The Evolving 5G Landscape

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1 Introduction: Overview of 5G

The "G" in wireless telephony is nominally associated with the generational changes in technologies and services in the carrier domain. The current iteration of 4G is a well-understood evolutionary implementation of the wireless mobile telecommunications network, enabling the wireless Internet and cloud capabilities available on contemporary mobile handsets and devices. Extending this framework, the fifth generation of the mobile broadband network, or 5G, will drive four primary usage models:

1. Enhanced Mobile Broadband (eMBB)
2. Ultra-Reliable Low Latency Communications (uRLCC)
3. Massive Machine Type Communications (mMTC)
4. Ultra-High Speed, Low Latency Communications (uHSLLC)

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S. McClellan (ed.), *Smart Cities in Application*,
https://doi.org/10.1007/978-3-030-19396-6_7

To achieve these functional models, the standards body for cellular communications (3GPP) has specified additional spectrum for 5G to support diverse workloads, as shown in Fig. 1. The figure provides a general overview of 5G "Phase 1" and "Phase 2" application characteristics in terms of data rate and latency. Phase 1 defines several new usage scenarios including eMBB, uRLLC, and mMTC which enable, improve, or extend contemporary applications. Next-generation applications enabled by new service classes, such as Ultra-High Speed Low Latency Communications (uHSLLC), could emerge in Phase 2 and beyond. As a result, 5G will provide a "hyperconnected environment" where data will be accessible to users in a reliable, flexible, and secure way independent of the device type, underlying architecture and OS environment [4, 5]. Software-Defined Networking (SDN), Network Function Virtualization (NFV), and virtualization of compute resources will drive changes to fundamental principles of the service provider's network structure, enabling a more decentralized architecture.

Applications which leverage the improvements to mobile broadband of eMBB include Augmented/Virtual Reality (AR/VR), cloud-based remote office functionality, and high-definition or broadband audio/video, as well as certain mission-critical and complex remote applications.

Applications which leverage the enhanced support for machine-to-machine (M2M) communications of mMTC include various approaches to the Internet of Things (IoT) as well as "Smart Home" and "Smart City" technologies which range from home security to intelligent water management to automated pollution

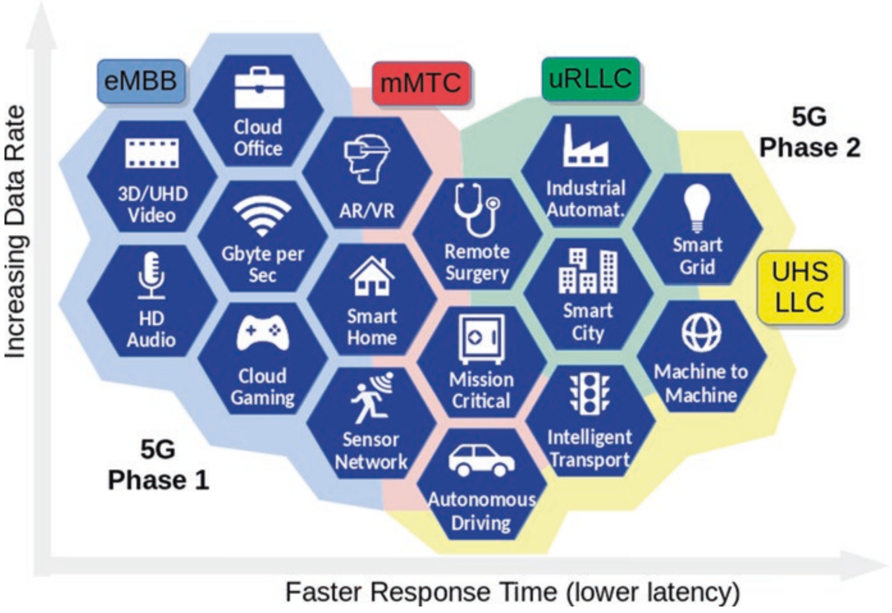

Fig. 1 Primary usage models of 5G, with examples of applications. Adapted from [1–3]

management and other applications important to the management of growing municipalities.

Applications which leverage the reliability and low latency of uRLCC include autonomous vehicles and intelligent transportation, including "V2X" or vehicle-to-everything communications, real-time, remote healthcare applications ("telemedicine"), and the emergence of the tactile Internet.

The flexibility of the virtualized architecture of 5G will also disrupt the enterprise datacenter, providing flexibility in network configuration and load balancing based on usage models, traffic types, and end-point mobility. Radical new use cases for 5G-capable systems will impact future designs for client devices, in areas such as power/spectrum management, optimized user experience across heterogeneous networks, the "always on" potential of cloud-based storage, and the "always-changing" potential of fog-based wireless interaction. As a result, new requirements for client devices will emerge to meet the rapidly changing needs of consumers and businesses [6], as shown in Fig. 2.

While 5G is not yet fully specified, there are several areas of intense activity, including end-to-end latency requirements, in-building service requirements, spectral reuse and propagation issues, and the always-present "Quality of Service" (QoS) problem. While standards are being finalized, the industry will see a phased, multi-year deployment of 5G with end devices (smart handsets) launched in trials with major carriers [7]. The following sections discuss some of the most important aspects of 5G, including issues associated with applications/services, air interface/spectrum requirements, and virtualization/software-defined subsystems.

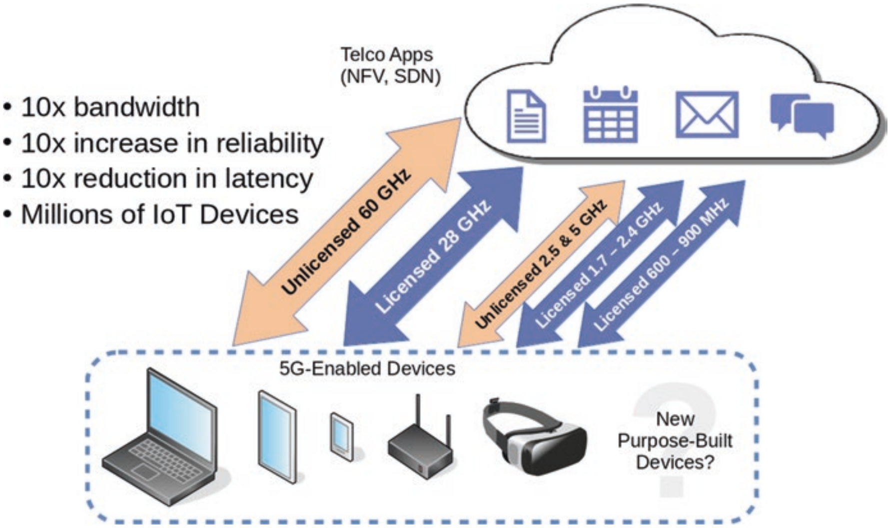

Fig. 2 New use cases for 5G systems will impact the design of client devices

1.1 Mission-Critical Services

Connecting mission-critical industries with ultra-reliable communications is a key driver of 5G. 5G will connect new industries and enable new services including mobile health and telemedicine systems, public safety/disaster alert, remote control of heavy machinery, factory automation, sustainable cities, and “smart” electrical generation and distribution.

Improved network capabilities will drive new use cases around mission-critical services and enterprise requirements, and will incorporate highly mobile applications. The planned high bandwidth, low latency features of 5G will drive more compute to the edge in a “distributed virtual cloud,” enabling richer end user experiences, data analytics, content delivery, and value added services in addition to mission-critical connectivity for new or enhanced municipal services.

1.2 Software-Defined Infrastructure

Network function virtualization (NFV) and software-defined networking (SDN) tools and architectures are enabling service providers to reduce network costs, simplify deployment of new services, and scale network growth and expansion. Other initiatives include the virtualization of the radio-access network, as well as development of cloud radio-access network architectures. This enabler addresses the need for computing beyond the edge and from the cloud infrastructure and the need for software solutions to enable such a service. Enhanced security and data management architectures will also play an important role for this enabler.

The software-defined infrastructure “stack” is typically composed of several interoperating hardware and software layers. These layers include the *physical infrastructure*, one or more *virtualization layers*, a suite of *software-defined capabilities* or functions, and an overarching *management function* which binds the layers of the stack together [8].

The *physical layer* of the stack leverages a variety of “real” devices and systems, including computers (servers), network storage systems, network-resident nodes (switches, routers), as well as the operating systems, firmware, subsystems, and other software components necessary for proper function in a networked environment, and for application-hosting purposes. The software-defined infrastructure which leverages these underlying systems is not directly dependent on specific instances of the hardware, so the supporting infrastructure can be managed, scaled, and deployed independently of the overarching, software-defined system.

The *virtualization layer* of the stack leverages a variety of software components which overlay the physical infrastructure systems and their associated subsystems. This abstraction presents the heterogeneous collection of resources as a homogeneous or “virtual” distributed computing system, complete with all necessary elements required for full operation. Virtualization software is loosely divided into two functional paradigms: complete system virtualization, and application-level virtualization facilities. Complete system virtualization generally provides a selection of well-known, emulated hardware/firmware capabilities, upon which a user or administrator can "install" unmodified operating system(s) and application image(s) which effectively realize a fully functional computer system. Examples of complete system virtualization include the Linux Kernel Virtual Machine (KVM) [9] and the VMWare software suite (e.g., vSphere and the VMWare NSX suite) [10]. Application-level virtualization generally provides a selection of well-known, emulated operating system capabilities, upon which a user or administrator can "run" specially packaged application(s) as long as the application package (or "container") includes all necessary software features (libraries, etc.) which enable the complete function of the application. An example of application-level virtualization facility is Docker [11].

The *software-defined capabilities* of the stack leverage a collection of emulated compute, storage, and networking systems which are implemented by the virtualized layer of computing resources. Automated and semi-automated telemetry, control, and configuration algorithms are deployed as a critical part of the software-defined capabilities. This "orchestration" of the emulated devices, via the virtualization layer, is capable of automatically transforming the underlying resources to respond to contextual requirements, or to enable new/different applications. System context may be prescribed by users via direct configuration of emulated systems, or by abstract description of performance or operating parameters. Deployment, configuration, and monitoring of the infrastructure and virtualized resources is then effected by the orchestrator in much the same fashion as a conductor manages a symphony orchestra in playing sheet music.

The *management function* of the software-defined infrastructure isn't a "layer." Rather, it's a vertical feature which interfaces with all layers, and is common to all telecommunication or computer networks. Management functions typically include a collection of vendor-specific user-interfaces which are used to define operational parameters, deploy and configure software components, and enable provisioning of specialized resources. Management functions also typically include a "marshaling" capability which enables a form of single-point control. In this fashion, management function ensures that necessary infrastructure operations are completed according to desired standards, and that service-level-agreements (SLAs) and performance are maintained during system operation. In some software-defined architectures, embedded configuration facilities for physical and/or virtual systems are abstracted so that a common management interface is presented to the user [12].

1.3 5G Air Interface

The 5G network will support a heterogeneous set of air interfaces, from evolutionary derivatives of current technologies (such as Wi-Fi and Mobile broadband) to new technologies and network architectures which haven't been developed yet.

Challenges remain on the coexistence of Wi-Fi (unlicensed spectrum) with 5G (licensed spectrum) and the potential for deployment of 5G into unlicensed bands (think of this as 5G NR-U). This new connectivity standard will provide multi-gigabit data throughput by using carrier aggregation, massive multi-input/multi-output antennas (MIMO), and simultaneous use of licensed and unlicensed spectrum. Seamless handover between heterogeneous wireless access networks will need to be a differentiated feature of 5G, as well as use of simultaneous radio access technologies to increase reliability, connectivity, and availability.

As part of the overall development of 5G, the 3GPP[1] defined a 5G NR (new radio) specification which operates in spectrum below 6GHz (sub-6GHz … which includes 4G technologies), and above 24 GHz, in the so-called mmWave bands. Operation in the mmWave bands will require the deployment of large numbers of new, small-footprint base stations which are capable of delivering high bandwidth payloads with extremely low latency (<1 ms)[2] to end-point devices and applications. While mmWave technologies can deliver very high data rates, optimizing radio-frequency propagation in these bands is a complex challenge.

Clearly, substantial work remains in the development of standards and coexistence schemes to drive a seamless “intelligent connected end device.” This paradigm will be central in the migration from Wi-Fi and 4G to 5G and a truly pervasive mobile connected environment.

1.3.1 5G as a Catalyst

The requirement for 5G wireless connectivity will provide a catalyst for the convergence of key technology transitions such as Artificial Intelligence (AI), Machine Learning (ML), Augmented Reality (AR), Virtual Reality (VR), the Internet of Things (IoT), and edge-based computing. To enable these applications, the NR specification will be band agnostic—meaning it can be deployed on low, medium, and high bands with no restrictions. The first wave of networks and devices will be classed as Non-Standalone (NSA). The 5G Standalone (SA) network and device standard is still under review by 3GPP, and will emerge in future revisions of the standard, which are known as “Releases.” 5G Releases are briefly described below, and the network transition is diagrammed in Fig. 3.

Release 15 (June, 2018): In R15, additional new spectrum, new protocols, client devices will connect to (new) 5G frequencies for data throughput leveraging the existing 4G packet-core infrastructure. 5G (NSA and SA) will provide increased data bandwidth and connection reliability via two new spectral allocations. As discussed previously, R15 overlaps and extends 4G LTE frequencies from 450 MHz to

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[1] 3GPP, or the “Third Generation Partnership Program,” is the federated, system-level industry standards organization for wireless telecommunications. More information at https://www.3gpp.org.

[2] For comparison, today the QoS Class Identifiers used in LTE specify packet delay values between 50 ms and 300 ms.

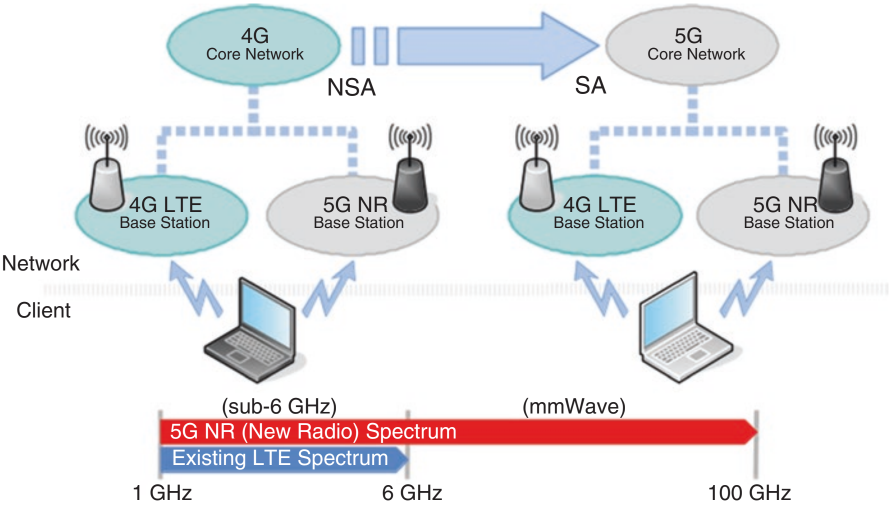

Fig. 3 Diagram of 5G network transition, spectrum, and connections

6 GHz in the sub-6GHz bands, and extends from 24.25 GHz to 52.6 GHz in the mmWave bands.

Release 16 (2019–2020 timeframe): In R16, The 5G network will extend to cover the low-mid and high bands (sub-6GHz and mmWave spectrum) and will be backward compatible with the NSA Network and device deployments. With this Release, carriers will migrate from 5G NSA to an all 5G SA infrastructure in a fashion transparent to the end-users, as diagrammed in Fig. 3.

1.3.2 Coexistence of Licensed and Unlicensed Networks

The expansion of wireless broadband access network deployments coupled with heavy video service usage is resulting in an increased scarcity of available radio spectrum. Cellular technologies and wireless local area networks will need to exist in the same unlicensed spectrum bands. The two most prominent technologies (LTE and Wi-Fi) are based on standards designed to operate in different part of the frequency spectrum and were not designed to coexist in the shared band. A previously fragmented licensed wireless industry has consolidated globally on LTE as the de-facto standard, and wireless Ethernet (Wi-Fi) has dominated unlicensed deployments due to cost and simplicity. 5G will be designed to integrate with LTE networks, and many 5G features may be implemented as LTE-Advanced extensions prior to full 5G availability.

Furthermore, “carrier aggregation” (a key LTE-Advanced feature) optimizes available spectrum more effectively, increasing capacity and increasing throughput. Deployment of LTE in unlicensed frequency bands will enable “neutral hosts” to offer “Enterprise LTE” as a service to enterprises and large campuses such as public venues, hospitals, and industrial facilities. A primary concern in coexistence of licensed and unlicensed networks is that devices capable of “license-assisted access” (LAA) will unfairly use the 5GHz band and other unlicensed bands due to the following reasons:

- Not implementing “listen before talk” (LBT) algorithms. For example, LTE-U does implement a carrier sense algorithm to set duty cycle for transmission but after then implements a fix interval transmission that can effectively jam a Wi-Fi signal thereafter.
- Parameters for the interval between carrier sensing and transmitting and duty cycle can be set aggressively, causing LTE to gain unfair access to shared spectrum.
- Listen level (i.e., carrier sense thresholds) for LTE-U implementation is set in the −62 dm range, while Wi-Fi access points listen down to −85 dBm. Thus it can be said Wi-Fi access points are more considerate of other, lower powered Wi-Fi access points.

1.3.3 Spectrum Reuse

The continued increase in the number of smart mobile devices and the emerging classes of IoT smart end points is driving the need for additional spectrum for cellular communication. Cellular spectrum allocation to each carrier is fixed, which requires new approaches to spectrum sharing to meet demand. As a result, 3GPP is supporting research in three key areas: (1) Spectral efficiency improvement, (2) Higher network cell density, and (3) Evaluation of underutilized spectrum resources.

These research areas require radio resources and mobility management techniques across both homogeneous and heterogeneous spectrum which increases both system complexity and cost. Spectrum sharing may occur between an incumbent commercial usage and a secondary commercial usage. An example of this is TV White Space (TVWS) as a commercial use, sharing this with Wi-Fi usage in a public–private application. In the case of 5G networks, governments, wireless vendors, carriers, operators, and standards associations worldwide are driving toward a common solution. However, with the range and scope of the use cases and functional requirements, network operators will most likely need to deploy a set of solutions across selected low and high band spectral allocations, which would include exclusive-use licensed, shared-access, and unlicensed spectrum.

All radio spectrum is reused in some way and historically, regulatory authorities have managed spectrum by organizing it into bands (fixed, land, mobile) with specific usage, and then channels within bands. Essentially there are a number of methods for spectrum reuse:

- Frequency as the primary reuse mechanism parameter with output power limitations, and transmission masks as additional reuse parameters. Access protocols provide real-time reuse using frequency division multiple access (FDMA).

- Spatial reuse leverages geographic separation as the primary parameter using controlled radiation patterns.
- Temporal reuse uses time as the primary parameter, using time slots with access protocols for time division multiple access (TDMA).
- Code space reuse uses orthogonal pseudorandom spreading sequences for code division multiple access (CDMA).
- Hybrid reuse—which combines space, time, and frequency parameters.

5G will likely use new hybrid combinations of these reuse techniques, combining cognitive radio technologies and geolocation-based techniques for spectrum sharing. Additionally, 5G networks will require additional spectrum in both low and high bands, more small cells and more ad-hoc small cells with multiple technologies. As a result, LTE Advanced will continue to evolve in bands below 6 GHz, in a backwards compatible way. In parallel, new radio access technologies will emerge in cm/mmWave bands (e.g., 28 GHz, 37–40 GHz, and 60+ GHz) and in mid-band microwave (3.4–4.2 GHz) with no backward compatibility constraints [13].

2 Attributes, Use Cases, and Market Drivers

In general, 5G networks are being designed to handle more connections, faster speeds, and lower latencies than conventional network architectures. These key attributes, as well as other important characteristics, are summarized in Fig. 4.

As a simple qualitative comparison with current-generation wireless technologies, the 5G network will handle 100× more endpoints (over 20 billion user devices and over 1 trillion terminals), and will offer a 100× increase in peak theoretical speeds (more than 10 Gbps[3]). These improvements in service will necessarily have to be delivered in a highly reliable fashion ("five 9's," or less than a few seconds of downtime per year), and at high ground speeds (velocities >300 miles/h). This is quite a tall order!

Additional key requirements addressed by 5G technologies include:

- 10× reduced end-to-end latency (<5 ms end-to-end latency, <1 ms over-the-air latency),
- 20× higher user data rates over 4G (5—20 Gbps peak data rates),
- 1000× higher mobile data volume per area,
- uniform experience regardless of user location ("edgeless"), and
- 10× longer battery life for low power machine-to-machine communications.

For a specific technology reference, Table 1 outlines the relative characteristics for each of the three primary communication media types over the past couple of decades. Note that 5G is comparable to 10 Gbps wired Ethernet which is

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[3] Gbps = gigabits per second.

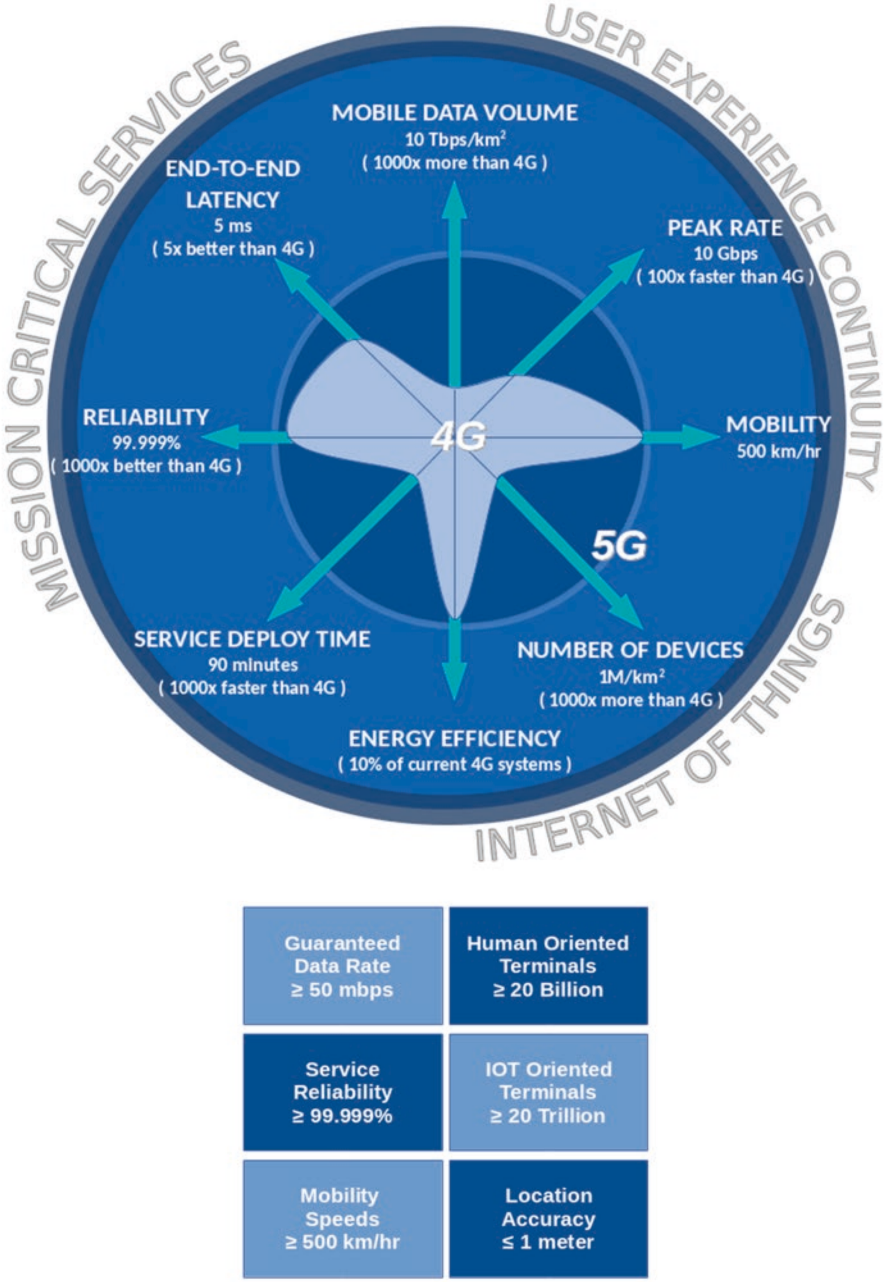

Fig. 4 Key characteristics of 5G. Adapted from [3]

Table 1 Reference points for networking technologies

	Ethernet		Wi-Fi		Cellular	
Media types	Standard	Data rates	Standard	Data rates	Standard	Data rate
1980s	802.3	10 Mbps			1G	24 Kbps
	802.3u	100 Mbps				
1990s	802.3ab	1 Gbps			2G	500 Kbps
			802.11b	11 Mbps		
2000s	802.3an	10 Gbps	802.11 g	54 Mbps	3G	2 Mbps
			802.11n	600 Mbps		
2010s	802.3bj	100 Gbps	802.11 ac	850 Mbps	4G	100 Mbps
			802.11ad	3 Gbps		
2018/20s	802.3bs	400 Gbps	802.11ax	1.2 Gbps	5G	10 Gbps
			802.11ay	7 Gbps		

currently used in today's datacenters, and at 10 Gbps a 1.25 GB movie downloads in roughly 1 s.

5G is positioned to support a fully mobile and connected environment. Due to the "always-on" context, socio-economic transformations will be enabled across all segments of society. Technologies from both the traditional carrier domain (licensed spectrum) and non-carrier domains (unlicensed spectrum[4]) will be united in a single, end-to-end networking paradigm. As a result, the business model for 5G is extremely complex. Conventional network operators will not be able to charge customers for increasing data usage via current air interfaces and bandwidth-limited networking infrastructures. The emerging model for monetization of 5G is likely to include partnerships and content delivery services with extension to other industries through the expansion of the IoT vertical markets (e.g., automotive, transportation, smart city infrastructures, etc.).

Key opportunities in this new mobile broadband market will include leveraging the multitude of devices available in this "network of networks" to transport data and content in the most cost-effective and efficient manner, based on applications, payload, and latency requirements. The diversity of some of the use cases driving the 5G environment is shown in Fig. 1. Additionally, the commoditization of many important networking technologies as well as the move toward virtualization of compute and network functions enables non-traditional equipment suppliers to play a larger role in the telecommunications ecosystem. As a result, 5G network rollouts will feature an increasingly larger role for original equipment manufacturers (OEMs) from the Information Technology sector (IT). This "hybrid" architecture and ecosystem is diagrammed in Fig. 5.

Additionally, annual surveys of telecom operators [14] reveal that the general areas of mobile connectivity, IoT and machine-to-machine (M2M) connectivity, and low latency applications are the leading drivers for 5G use cases. Not surprisingly,

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[4] Wi-Fi, WiGig, and other emerging technologies.

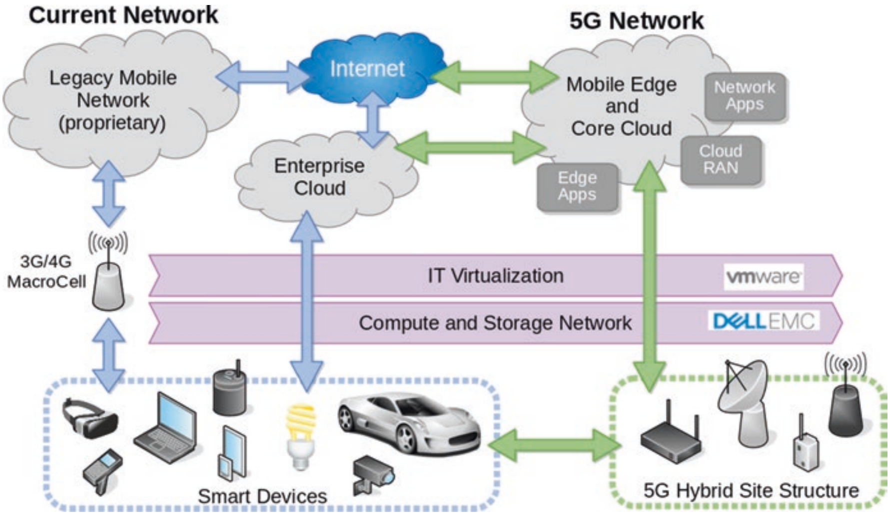

Fig. 5 5G will enable IT OEM suppliers to provide a larger portion of the infrastructure

security concerns vary widely for common use cases, with heightened security demands and challenging implementation requirements expected for ultra-reliable, low latency, and M2M scenarios. In general, network service providers agree that enhancements to mobile broadband, massive IoT/M2M requirements, and applications requiring ultra-reliable/ultra-low latency services will be significantly transformed by the capabilities of 5G networks.

Based on these technical capabilities and features, the emerging use cases that can take advantage of features can be broken down into three key areas that are central to the vision for 5G, and which are discussed in more detail in the subsequent sections. Additionally, a fourth key area will arise as the volume of information necessarily increases—artificial intelligence, machine learning, and data analytics.

1. Mobile Connectivity
2. Internet of Things (IoT)
3. Mission-Critical Services

2.1 Mobile Connectivity

Mobile connectivity continues to be one of the main drivers for the next-generation broadband network. As the demand for mobile connectivity increases at an astounding 50–60% compound annual growth rate (CAGR), the mobile broadband requirements for 5G extend far beyond basic Internet access and covers connectivity in very

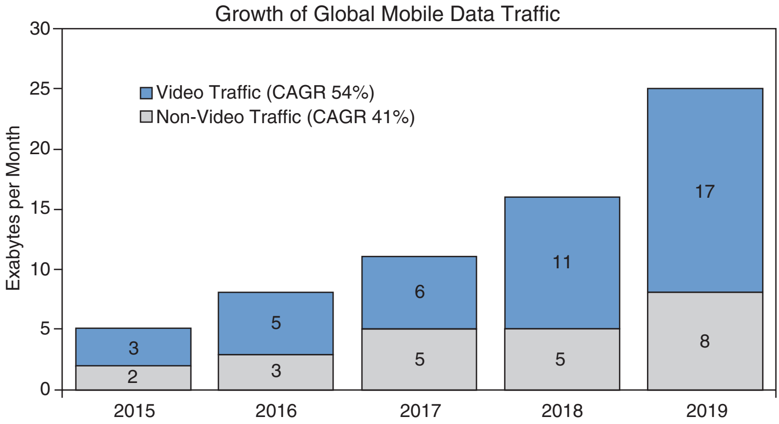

Fig. 6 Predicted mobile data traffic growth toward 2020, in exabytes per month. The trend shows a combined 53% compound annual growth rate (CAGR). Adapted from [15]

dense environments, ultra-high speed connectivity, and access to rich media anytime, anywhere. According to most sources, and as depicted in Fig. 6, the growth in mobile data traffic will be driven by the popularity of applications with requirements for video streaming [16], including ultra-high-definition media, virtual conferencing, immersive virtual reality, tactile Internet, and immersive gaming.

Reliable and persistent connectivity in challenging situations such as high mobility applications, very dense or sparsely populated areas, and the journeys covered and supported by heterogeneous networks and technologies. As content continues to migrate to the Internet, 5G will accelerate the mobile Internet for delivery of multimedia, voice, video, and services in this new hyperconnected wireless environment [5]. 5G addresses these challenges through the paradigm of "eMBB," or enhanced Mobile Broadband which leverages LTE installed infrastructures (voice/control).

With the increased bandwidth and low latency features of a 5G mobile network environment, service providers will take advantage of these features to deliver better interactive experiences with real-time applications that will run on the edge of their networks. It will be possible to leverage software-defined Wide Area Networks (SD-WANs) and network function virtualization software to deliver services from virtual data centers hosted in the cloud. The high bandwidth features and low latency of 5G will support enhanced features and applications such as AR/VR, IoT, and real-time multimedia and location based services that are deployed at the edge of a service provider's network.

It is important to remember that devices connected to 5G networks are not going to be less intelligent than they are today (perception is that all things will come from the cloud given data rates/low latency), with less storage and computing capabilities. With the addition of more AI/ML features to end-point/client compute devices, 5G capable devices will have more advanced features and computing capabilities than they have today, with more sensor and intelligence that enables them to become more powerful and capable edge devices. More intelligence, more computing will migrate from the cloud down to the edge devices, driving more demand for local storage (big data analytics), more sensors, and intelligence on these devices [15].

Converged Compute and Mobility

As 5G networks deliver very high throughput and very low latency communications, devices will be able to leverage distributed and cloud computing solutions. This will enable more compact and thin end user devices.

In addition, deployment of small cells in dense campus environments together with mobile edge compute solutions will enable local LTE networks used exclusively by enterprises and large campuses (public venues, hospitals, industrial facilities, etc.). By converging local compute and carrier-grade mobility "Enterprise LTE" networks will enable low latency and high privacy networking solutions.

Market Landscape:

- Enterprise mobility market is set to rise at 25% CAGR through 2022 as more enterprise users prefer device flexibility.
- Enterprises will have to deliver 300% more wireless access points to provide future Internet performance that is similar to the performance in the pre-BYOD era.

Enhanced Video

5G Networks are expected to deliver 10× more bandwidth which will drive enhanced video experience in various form factors and enable 360 Conferencing, UHD Streaming, and VR applications.

Market Landscape:

- By 2019, ~70% of global Internet consumption will be video content.
- 4 K technology market is expected to grow at a CAGR of ~22% from 2015 to 2020.
- Cloud-based video conferencing market to grow at a CAGR of ~40% by 2019.

Connectivity Everywhere

5G is expected to connect low ARPU areas through non-traditional access points, such as drones, balloons, satellites, operating in both unlicensed and licensed spectrum. 5G networks will also be able to increase the network capacity in dense areas, like stadiums, airports, open air assemblies, etc., by enabling more spectrum for access, deploying small cells, and dynamically managing the network resources via leveraging virtualization and SDN technologies together with mobile edge computing.

Market Landscape:

- There are still >4 billion people not connected to the Internet, most of them in the developing world.
- By 2020 mobile Internet penetration rates in developing markets will reach 45% from 28% today. However, most of the growth will be in small form factor handsets.
- By 2020, small cells are expected to carry a majority of traffic with overall data volume expected to grow up to 1000 times compared to 2010.

Seamless Mobility

Mobile devices moving between heterogeneous networks while maintaining continuous connection will be a key requirement for 5G networks. Heterogeneous network technologies with considerable emphasis include disparate unlicensed networks (e.g., Wi-Fi) and multiple tiers of licensed cellular networks (Macro, Mico, and Femto cells). These network paradigms all utilize various types of physical-layer communications schemes, media access controls, and management architectures.

To-date, mobility in Wi-Fi networks has been limited, although newer technologies are being developed to address issues such as roaming (802.11r), FILS (802.11i), and seamless authentication (Passpoint). Multi-layer connection control based on end device speed will allow all endpoints to become more efficiently connected to the broadband network, and minimize the need for handoffs of a single connection between multiple network instances.

Market Landscape:

- Smart connection managers that can aggregate traffic across licensed and unlicensed networks as well as select optimal connection contexts will help system and device providers differentiate via improved connection experiences.
- These new smart connection managers will also improve connection resilience and reliability for IoT devices.

2.2 Internet of Things

The ability of 5G networks to connect massive number of endpoints is targeted for the growing Internet of Things (IoT) market, which is dominated by “headless” devices tasked with automating various processes. 5G provides a robust platform to support a massive number of sensors and actuators with stringent energy and transmission constraints. The delivery of IoT systems, characterized by the need to integrate the management of massive number of connected devices, will continue to drive the growth and expansion of the 5G network, offering a potential economic impact of $4–11 T a year in 2025 [17], with most applications dependent on cellular connectivity.

Some of the key use cases driving 5G technology in IoT scenarios include connected cars and autonomous vehicles, smart homes, sensor networks, surveillance applications, continuous health monitoring, infrastructure monitoring, and modernization of utilities and municipal services. These challenges are addressed through the 5G paradigm of “mMTC,” or massive Machine Type Communications.

Intelligent Transportation Systems

Highly reliable and low cost 5G technologies will enable connecting transportation systems for logistics and vehicle-to-vehicle communication applications.

Market Landscape:

- A quarter-billion connected vehicles will be on the road by 2020, with new vehicles increasing the proportions of connected cars.

- Embedded connectivity and multiple types of network options will dominate the connected car market, making automobiles effectively mobile data and entertainment centers.

Smart Society

5G networks will support long range, low cost, and low power technologies that will enable smart city applications, such as intelligent traffic control and smart parking solutions.

Market Landscape:

- Regulatory initiatives such as smart meters estimate an 80% penetration by 2020 are driving rapid adoption of data analytics for municipal applications. The increasing number of intelligent vehicles will propel initiatives of this nature.
- Services in the municipal space result in low average revenues per-user (ARPU) and are generally hard to scale without appropriate partnerships. As a result, additional public/private partnerships for virtualized infrastructure services may emerge.

Sensor Networks

Low power and low cost solutions driven by 5G networks will enable cellular connectivity on devices, such as wearables, smart meters, and environment monitoring sensors.

Market Landscape:

- Shipments of smart wearables will continue their rate of growth (28% CAGR since 2015), exceeding the estimated 215 M units in 2019.
- This is a highly crowded market with several players from Google (smart glass, Nest thermostat) to location service providers. The data produced by sensors and other devices connected to the 5G network will propel new approaches to data mining and analytics.

2.3 *Mission-Critical Services*

Some important applications and usage models require very high levels of reliability, global coverage, and/or very low latency. These areas have traditionally been supported by dedicated, application-specific networks, such as public safety and emergency services. 5G will provide a more efficient platform for connecting existing mission-critical services such as mobile health and telemedicine systems, public safety/disaster alert applications, remote control of machinery or systems in dangerous conditions, factory automation, municipal sustainability initiatives, and the Smart Grid. The 5G network’s use of mmWave spectrum will reduce the latency and improve response time of new mission-critical operations such as autonomous vehicle management, remote robotic surgery, and precise location services. These challenges are addressed through the 5G paradigm of “uRLLC,” or Ultra-Reliable Low Latency Communications.

High Reliability Communications

5G networks will deliver 10× reduction in end-to-end latency, peak data rates of 10 Mbps, higher reliability, and support for mobility applications up to 500 km/h. This will enable more robust communication services for disaster recovery and public safety applications.

Market Landscape:

- The market for disaster recovery as a service (DRaaS) is estimated to grow from \$1.4 Billion in 2015 to over \$12 Billion in 2020, at a CAGR of 53%. This market will emerge as a niche segment, with high margins.
- Rugged device form factors are most suitable for this usage model, with specialized software, registration, and interconnection services increasing due to management/monitoring requirements.

Industrial Controls

Flexible network slicing and virtualization of the network core will enable 5G networks to support diverse workloads and applications based on the needs of bandwidth, latency, and capacity. The Telco and service provider networks will need to transform to an open virtualized flexible and agile models for these and new workload types.

Tele-Health

High data rates, low latency, and high reliability networks enabled by 5G networks will enable new applications, such as tele-health applications, such as remote surgery, distant care, and support for a tactile Internet.

Market Landscape:

- The market for tele-health applications will exceed \$35B by 2020, growing at a CAGR of over 14% between 2015 and 2020. The mobile health market will increase beyond \$18 B, growing at an estimated 40% for the next several years.
- Regulations and highly customized needs make tele-health a specialist segment, with high margins and substantial governmental oversight providing additional data analytics opportunities.

2.4 AI/ML and Big Data Analytics

There are a number of key emerging technologies that are changing the information and communications ecosystem—including 5G, Wi-Fi6, AI/ML, AR/VR, and IoT. 5G is a pivotal platform that will drive and enable a hyperconnected society and accelerate innovation and widespread adoption of these technologies and applications and the combination of these over the next number of years will have a dramatic influence on innovation and vertical industries that depend on the IT and telecom industries and services—such as user experiences in communication, human-to-machine interaction, real-time applications, multimedia, and digital content generation and delivery.

Market Landscape:

- The scale required for IoT will drive a longer term requirement for additional capacity as well as bandwidth on demand. Quality of Service (QoS) requirements for many IoT-enabled services will produce new avenues for value and differentiation.
- The transition to a software-defined infrastructure will leverage the capabilities of compute, networking, and storage virtualization to drive new capital and operational business models. Simultaneously, infrastructure changes based on 5G mmWave features will lead to a transformation of municipal network and carrier business models.

3 Conclusions

5G will be the first end-to-end cellular networking architecture which is fully software-defined from the edge radio though to the core. It has being designed to provide significant increases in mobile bandwidth, low latency, network capacity enabled by a disaggregated, virtualized network architecture [18]. These critical architecture features form the network platform for new innovative business, operational, and technology outcomes across all segments of society enabling a more connected environment between humans, machines, and things.

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