocells by up to 30 percent compared to orthogonal multiple access schemes.[6]

Massive Connectivity and the IoT

In the long term, it is expected that all devices that benefit from network connectivity will eventually become connected,[11] and the number of connected devices will exceed the number of human devices. With the increased availability of mobile broadband, connectivity has become a realistic issue for M2M communication.

However, the massive traffic growth expected from machine-type communication as a result of billions of connected devices will cause the network to become congested. So, a several orders of magnitude increase in network connectivity and capacity is required, which can be met with network densification, dense small cell deployment, and M-MIMO.

Moving data access to the cloud will also play a significant part in 5G, so that the network can be accessed from anywhere. Network function virtualization (NFV) can make functions with hardware compatibility issues run on cloud computing infrastructure. Thus, there will be a higher reuse of network infrastructure than in the current network. In addition, CoMP can turn interference into useful signals.[5,11] Table 2 illustrates some challenges that can be tackled with specific technologies in the 5G system.

Table 2. How 5G will tackle network challenges.

Feature	Descriptions	Technology
Extreme data rate (Gbps)	The peak data rate will be 10–20 times 4G speeds.	Millimeter-wave band Massive multiple input, multiple output (M-MIMO)
Number of connected devices (# device/m^2)	All devices that benefit from wireless connectivity will become connected in 5G (sensors, machines, weather and medical sensors, and so on).	Internet of Things (IoT) stemming from massive machine-to-machine communications Device-to-device (D2D) communications Wider bandwidth (millimeter-wave) Dense small cells
Spectral efficiency (b/s/Hz)	5G will further improve spectral efficiency.	New waveform (FBMC, NOMA) M-MIMO Coordinated multipoints
End-to-end latency (ms)	5G will support much lower latency than 4G.	D2D communications Dense small cell deployment Smart data caching
Data processing speed (Mbps/m^2)	5G will be able to process data 100 times faster than 4G in an area.	Millimeter-wave band Dense small cells Network function virtualization D2D communications
Energy efficiency (millijoule/bit)	5G will be able to transfer data with much less power, reducing its carbon footprint.	M-MIMO in conjunction with millimeter-wave band Millimeter-wave multihop relay stations
Mobility (m/s)	Faster user speeds will be supported by 5G.	Advanced heterogeneous networks

Migrating Technologies to 5G

In 5G, coverage holes are expected due to high path loss at the millimeter-wave band. Thus, the 4G system will be required to cover the overall area during the early stages of 5G deployment. 5G must use the primary MW band in addition to the complementary millimeter-wave band. This spectrum must be migrated to 5G, or poor coverage can be expected. In addition, among the new features heralded by 5G, D2D transfers could have a prominent role. The adoption of D2D transfers is driven by safety and disaster systems, applications requiring low latency, and network traffic offloading. M2M is the engine for the future IoT; CoMP technology and carrier aggregation will also be transferred for better spectral efficiency and QoS. Beamforming and M-MIMO are key enabling technologies for the millimeter-wave band, so their transfer can be taken for granted.

On the Way Toward 5G

The trend in future mobile networks (5G) has shown a different pattern from that of existing networks, because the main objective has changed from enabling users to connect wirelessly to the Internet to enabling massive numbers of users and devices to seamlessly connect in smart cities (IoT) by 2020 and beyond (www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx).

At WRC 2015, the main objective focused on adding extra spectrum for mobile communications below 6 GHz. However, the massive growth in global mobile traffic cannot be fulfilled by this addition alone. 5G will need to access and extend its operation to the millimeter-wave band to enable multi-Gbps data rates. Therefore, it was decided that at WRC in 2019, the identification of bands above 6 GHz will be included.

The ITU-R Working Party 5D will define the technical performance requirements for next-generation systems and develop an evaluation process to occur between 2016 and 2017. According to the ITU timeframe, standardization and proposals will be studied in 2018. From 2018 through 2020, an evaluation will be held by external groups, and the definition of new radio interfaces will be included in the most recent International Mobile Telecommunication system (IMT-2020), similar to what happened for IMT-2000, and IMT-Advanced. Table 3 shows the difference between 5G and old mobile network generations, listing changes to several features.[13–17]

Table 3. Basic comparison among mobile system generations.

Feature	**1G**	**2G**	**3G**	**4G**	**5G**
Deployment	1980	1990	2001	2010	2020 or beyond (www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx)
Frequency band	800 MHz	900 MHz	2,100 MHz	2,600 MHz	3–90 GHz[15]
Speed	2 Kbps	64 Kbps	2 Mbps	1 Gbps	Higher than 1 Gbps
Technology	Analogue cellular	Digital cellular	Code division multiple access, Universal Mobile Telecommunications System	Long-Term Evolution Advanced, Wi-Fi	Multi-radio access technology, Wi-Fi, Wi-Gig[16]
Services	Voice	Digital voice, SMS, packet (General Packet Radio Service), low-rate data	Higher quality audio and video calls, mobile broadband	High data rate, wearable devices	Very high data rate[13] to fulfill extreme user demands, device-to-device, machine-to-machine, Internet of Things
Multiplexing	Frequency division multiple	Time division multiple access	Code division multiple access	Orthogonal frequency-division multiple access	Orthogonal frequency-division multiplexing, filter bank multicarrier,

	access				nonorthogonal multiple access[14]
Handover	No	Horizontal	Horizontal	Horizontal/vertical	Horizontal/vertical
Switching	Circuit	Circuit/packet	Packet	All packet	All packet[17]
Core network	Public switched telephone network	Public switched telephone network	Packet network	Internet	Internet

Current Development to 5G Realization

Given that current mobile phones operate in frequencies between 0.8 to 2.5 GHz, they are capable of download speeds of only 230 Mbps. Therefore, mobile devices operating in the millimeter-wave band are essential to cope with the higher-speed data transmissions required from 5G. Fujitsu has developed a millimeter-wave prototype receiver small enough to be incorporated into a mobile phone.[3] This receiver has achieved 20-Gbps download speeds. Fujitsu began field-testing in 2016 and will launch the receiver in 2020. Furthermore, IEEE has developed the IEEE 802.11ad standard, which operates at 60 GHz and supports a speed of 7 Gbps within a short distance.[18]

Samsung has announced that it has achieved 7.5 Gbps, the fastest ever 5G data transmission rate in a stationary environment.[19] The company has achieved a stable connection at 1.2 Gbps in a mobile environment from a vehicle at a speed of 100 km/h at 28 GHz. In addition, Nokia has used the 73-GHz carrier with 2-GHz bandwidth to achieve a speed of 10 Gbps with latency around 1 ms.[20] The ITU set a timeframe for 5G systems; its IMT-2020 group reviewed many research proposals and will soon set the first 5G network design.[13]

As the demand for high-speed and low-latency applications increases dramatically, the 5G system should have the technology and flexibility to meet these those requirements and support multifold increases in network capacity and connectivity.

The extremely high data throughput and very low latency required from 5G cannot be satisfied only through evolution or modification of the existing 4G network. Therefore, researchers must focus on technologies that would have a major impact on system performance. This will come by introducing radical changes at the base station (component) and network (core and backhaul) levels. The most prominent technologies and aspects that currently have this ability are millimeter-wave band, dense deployment of small cells, D2D, M2M, and M-MIMO with beamforming. With help from these technologies, future wireless systems will include myriad smart features and applications to make 5G the most intelligent and dominant wireless technology thus far.

Acknowledgments

This work is sponsored by the ministry of higher education and scientific research, University of Anbar, Iraq.

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Mobile data traffic has grown substantially owing to the widespread use of data-hungry devices such as smart handsets and laptops. This has encouraged researchers and system designers to develop more efficient network designs. The authors review the technologies that can support speeds of multiple Gbps for future fifth-generation (5G) networks. They examine the many challenges, problems, and questions that arise in the research and design stage, and conclude that the

anticipated high-traffic demands and low-latency requirements stemming from the Internet of Things (IoT) and machine-to-machine (M2M) communications can be met only with radical changes to the network paradigm. These include harnessing the millimeter-wave band for the dense deployment of small cells. Future wireless systems will include myriad smart features and applications to make 5G the most intelligent and dominant wireless technology thus far.