

Review Article

Practical Aspects for the Integration of 5G Networks and IoT Applications in Smart Cities Environments

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Both 5G cellular and IoT technologies are expected to see widespread deployment in the next few years. At the practical level, 5G will see initial deployments in urban areas. This is perhaps fortuitous from an IoT perspective, since many “mainstream” applications of IoT will support Smart Cities, Smart Campuses and Smart Buildings. Bandwidth demand for a number of Smart City applications is the main driver for enhanced mobile broadband (eMBB)-based 5G services in general, and new-generation 5G IoT applications, in particular. In turn, the use of the millimeter wave spectrum is required to enable 5G cellular technologies to support high data rates. Millimeter wave solutions, however, impose a requirement for small cells. Generally, an implementer tries to use one or a small handful of IoT technologies; preferably, and for managerial simplicity, the implementer would want to use a cellular/5G IoT technology for all nodes, whether indoors or outdoors, instead of a heterogeneous mix of various IoT technologies that have evolved over the years. This overview paper discusses a number of practical issues related to 5G-based IoT applications, particularly in Smart City environments, including the need for small cells, the transmission issues at millimeter wave frequencies, building penetration issues, the need for Distributed Antenna Systems, and the near term introduction of pre-5G IoT technologies such as NB-IoT and LTE-M, these being possible proxies for the commercial deployment and acceptance of 5G IoT.

1. Background

As the second decade of the 21st century comes to a close, we are witnessing an expansion of urban ecosystems, as populations continue to sustain the transition from rural and some suburban areas into large urban areas, driven by economic opportunities, demographic shifts and generational preferences. Seventy percent of the human population is expected to live in cities by the year 2050, and there already are more than 400 cities with over one million inhabitants [1]. Societal movement of people is a basic human existence dynamic and is one of the key mechanisms that drives the growth of cities. Yet, especially in the Western World, cities often have aging infrastructure, including roads, bridges, tunnels, rail yards, and power distribution plants. It follows that new technological solutions are needed to optimize the increasingly-scarce infrastructure resources, especially given the population growth and the limited financial resources available to most cities and municipalities. When cities

deploy state-of-the-art Information and Communication Technologies (ICT) on a large-scale, including Internet of Things (IoT) technologies, they are referred to as being “Smart Cities”.

Livability, infrastructure management, asset management, traffic transportation and mobility, logistics, electric power and other utilities, and physical security are the key aspects of a city’s operation. IoT technologies offer the opportunity to improve resource management of many assets related to city life and urban Quality of Life (QoL), including Intelligent Transportation Systems (vehicular automation and traffic control), energy consumption, the flow of goods, smart buildings, space/occupancy management (indoors and outdoors), pollution monitoring (for example from automobile traffic, factories, incinerators, crematoria), resource monitoring and sensing, immersive services (including wearables and crowdsensing), physical security, sustainability, and the greening of the environment. Smart City IoT applications cover indoor and outdoor applications; they also span



FIGURE 1: Illustrative example of Smart City resources that can benefit from IoT in general and 5G cellular in particular.

stationary and mobile end-nodes and sensors. There is an extensive body of literature on this topic; some references of interest include but are certainly not limited to [2–12]. Up to the present, the IoT has been mostly utilized for supporting a large population of relatively low-bandwidth sensing devices, and where the sensing devices are typically deployed in stationary locations (e.g., electric meters, building management systems, meteorological weather stations). However, video-oriented applications that require streams ranging up to Ultra-High Definition resolution are emerging (e.g., surveillance, physical security). In the evolving IoT environment, the endpoint devices include environmental and situational sensors, vehicles, wearables, drones, robots, and Virtual Reality gear. In some applications IoT actuators are also utilized to control the physical ecosystem in response to a sensed set of data or some analytical calculation – for example, changing the barriers and signs on a road to reverse traffic lanes during the day; or, changing the parameters of a pump to control water or sewer flows. Figure 1 depicts graphically some of the common Smart City applications.

While a large number of definitions and descriptions of the IoT exist, this is one definitional/descriptive quote

from the author’s previous work, which we utilize here: “The basic concept of the IoT is to enable objects of all kinds to have sensing, actuating, and communication capabilities, so that locally-intrinsic or extrinsic data can be collected, processed, transmitted, concentrated, and analyzed for either cyber-physical goals at the collection point (or perhaps along the way), or for process/environment/systems analytics (of a predictive or historical nature) at a processing center, often “in the cloud”. Applications range from infrastructure and critical-infrastructure support (for example smart grid, Smart City, smart building, and transportation), to end-user applications such as e-health, crowdsensing, and further along, to a multitude of other applications where only the imagination is the limit” [13–27]. According to the Global System for Mobile Communications Association (GSMA), between 2018 and 2025, the number of global IoT connections will triple to 25 billion, while global IoT revenue will quadruple to \$1.1 trillion [28]; others offer higher numbers (e.g., according to Statista there will be about 80 billion IoT devices worldwide in 2025 [29]).

5G (5th Generation) is the term for the next-generation cellular/wireless service provider network that aims at

delivering higher data rates -- 100 times faster data speeds than the current 4G Long Term Evolution (LTE) technology -- lower latency, and highly-reliable connectivity. In a sense, it is an evolution of the previous generations of cellular technology.

Smart Cities do not depend on any unique or specific IoT technology per se, but include a panoply of IoT technologies, such as mission-specific sensors, appropriate networks, and function-and-use-efficient analytics, these often in the cloud. Wireless connectivity plays an important role in the utility of this technology, especially at the geographic scope of a large or even medium-size city. For practical reasons wireless is also important in Smart Campus and Smart Building applications. Table 1 identifies a number of Smart City challenges and needs, possible IoT-based solutions, wireless requirements, and the applicability of 5G solutions. 5G IoT is *licensed cellular IoT*. In this table “low bandwidth” equates to 200 kbps or less, “medium bandwidth” equates to 200 kbps to 2 Mbps, and “high bandwidth” equates to more than 2 Mbps. Some IoT applications entail periodic “batch” communication while other applications require real-time communication; in the table “low latency” means real-time and “medium latency” means 1-to-5 seconds. Table 2 provides a snapshot of key wireless technologies that are applicable to the IoT environment. A number of wireless technologies are available, each with its specific applicability and functionality. The direct use of traditional cellular services (e.g., 4G/LTE networks) is not optimal for IoT applications, both for cost and nodal power-consumption reasons. Furthermore, these services are not ideal for a number of IoT applications where a small amount of data is transmitted infrequently (e.g., electric, gas, or water meters for reading). Node density is also an issue. Cellular IoT solutions endeavor to address low-power, low data rate requirements. Several iterations and alternatives solutions have emerged in recent years (e.g., Cat1/Rel 8, Cat 0/Rel 12, Cat-M/Rel 13, EC-GSM, and NB-IoT/Rel 13). The 5G IoT system is the next evolutionary step, perhaps also affording some simplification and technology homogeneity.

Figure 2 depicts the pre-5G and the 5G IoT connectivity ecosystem, which is further elaborated in the rest of this paper. The figure illustrates a typical case of Wi-Fi (in-building) aggregation of sensor data for a handoff to the cloud over a traditional router; it illustrates the use of Low Power Wide Area Network (LPWAN) overlay technologies such as LoRa and Sigfox; it shows the use of pre-5G IoT technologies; and then illustrates the use of 5G IoT in a native mode, or in a more realistic Distributed Antenna System (DAS)-assisted mode.

This review, position and assessment paper provides an overview of salient 5G features and then discusses some practical design issues applicable to the IoT. A lot of the important 5G IoT information is included in the figures and tables. This paper is not intended to be a full 5G overview per se, nor a discussion of IoT, for both of which there are many references (e.g., [30–34] for 5G, and close to one hundred books on the IoT topic alone).

2. 5G Concepts and Technology

5G cellular networks are now starting to be deployed around the world, as the underlying standards and the system-wide technology become more mature (the term “*International Mobile Telecommunications-2020 [IMT-2020]*” is also used by the standards bodies.) Industry observers predict that societal developments will lead to changes in the way communication systems are used and that these developments will, in turn, lead to a significant increase in mobile and wireless traffic volume; such traffic volume is expected to increase a thousand-fold over the next decade. Observations such as this one are common in the literature positioning the technology: “*Unlike previous generations of mobile networks, the fifth generation (5G) technology is expected to fundamentally transform the role that telecommunications technology plays in the society*” [34].

The 5G system expands the 4G environment by adding New Radio (NR) capabilities, but doing so in such a manner that LTE and NR can evolve in complementary ways. As it might be envisioned, a 5G system entails devices connected to a 5G access network, which in turn is connected to a 5G core network. The 5G access network may include 3GPP (3rd Generation Partnership Project) radio base stations and/or a non-3GPP access network. The 5G core network offers major improvements compared with a 4G system in the area of network slicing and service-based architectures (SBAs); in particular, the core is designed to support cloud implementation and the IoT. 5G systems subsume important 4G system concepts such as the energy saving capabilities of narrowband IoT (NB-IoT) radios, secure low latency small data transmission for low-power devices -- low latency is a requirement for making autonomous vehicles safe -- and devices using energy-preserving dormant states when possible. Network slicing allows service providers to deliver “Network as a Service (NaaS)” to large/institutional users affording them the flexibility to manage their own services and devices on the 5G provider’s network.

Applications driving wireless traffic include but are not limited to on-demand mobile information and high-resolution entertainment, augmented reality, virtual reality and immersive services, e-health, and ubiquitous IoT roll-outs. While 5G technology could still take several distinct service directions, it appears at this juncture that the view favoring a super-fast mobile network, where densely-clustered small cells provide contiguous urban coverage to mobile as well as stationary users, is the approach envisioned by the standards development bodies and by the implementers. It should be noted that in the U.S., upwards of 55 percent of residential users now utilize cellular-services-only at home in place of a landline, and about 30 percent of residential users utilize both, with the trend favoring an eventual transition to the former. Therefore, the evolving 5G systems will have to properly support this growing segment of the market. A goal of 5G networks is to be five times as fast as compared to the highest current speed of existing 4G networks, with download speeds as high as 5 Gbps -- 4G offering only up to a maximum of 1 Gbps. Deployment of 5G networks started in 2018 in some advanced countries, although further developments on fundamentals will continue; naturally, the current

TABLE 1: Key Urban Challenges and IoT-supported Solutions.

Smart City Issue and Requirements	IoT support/solutions	Indoors wireless needed	Outdoors wireless needed	5G applicability	Bandwidth / latency/ reliability
Infrastructure and real estate management.	Networked sensors (possibly including drones) to provide real-time and historical trending data allowing city agencies to provide enhanced visibility into the performance of resources, facilitating environmental and safety sensing, smart parking and smart parking meters, smart electric meters, and smart building functionality.	Y	Y	High	Low/ Low/ Medium
Requirement: monitor status and occupancy of spaces, buildings, roads, bridges, tunnels, railroad crossings, and street signals.					
Livability.	Networked sensors (possibly including drones) to facilitate smart multi-modal transportation, information-rich environments, location-based services, real-time connectivity to health-monitoring resources (e.g. air quality).	Y	Y	High	Medium/ Medium/ Medium
Requirement: Quality of Life, expeditious access to services, efficient transportation, low delays, safety.					
Logistics.	Networked sensors (possibly including drones) to enable the streamlining of warehousing, transportation, and distribution of goods. Traffic management is a facet of such logistical support.	Y	Y	High	Medium/Medium/ High
Requirement: supplying city dwellers with fresh food, supplies, goods, and other materials.					
Physical security.	Networked sensors (possibly including drones and gunshot detection systems) to support IP-based surveillance video, license plate reading, gun-shot detection, bio-hazard and radiological contamination monitoring, face recognition, and crowd monitoring and control.	Perhaps	Y	High	High/ Low/ High
Requirement: security in streets, parks, stations, tunnels, bridges, trains, buses, ferries,					

TABLE I: Continued.

Smart City Issue and Requirements	IoT support/solutions	Indoors wireless needed	Outdoors wireless needed	5G applicability	Bandwidth / latency/ reliability
Power and other city-supporting utilities.					
Requirement: reliable flow of electric energy, gas, and water; optimized waste-management and sewer; safe storage of gasoline.	Smart Grid solutions and sensor-rich utility infrastructure	N	Y	High	Low/ Medium/ High
Traffic, transportation and mobility.					
Requirement: optimized traffic flow, low congestion, low latency and high expediency, low noise, minimal waste of fuel and CO ₂ emissions, safety.	Networked sensors to support traffic flow, driverless vehicles including driverless bus transit, and multi-modal transportation systems. For driverless vehicles sensors will allow high-resolution mapping, telemetry data, traffic and hazard avoidance mechanisms	N	Y	High	Medium-to-High/ Low/ High
Electric and other utility manhole monitoring.					
Requirement: Electric power manholes require monitoring to avoid and/or prevent dangerous situations	Cost-effective and reliable sensors are needed. Technology being investigated by Con Edison in New York city	N	Y	High	Low/ Medium/ High
Pollution monitoring.					
Requirement: monitor emission of dioxins, vaporized mercury, nanoparticles, radiation from factories, incinerators, urban crematoria, especially if these sources are close to train tracks or other wind-turbulence elements (e.g., canyons)	Networked sensors throughout town (or within 10 km of a point source) to monitor toxic, health-impacting emission from point sources including factories, generation plants (if any) and crematoria (if any) [35–46]	N	Y	High	Medium/Medium/ High

TABLE 1: Continued.

Smart City Issue and Requirements	IoT support/solutions	Indoors wireless needed	Outdoors wireless needed	5G applicability	Bandwidth / latency/ reliability
Environmental Monitoring. Requirements: monitor outdoor temperature, humidity and other environmental gases	Sensors to that can be placed in easy-to-deploy locations, e.g., atop existing Smart City light poles to continuously monitor temperature, humidity and other environmental gases	N	Y	High	Low/ Medium/Medium
Flood Abatement. Requirement: Flood and storm drainage control	Distributed ruggedized sensors to monitor Flood and storm drainage to provide early warning and fault detection	N	Y	High	Low/ Medium/ High
Smart City Lighting. Requirement: Conversion to LED lighting and ensuring control via IoT for weather conditions, phases of the moon, seasons, traffic occupancy, and so on	Cities spend large amounts of money yearly for street lighting (usually 1000 street lights per 10,000 inhabitants, and \$125 per year per light for 4662 hours of usage yearly and system amortization.) LED lighting requires 1/3 rd the amount of power for the same amount of luminance. Payback for conversion is now around 5-6 years. Sensors are needed for IoT-directed light management for weather conditions, phases of the moon, seasons, traffic occupancy, and so on	N	Y	High	Medium/ Medium/ Medium

TABLE 2: Key Wireless Technologies applicable to IoT.

Technology	Indoor usability	Outdoor usability	Basic aspects
5G	Yes, perhaps with Distributed Antenna Systems (DASs)	Yes, about 10-15 miles	<ul style="list-style-type: none"> (i) Evolving, not yet widely deployed (ii) Several bands, low latency, high sensor density (iii) Cellular network architecture (iv) Licensed spectrum, 0.01 Mbps in some implementations, battery ~10 years (v) Broadband features available for surveillance/multimedia (vi) Cost-effective (vii) Expected to be available worldwide (viii) Building penetration may need Distributed Antenna Systems (DASs)
NB-IoT (Narrowband IoT)	Yes	Yes, up to about 20miles	<ul style="list-style-type: none"> (i) Several bands, licensed spectrum (ii) LTE-based (iii) 0.1-0.2 Mbps data rates, battery ~10+ years (iv) Low cost, low modem complexity, low power, energy saving mechanisms (high battery life) (v) Does not require a gateway: sensor data is sent directly to the destination server (other IoT systems typically have gateways that aggregate sensor data, which then communicate with the destination server) (vi) Reasonable building penetration (improved indoor coverage) (vii) Large number of low throughput devices (up to 150,000 devices per cell)

TABLE 2: Continued.

Technology	Indoor usability	Outdoor usability	Basic aspects
LTE-M (Long-Term Evolution Machine Type Communications) Rel 13 (Cat M1/Cat M)	Yes	Yes, about 10-20 miles	<ul style="list-style-type: none"> (i) Cellular network architecture, LTE compatible, easy to deploy, new cellular antennas not required (ii) Uses 4G-LTE bands below 1GHz, licensed spectrum (iii) Considered the second generation of LTE chips aimed at IoT applications (iv) Caps maximum system bandwidth at 1.4 MHz (as opposed to Cat-0's 20 MHz), thus is cost-effective for Low Power Wide Area Network (LPWAN) applications such as smart metering, where only small amount of data transfer is required. (v) 1 Mbps upload/download, battery ~10 years (vi) Relatively low complexity and low power modem (vii) Can be used for tracking moving objects (Location services provided through cell tower mechanisms)
LoRa	Yes	Yes (6-15 miles with LOS)	<ul style="list-style-type: none"> (i) Band below 1 GHz (ii) IoT-focused from the get-go (iii) Proprietary (iv) Low power
Sigfox	Somewhat limited	Yes (30 miles in rural environments; 1-6 miles in city environments)	<ul style="list-style-type: none"> (i) Band below 1 GHz (ii) Narrowband (iii) Low power (iv) Star topology

TABLE 2: Continued.

Technology	Indoor usability	Outdoor usability	Basic aspects
Wi-Fi	Yes, 300 feet	To some degree, requires inter-spot connectivity backbone (wired or wireless) (e.g., 802.11ah: distance range up to about 1/2 mile)	<p>(i) Several bands</p> <p>(ii) In 2018 the FCC allowed the expansion of the 6 GHz band to next-generation Wi-Fi devices with 1.2 GHz of additional spectrum spanning 5.925 to 7.125 GHz (current Wi-Fi networks operate at 2.4 GHz and 5 GHz with a few vendors offering 60 GHz “WiGig”, this having a range of 30 feet – IEEE 802.11ad and IEEE 802.11ay.)</p> <p>(iii) High adoption; most (but not all) indoor IoT utilize Wi-Fi; good functionality</p> <p>(iv) Free “air time”</p> <p>(v) Subject to interference: malicious or non-malicious interference (e.g., too many hot spots) could impair the sensor from sending data either on a fine-grain or coarse-grain basis</p>
Bluetooth	Yes, 30 feet	No (or for Personal Area only)	<p>(i) Low bandwidth (2 Mbps)</p> <p>(ii) Used in medical devices and industrial sensors Low power, good for wearables</p> <p>(iii) Usable for Real time location systems with medium accuracy</p>
Zigbee	Yes (30-300 feet)	No (or for Personal Area only)	<p>(i) Low data rate</p> <p>(ii) Industrial and some home applications (e.g., home energy monitoring, wireless light switches)</p> <p>(iii) Low transmit power/Low battery consumption</p>

Note: A few other legacy IoT wireless technologies exist (e.g., Cat 0, Cat 1, EC-GSM, Weightless) but are not included in this table

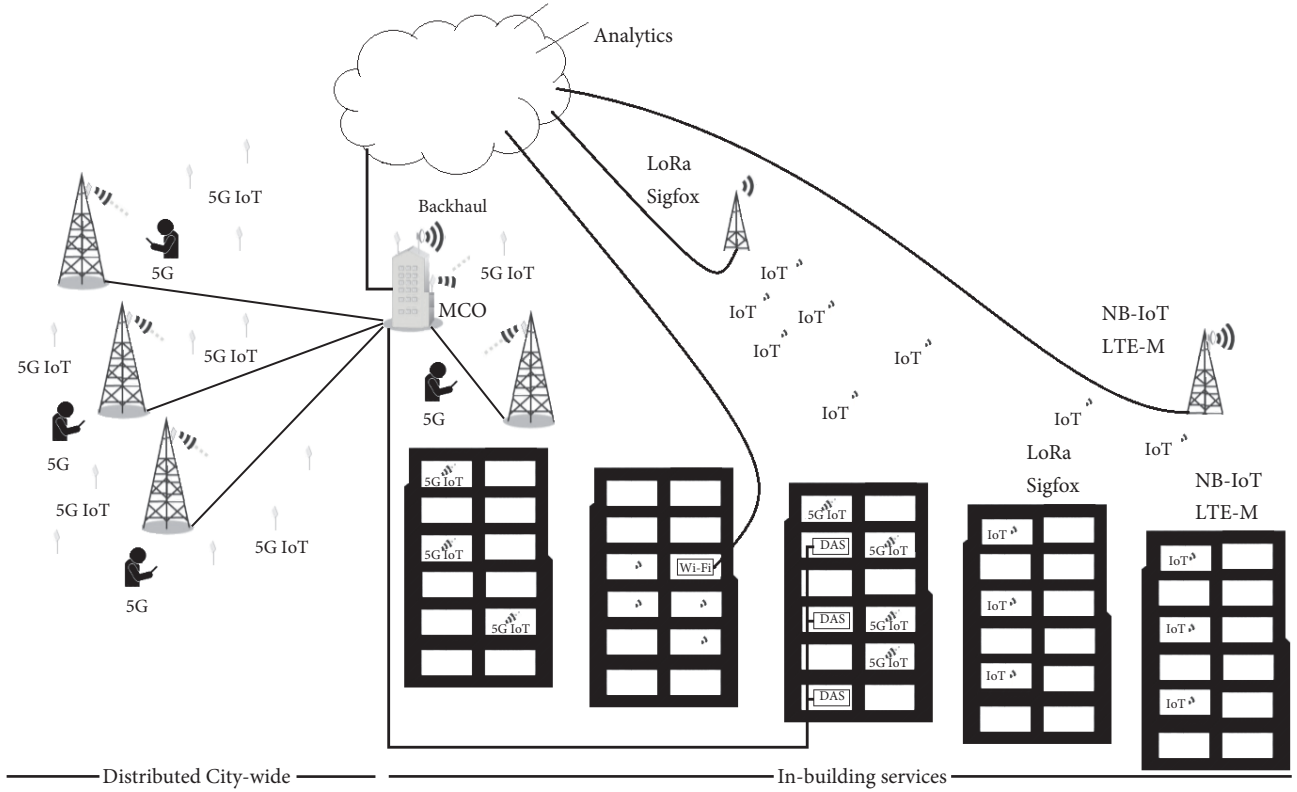


FIGURE 2: The pre-5G and the 5G IoT connectivity ecosystem.

4G/LTE and 5G are expected to coexist for many years. However, it is fair to say that like many other technologies before 5G, this technology is probably going through a “hype-cycle”, where a technology is supposed to be “all things to all people” and be the “be-all-and-end-all technology”; both claims will be abrogated in time. Proponents argue that 5G will “maximize the satisfaction of end-users by providing immersiveness, intelligence, omnipresence, and autonomy”.

2.1. 5G Standardization and Use Cases. Standardization work for 5G systems has been undertaken by several international bodies with the goal of achieving one unified global standard. Many well-known research centers, universities, standards bodies, carriers and technology providers have been involved in advancing the development of the technology for a 2020 rollout, including the Internet Engineering Task Force (IETF), the Open Network Automation Platform (ONAP), the GSMA, and the European Telecommunications Standards Institute Network Function Virtualization (ETSI NFV). In particular, work on 5G requirements, services and technical specifications has been undertaken in the past few years by three key entities: (i) International Telecommunication Union-Radio Communication Sector (ITU-R) [30], (ii) Next Generation Mobile Networks (NGMN) Alliance [31], and (iii) the 3rd Generation Partnership Project (3GPP) [32]. The ITU-R has assessed usage scenarios in three classes: ultra-reliable and low-latency communications (URLLC), massive machine-type communications (mMTC), and enhanced mobile broadband (eMBB). eMBB is probably the earliest

class of services being broadly supported and implemented. Key performance indicators are identified for each of these classes, such as spectrum efficiency, area traffic capacity, connection density, user-experienced data rate, peak data rate, and latency, among others. The ability to efficiently handle device mobility is also critical. Some examples of eMBB use cases include Non-SIM devices, smart phones, home/enterprise/venues applications, UHD (4K and 8K) broadcast, and virtual reality/augmented reality. mMTC use cases include smart buildings, logistics, tracking, fleet management and smart meters. URLLC cases include traffic safety and control, remote surgery, and industrial control. 5G systems are expected to support:

- (i) Tight latency, availability, and reliability requirements to facilitate applications related to video delivery, healthcare, surveillance and physical security, logistics, automotive locomotion, and mission-critical control, among others, particularly in an IoT context;
- (ii) A panoply of data rates, up to multiple Gbps, and tens of Mbps to facilitate existing and evolving applications, particularly in an IoT context;
- (iii) Network scalability and cost-effectiveness to support both clustered users with very high data rate requirements as well a large number of distributed devices with low complexity and limited power resources, particularly in an IoT context, where, as noted, a rapid increase in the number of connected devices is anticipated; and,

TABLE 3: Radio interface goals as defined in IMT-2020.

-
- (i) MR for downlink peak data rate is 20 Gbps
 - (ii) MR for uplink peak data rate is 10 Gbps
 - (iii) Target downlink “user experienced data rate” is 100 Mbps
 - (iv) Target uplink “user experienced data rate” is 50 Mbps
 - (v) Downlink peak spectral efficiency is 30 bps/Hz
 - (vi) Uplink peak spectral efficiency is 15 bps/Hz
 - (vii) MR for user plane latency for eMBB is 4ms
 - (viii) MR for user plane latency for URLLC is 1ms
 - (ix) MR for control plane latency is 20ms (a lower control plane latency of around 10ms is encouraged)
 - (x) Minimum requirement for connection density is 1,000,000 devices per km²
 - (xi) Requirement for bandwidth is at least 100 MHz
 - (xii) Bandwidths up to 1 GHz are required for higher frequencies (above 6 GHz)
-

MR = Minimal Requirement

Source: ITU-R SG05 Contribution 40, “Minimum requirements related to technical performance for IMT-2020 radio interface(s)”, Feb 2017.

- (iv) Pragmatic deployment cost metrics, along with acceptable service price points across the gamut of applications and data rates, particularly in an IoT context.

Specifically, some of the design details are a latency below 5 msec. (as low as 1 msec.), support for device densities of up to 100 devices/m², reliable coverage area, integration of telecommunications services including mobile, fixed, optical and MEO/GEO satellite, and seamless support for the IoT ecosystem. For example, the technical objective 5G as envisioned of METIS (*Mobile and Wireless Communications Enablers for the Twenty-twenty Information Society* -- a European Community advocacy effort related to mobility) are as follows [47–54]:

- (i) 1000 x higher mobile data volume per area than current systems;
- (ii) 10 to 100 x higher number of devices than current systems (i.e., dense coverage);
- (iii) 10 to 100 x higher user data rate than current systems (e.g., 1-20 Gbps);
- (iv) 10 x longer battery life for low power IoT devices than current systems (up to a 10-year battery life for machine type communications); and,
- (v) 5 x reduced end-to-end latency than current systems.

Table 3 defines the 5G radio interface goals as defined in IMT-2020. A number of these requirements are in fact being met (in various measure) by the systems now being deployed. The expectation is that to provide the full panoply of 5G services significant changes in both wireless technologies and core networks will be required.

As a point of observation, 3GPP/TR 22.891 has defined and/or described the following service groups: eMBB, Critical Communication, mMTC, Network Operations, and Enhancement of Vehicle-to-Everything (V2X). NGMN has defined and/or described the following service groups: Broadband access in dense area, Indoor ultra-high broadband access, Broadband access in a crowd, 50+ Mbps everywhere, Ultra low-cost broadband access for low ARPU areas,

Mobile broadband in vehicles, Airplanes connectivity, Massive low-cost Low long-range/low-power MTC, Broadband MTC, Ultra low latency, Resilience and traffic surge, Ultra-high reliability and Ultra low latency, Ultra-high availability and reliability, and Broadcast-like services.

Figure 3 depicts some of the key 5G services that can be utilized for the IoT, in the medium term in Smart Cities; other services shown might also be used over time. Although some have associated Smart Cities with mMTC, we are of the opinion that the early applications will be more within the eMBB domain (some others also agree [55]). Also, one would expect eMBB to be deployed more broadly, driven by the commercial “appeal” of the video services it facilitates. Augmented and/or virtual reality (AR/VR) are emerging as keys application of 5G networks, also involving some IoT aspects. To meet the requirements of lower latency and massive data transmission in AR/VR applications, software-defined networking (SDN) with a multi-path cooperative route (MCR) scheme that minimizes delay may be ideally positioned for 5G small cell networks [56]. Note parenthetically that video requirements range from about 8 Mbps for HD, 25 Mbps for UHD, 50 Mbps for 360-degree UHD video, 200 Mbps for 360-degree HDR (high dynamic range) video, and up to 1 Gbps for 6DoF/MPEG-I. The evolving MPEG-I Visual standard addresses visual technologies of immersive media; 360 video provides panoramic video texture projected onto a virtual shape surrounding the user’s head, from which the user visualizes a portion for an immersive video experience; 6DoF (6 Degrees of Freedom) supports movements along three rotation axes and three translations and presumes that full freedom of movement through the scene is possible [57]. 5G/eMBB may eventually support some (but not necessarily all) of these video applications, but these applications are well beyond the IoT applications discussed in this paper. IP-based video surveillance in Smart Cities that may be supported by IoT can operate rather well at the 0.384-2.5 Mbps bandwidth range.

Figure 4 highlights some technical features of 5G services that can be utilized for the IoT in Smart Cities in terms of data rates, latency, reliability, device density and so on. 5G IoT overcomes the well-known limitation of unlicensed LPWAN

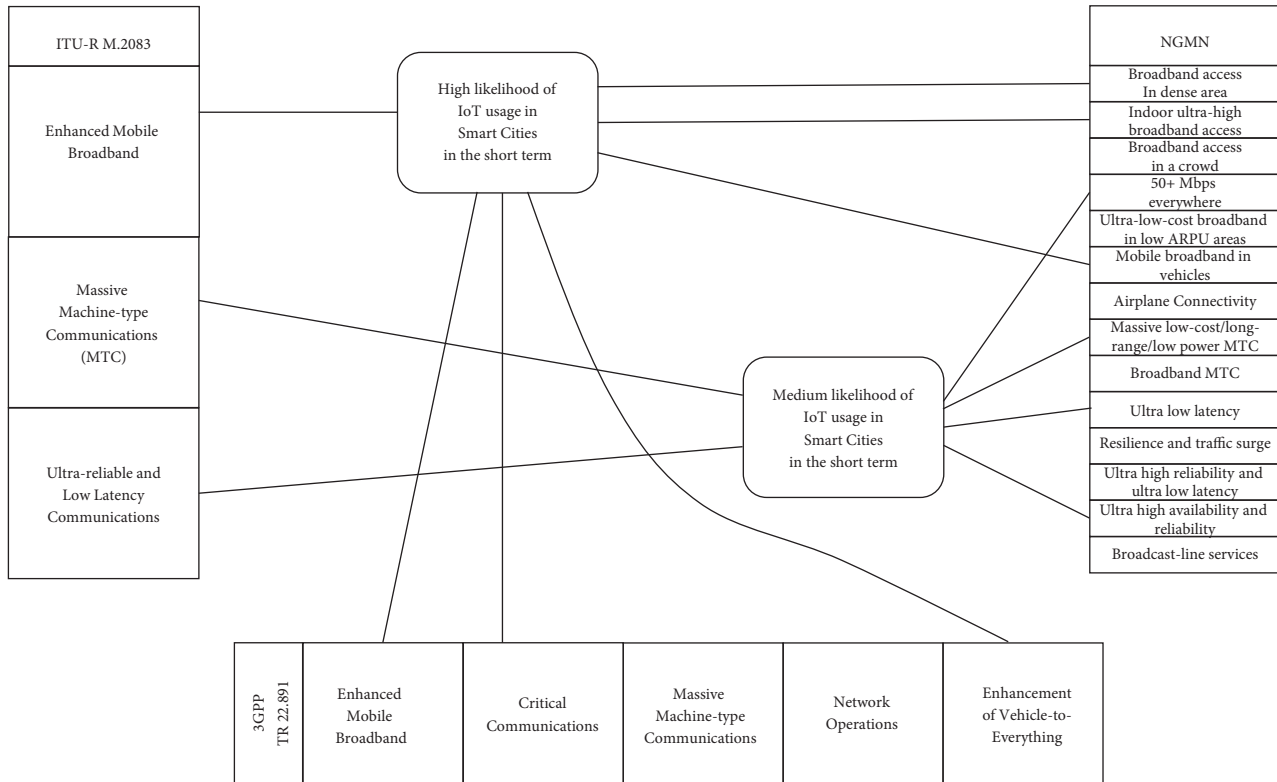


FIGURE 3: 5G services that can be utilized for the IoT in Smart Cities.

technologies that utilize crowded license-free frequency bands, especially in large cities; therefore, 5G IoT is ideal for Smart City for mission-critical and Quality of Service (QoS)-aware applications (for example, traffic management, smart grid, utility control.)

2.2. 5G Evolution. 3GPP has specified new 5G radio access technology, 5G enhancements of 4G (fourth generation) networks, and new 5G core networks. Specifically, it has defined a new 5G Core network (5GC) and a new radio access technology called 5G “New Radio” (NR). The new 5GC architecture has several new capabilities built inherently into it as native capabilities: multi-Gbps support, ultra-low latency, Network Slicing, Control and User Plane Separation (CUPS), and virtualization. To deploy the 5GC new infrastructure will be needed. There is a firm goal to support for “forward compatibility”. The 5G NR modulation technique and frame structure are designed to be compatible with LTE. The 5G NR duplex frequency configuration will allow 5G NR, NB-IoT and LTE-M subcarrier grids to be aligned. This will enable the 5G NR user equipment (UE) to coexist with NB-IoT and LTE-M signals. As might be expected, however, it is possible to integrate into 5G elements of different generations and different access technologies—two modes are allowed: the SA (standalone) configuration and the NSA (non-standalone) configuration (see Figure 5, also positioning IoT support).

- (i) 5G Standalone (SA) Solution: in 5G SA an all new 5G packet core is introduced. SA scenarios utilize only one radio access technology (5G NR or the evolved

LTE radio cells); the core networks are operated independently.

- (ii) 5G Non-Standalone Solution (NSA): in 5G NSA Operators can leverage their existing Evolved Packet Core (EPC)/LTE packet core to anchor the 5G NR using 3GPP Release 12 Dual Connectivity feature. This will enable operators to launch 5G more quickly and at a lower cost. This solution might suffice for some initial use cases. However, 5G NSA has a number of limitations, thus these Operators will eventually be expected to migrate to 5G Standalone solution. NSA scenario combines NR radio cells and LTE radio cells using dual-connectivity to provide radio access and the core network may be either EPC or 5GC.

Multiple evolution/deployment paths may be employed by service providers (service providers of various services, including IoT services) to reach the final target configuration; this migration could well take a decade, and may also have different timetables in various parts of a country, e.g., top urban areas, top suburban areas, secondary urban areas, secondary suburban areas, exurban areas, rural areas. Figure 6 depicts the well-known migration paths. The IoT implementer will need to be keenly aware of what 5G (5G IoT) services are available in a given area as an IoT implementation is contemplated. In Figure 6, Scenario 1 illustrates that the IoT Service provider will continue to use LTE and EPC to provide services (e.g., NB-IoT); here only legacy IoT devices can be supported. The provider only has a standalone radio

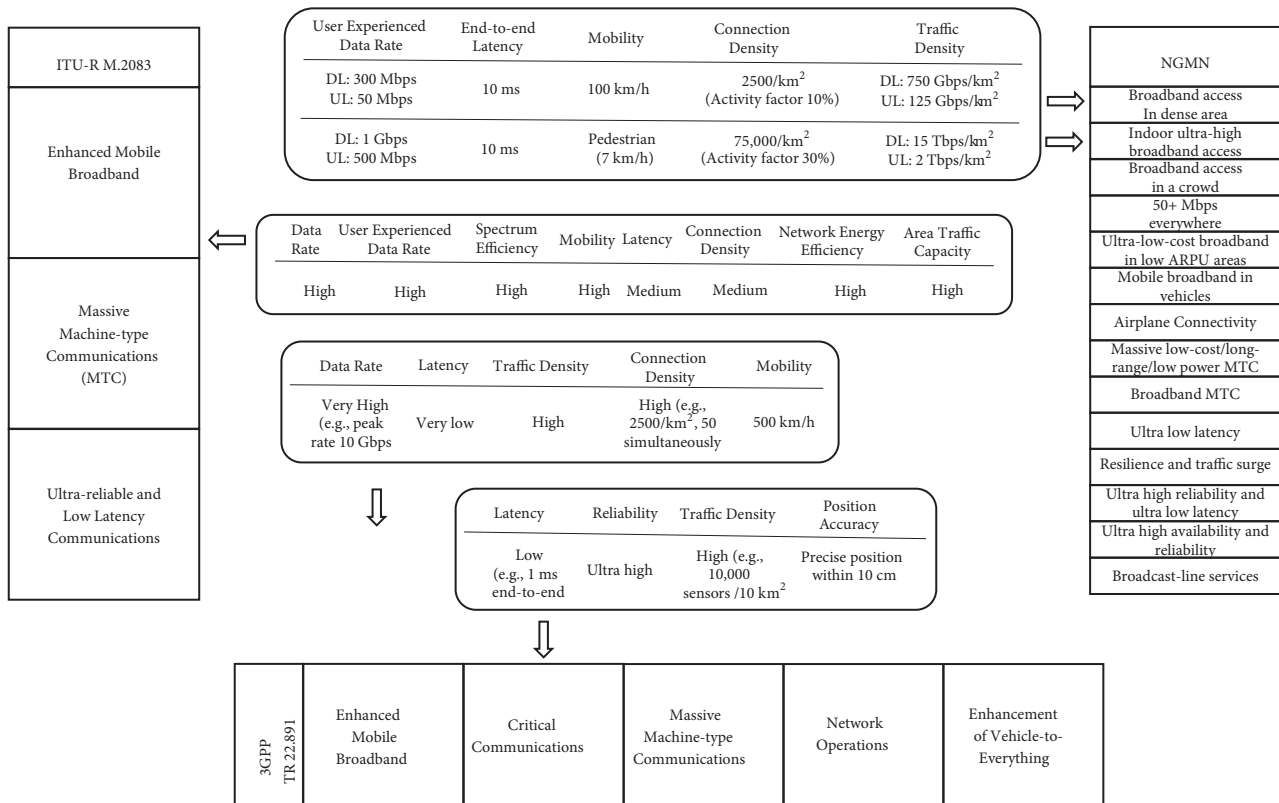


FIGURE 4: Some technical features of 5G services that can be utilized for the IoT in Smart Cities.

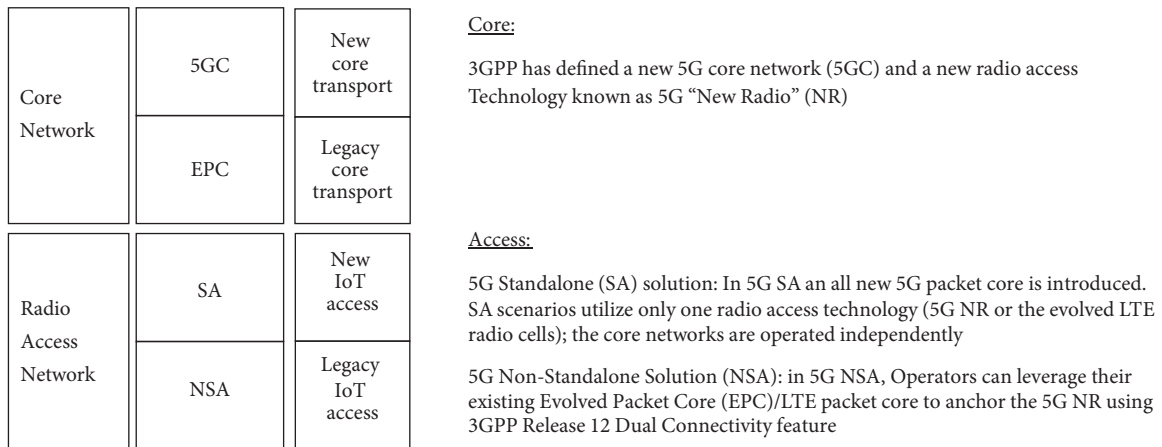


FIGURE 5: 5G Transition Options and IoT support.

technology, in this case LTE only. Scenario 2 illustrates an IoT Service provider has migrated completely to NR (again only providing a standalone radio technology), but will retain the existing core network, the EPC. (Only) new 5G IoT devices can be used. In scenarios 5 and 6 the service providers will support both the legacy LTE and the new NR (clearly in this non-standalone arrangement, both radio technologies are deployed.) Some of these providers retain the legacy core and some will deploy the new 5GC core. Both legacy and 5G IoT devices can be supported.

3GPP approved the 5G NSA standard at the end of 2017 and the 5G SA standard in early 2018 in the context of its Release 15. Release 15 also included the support eMBB, URLLC, and mMTC in a single network to facilitate the deployment of IoT services; Release 15 also supports 28 GHz millimeter-wave (mmWave) spectrum and multi-antenna technologies for access.

2.3. 5G Frequency Bands. Focusing on the radio technology, there are number of spectrum bands that can be used in

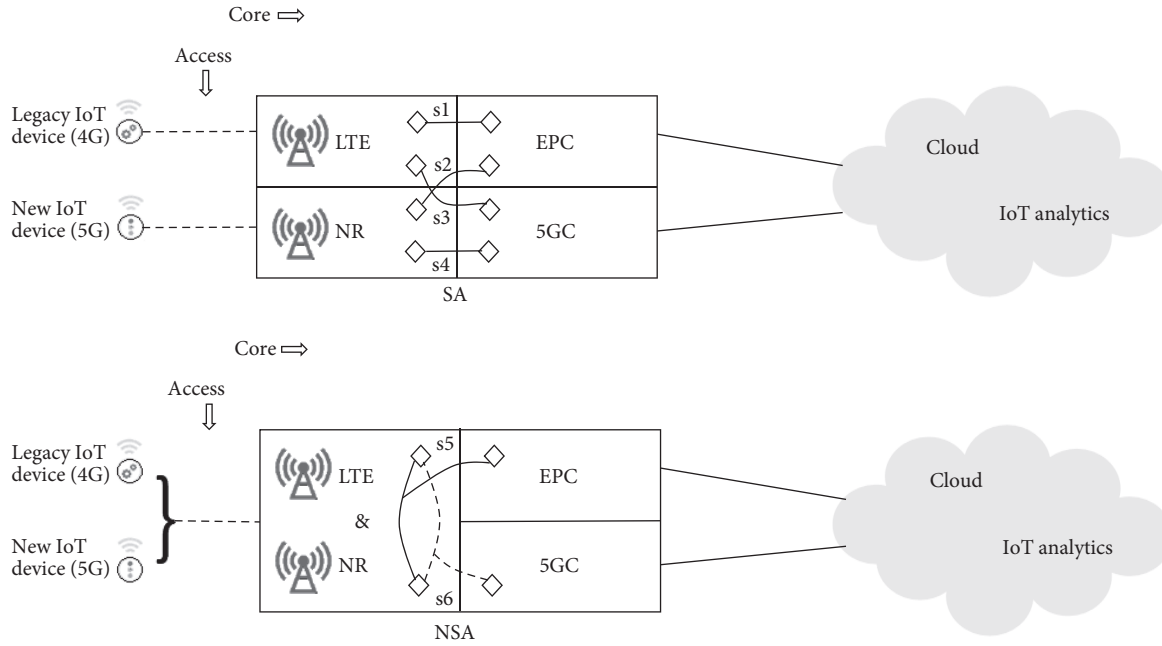


FIGURE 6: Detailed 5G Transition Options and IoT support.

5G; these bands can be grouped into three macro categories: sub-1 GHz, 1-6 GHz and above 6 GHz. The more advanced features, especially higher data rates require the use of the millimeter wave spectrum. New mobile generations are typically assigned new frequency bands and wider spectral bandwidth per frequency channel (1G up to 30 kHz, 2G up to 200 kHz, 3G up to 5 MHz, and 4G up to 20 MHz). Up to now cellular networks have used frequencies below 6 GHz. Generally, without advanced MIMO (Multiple In Multiple Out) antenna technologies one can obtain about 10 bits-per-Hertz-of-channel bandwidth. But the integration of new radio concepts such as Massive MIMO, Ultra Dense Networks, Device-to-Device, and mMTC will allow 5G to support the expected increase in the data volume in mobile environments and facilitate new IoT applications. Implementable standards for 5G are being incorporated in 3GPP Release 15 onwards. As noted, 3GPP Rel 15 defines New 5G Radio and Packet Core evolution to facilitate interoperable deployment of the technology.

The millimeter wave spectrum, also known as Extremely High Frequency (EHF), or more colloquially mmWave, is the band of electromagnetic spectrum running between 30 GHz and 300 GHz. Bands within this spectrum are being considered by the ITU and the Federal Communications Commission in the U.S. as a mechanism to facilitate 5G by supporting higher bandwidth. The use of a 3.5 GHz frequency to support 5G networks is also gaining some popularity, but the higher speeds networks will use other frequency bands, including millimeter-wave frequencies (these bands ranging from 28 GHz to 73 GHz, specifically the 28, 37, 39, 60 and 72-73 GHz bands). In the U.S., recently the FCC approved spectrum for 5G, including millimeter-wave frequencies in the 28 GHz, 37 GHz and 39 GHz bands, although these targeted cellular frequencies may nominally

overlap with other pre-existing users of the spectrum, for example point-to-point microwave paths, Direct Broadcast satellite TV, and high throughput satellite (HTS) systems (Ka-band transmissions).

Initially 5G will, in many cases, use the 28 GHz band, but higher bands will very likely be utilized later on; initial implementations, will support a maximum speed of 1 Gbps. Lower frequencies (at the so-called C band) are less subject to weather impairments, can travel longer distances, and penetrate building walls more easily. Waves at higher frequencies (Ku, Ka and E/V bands) do not naturally travel as far or penetrate walls or objects as easily. However, a lot more channel bandwidth is available in millimeter-wave bands. Furthermore, developers see the need for “an innovative utilization of spectrum”; “small cell” approaches are required to address the scarcity of the spectrum, but at the same time covering the geography. V band spectrum covers 57-71 GHz, which in many countries is an “unlicensed” band, and E band spectrum covers 71-76 GHz, 81-86 GHz and 92-95 GHz.

In the U.S., in 2018 the FCC also opened up, as an “interim” step for 5G, a “mid-band” radio spectrum at 3.5 GHz which was previously reserved for naval radar use. The 3.5 GHz band provides a combination of signal propagation distance, acceptable building penetration, and increased bandwidth. The FCC created 15 channels within the 3.550-3.700 GHz band, auctioning seven channels to “priority access licenses” and making eight channels available for general access -- the U.S. Navy still getting priority across the band when and as needed. With this approval, 5G devices can be built to support the same 3.5GHz ranges across North America, Europe, and Asia [58].

In addition to new bands, 5G technology is expected to use beam-forming and beam-tracking, where a cell’s antenna can focus its signal to reach a specific mobile device and

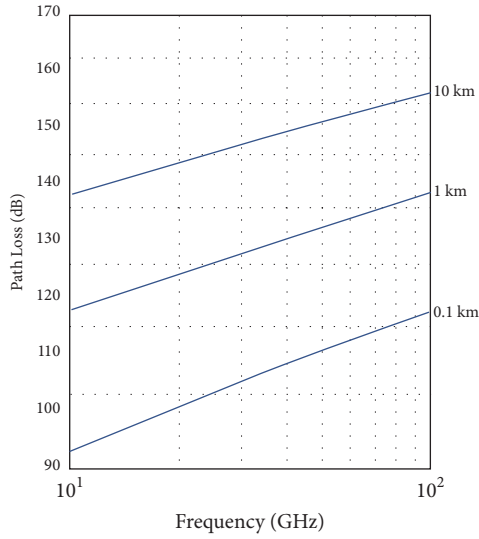


FIGURE 7: Path loss as a function of distance and frequency.

then track that device as it moves. Beamforming utilizes a large number (hundreds) of antennas at a base station to achieve highly directional antenna beams that can be “steered” in a desired direction to optimize transmission and throughput performance. Massive MIMO is a system where a transmission node (base station) is equipped with a large number (hundreds) of antennas that simultaneously serve multiple users; with this technology multiple messages for several terminals can be transmitted on the same time-frequency resource.

2.4. 5G Transmission Characteristics at Higher Frequencies. Due to RF propagation phenomena that are more pronounced at the higher frequencies, such as multipath propagation due to outdoor and indoor obstacles, free space path loss, atmospheric attenuation due to rain, fog, and air composition (e.g., oxygen), small cells will almost invariably be needed in 5G environments, especially in dense urban environments. Additionally, Line of Sight (LOS) will typically be required. ITU-R P series of recommendations has useful information on radio wave propagation including ITU-R P.838-3, 2005; ITU-R P.840-3, 2013; ITU-R P.676-10, 2013; and ITU-R P.525-2, 1994. Figures 7, 8, 9, and 10 highlight the issues at the higher frequencies, including the millimeter-wave frequencies. Figure 7 depicts the path loss as a function of distance and frequency. Figure 8 shows the attenuation as a function of precipitation and frequency. Figure 9 illustrates the attenuation as a function of fog density and frequency. Figure 10 depicts the attenuation as a function of atmospheric gases and frequency (notice high attenuation around 60 GHz).

In addition to the broad service requirements briefly highlighted in Table 3 (for example latency, user density distribution, etc.), there are specific IoT nodal considerations that have to be taken into account as one develops the next generation network. For example, IoT nodes typically are low-complexity devices and have limited on-board power. 5G systems have to take these restrictions and considerations

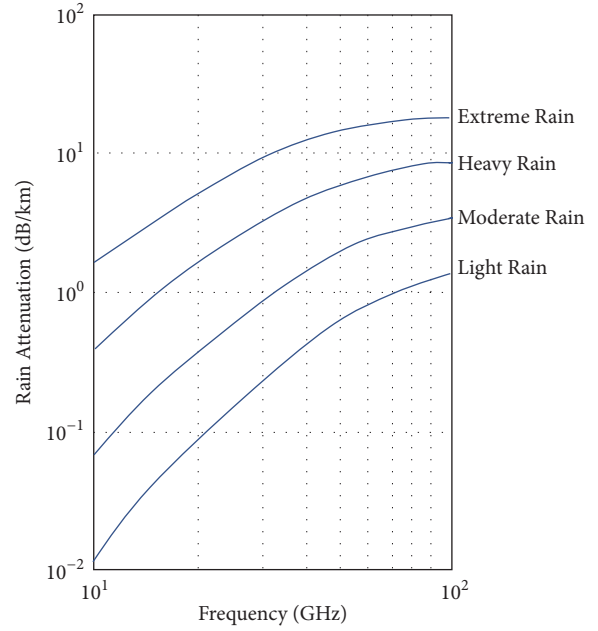


FIGURE 8: Attenuation as a function of precipitation and frequency.

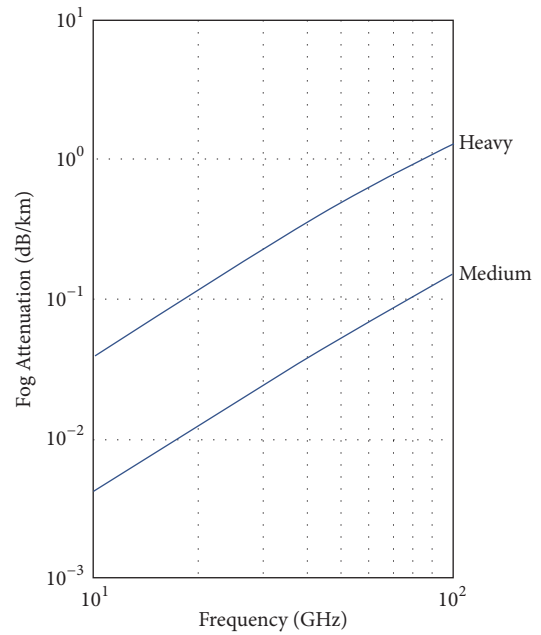


FIGURE 9: Attenuation as a function of fog density and frequency.

into account. Table 4 provides a summary of some of these considerations and the 5G support.

3. Small Cell and Building Penetration Issues

As expected, communications at mmWave frequencies have attracted a lot of interest, due to the large available spectrum bandwidth that can potentially result in multiple gigabit per second transmissions per user. This follows a similar trend

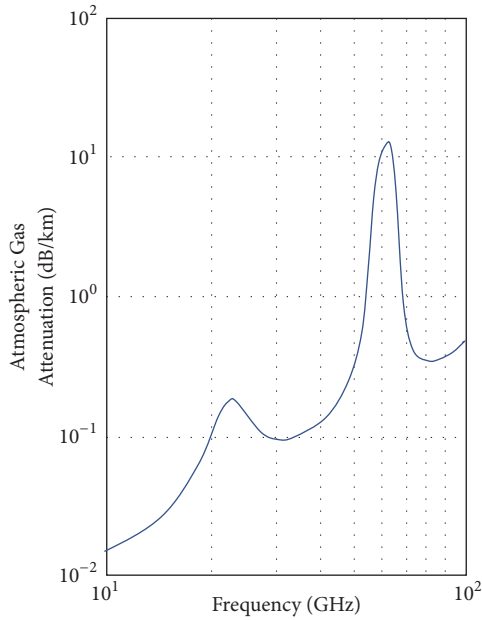


FIGURE 10: Attenuation a function of atmospheric gases and frequency. (notice high attenuation around 60 GHz).

in satellite communications with the introduction of Ka services, especially HTSs. High bandwidth will typically require a wide spectrum. Millimeter wave frequencies (signals with wavelength ranging from 1 millimeter to 10 millimeters) support a wide usable spectrum. The millimeter wave spectrum includes licensed, lightly licensed and unlicensed portions. Bandwidth demand and goals are the main driver for the need to use the millimeter wave spectrum, particularly for eMBB-based applications, allowing users to receive 100 Mbps as a bare minimum and 20 Gbps as a theoretical maximum. The use of millimeter wave frequencies, however, will imply the use of a much smaller tessellation of cells and supportive towers or rooftop transmitters due, as noted, to transmission characteristics, such as high attenuation and directionality. This is an important design consideration for 5G, especially in dense city/urban environments. The aggregation of these towers will by itself require a significant backbone network, whether a mesh based on some point-to-point microwave links, an fiber network or a set of “wireless fiber” links. Millimeter wave system utilize smaller antennas compared to systems operating at lower frequencies: the higher frequencies, in conjunction with MIMO techniques, can achieve sensible antenna size and cost. The millimeter wave technology can be utilized both for indoors and outdoors high-capacity fixed or mobile communication applications. The term “densification” is also used to describe the massive deployment of small cells in the near future.

MmWave products used for backhauling typically operate at 60 GHz (V Band) and 70/80 GHz (E Band) and offer solutions in both Point to Point and Point to Multipoint (PtMP) configurations providing end to end multi-gigabit wireless networks, for example, 1 Gbps up to 10 Gbps symmetric performance. Very small directional antennas, typically less than a half-square foot in area, are used to transmit and/or receive

signals which are highly focused beams. stationary radio systems are often installed on rooftops or towers. MmWave products are now appearing on the market targeting high capacity Smart City applications, 5G Fixed, Gigabit Wireless Access solutions, and Business Broadband. Urban canyons, however, may limit the utility of this technology to very short LOS paths. Mobile applications of mmWave technology are more challenging. On the other hand, one advantage of this technology is that short transmission paths (high propagation losses) and high directionality allow for spectrum reuse by limiting the amount of interference between transmitters and/or adjacent cells. Near LOS (NLOS) applications may be possible in some cases (especially for short distances).

Currently, mm wave frequencies are being utilized for high-bandwidth indoor applications, for example streaming (“miracasting”) of HD or UHD video and VR support (e.g., using 802.11ad Wi-Fi). Traditionally, these frequencies have not been used for outdoor broadband applications due to high propagation loss, multipath interference, and atmospheric absorption (gases, rain, fog and humidity) cited above; in addition, the practical transmission range is a few kilometers in open space [68]. Recently the FCC proposed new rules for wireless broadband in wireless frequencies above 24 GHz stating that it is “taking steps to unlock the mobile broadband and unlicensed potential of spectrum at the frontier above 24 GHz” [69]. The ITU and the 3GPP have defined two-phases of research; the first phase (expected to complete by press time) is to assess frequencies less than 40 GHz to address short-term commercial requirements; the second phase entails assessing the IMT 2020 requirements by studying frequencies up to 100 GHz. The following mmWave bands being considered, among other bands [70]:

- (i) 7 GHz of spectrum in total in the band 57 GHz to 64 GHz unlicensed.
- (ii) 3.4 GHz of spectrum in total in the 28 GHz/38 GHz licensed but underutilized region.
- (iii) 12.9 GHz of spectrum in total 71 GHz/81 GHz/92 GHz light-licensed band

Following the most recent World Radiocommunications Conference, the ITU also identified a list of proposed globally-usable frequencies between 24 GHz and 86 GHz, as follows: 24.25–27.5 GHz, 31.8–33.4 GHz, 37–40.5 GHz, 40.5–42.5 GHz, 45.5–50.2 GHz, 50.4–52.6 GHz, 66–76 GHz, and 81–86 GHz.

3.1. Cell Types. MmWave transmission will drive the requirement for small cells [71, 72]. “Small cells” refer to relatively low-powered radio communications equipment (base stations) and ancillary antennas and/or towers that provide mobile, internet, and IoT services within localized areas. Small cells typically have a range up to one-to-two kilometers, but can also be smaller -- on the other hand, a typical mobile macrocell (such as urban macro-cellular [UMa] or rural macrocell [RMa]) has a range of several kilometers up to 10-to-20 of kilometers.) The terms femtocells, picocells, micro-cells, urban microcell (UMi), and metrocells are effectively synonymous with the “small cells” concept. Small(er) cells

TABLE 4: Example of IoT nodal considerations for 5G systems.

IoT device issue	5G Support
Low complexity devices	Broad standardization leads to simplification e.g., SOC (System on a Chip) and/or ASIC (Application Specific IC) development
Limited on-board power	Technology allows a battery life ~10 years
Device mobility	Good mobility support in a cellular/5G system
Open environment	Broad standardization leads to broad acceptance of the technology
Devices universe by type and by cardinality	Standardized air interfaces can reduce certain aspects of the end-node, just like Ethernet simplified connectivity to a network, regardless of the functionality of the processor per se
Always connected/always on mode of operation	Cost-effective connectivity services allow the always on mode of operation
IoT security (IoTSec) concerns [59, 60]	Security capabilities are being added. The use of 256-bit symmetric cryptography mechanisms is expected to be fully incorporated. The encryption algorithms are based on SNOW 3G, AES-CTR, and ZUC; and integrity algorithms are based on SNOW 3G, AES-CMAC, and ZUC. The main key derivation function is based on HMAC-SHA-256. Identity management (e.g., via the 5G authentication and key agreement [5G AKA] protocol and/or the Extensible Authentication Protocol [EAP]), Privacy (conforming to the General Data Protection Regulation [GDPR]), and Security assurance (e.g., using Network Equipment Security Assurance Scheme [NESAS]) are supported. Some of these mechanisms are described [61–65]. As another example, the ETSI Technical Committee on Cybersecurity issued in 2018 two encryption specifications for access control in highly distributed systems such as G and IoT. Attribute-Based Encryption (ABE) that describes how to secure personal data.
Lack of agreed-upon end-to-end standards	Broad standardization possible with 5G if the technology is broadly deployed and is cost-effective
Lack of agreed-upon end-to-end architecture	Standardization at the lower layers (Data Link Control and Physical) can drive the development of a more inclusive multi-layer multi-application architecture

have been used for years to increase area spectral efficiency -- the reduced number of users per cell provides more usable spectrum to each user. However, the smaller cells in 5G are also dictated by the propagation characteristics. In the 5G context UMi typically have radii of 5-120 meters for LOS and 20 to 270 meters in NLOS; UMa typically have radii of 60-1000 meters for LOS and 50-1500 meters for NLOS [73]. Given their size, 5G/mmWave UMi cells will be able to support high bandwidth enabling eMBB services over small areas of high traffic demand. At the mmWave operation, user-device proximity with the antenna will enable higher signal quality, lower latency, and by definition, high data rates and throughput. Also, to be noted, mmWave frequencies make the size of multi-element antenna arrays practical, enabling large Multi-user MIMO (MU-MIMO) solutions.

Signal penetration indoors may represent a challenge, just as is the case even at present with 3G/4G LTE, even for traditional voice and internet access and data services. This has driven the need for DAS systems, especially in densely-constructed downtown districts. Free space attenuation at the higher frequency, power budgets, directionality requirements, and weather, all impact 5G and 5G IoT. Outdoor small cells and building-resident Distributed Antenna Systems (DAS) systems utilize high-speed fiber optic lines or “wireless fiber” to interconnect the sites to the backbone and the Internet cloud.

Figure 11 depicts a 5G IoT ecosystem where mmWave technology is used. Figure 12 shows typical (4G LTE) urban microcell towers. Figure 13 depicts a Smart City supported via (5G) urban microcells.

3.2. *Assessment of Transmission Issues.* Reference [74] provides a fairly comprehensive assessment of the transmission channel issues as they apply to 5G. The importance of this topic is accentuated by the large number of agencies actively researching this topic, including [55, 73–87]:

- (i) METIS
- (ii) 3GPPP
- (iii) MiWEBA (Millimetre-Wave Evolution for Backhaul and Access)
- (iv) ITU-R M
- (v) COST2100
- (vi) IEEE 802.11
- (vii) NYU WIRELESS: interdisciplinary academic research center
- (viii) IEEE 802.11 ad/ay
- (ix) QuaDRiGa (Fraunhofer HHI)
- (x) 5th Generation Channel Model (5GCM)

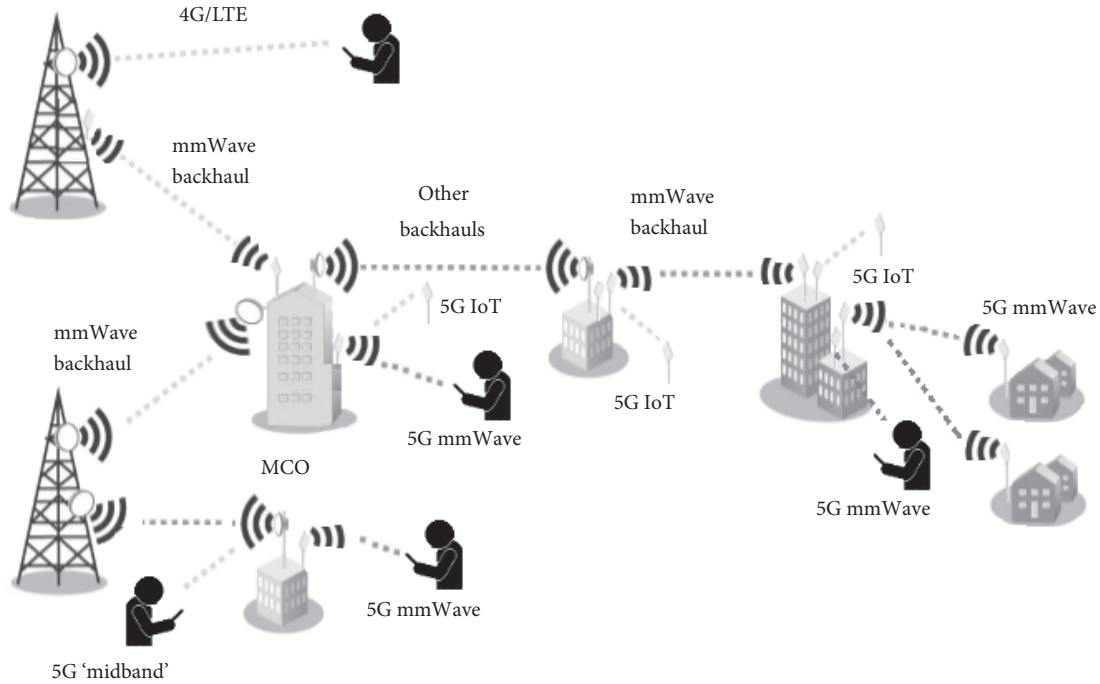


FIGURE 11: The 5G IoT ecosystems.

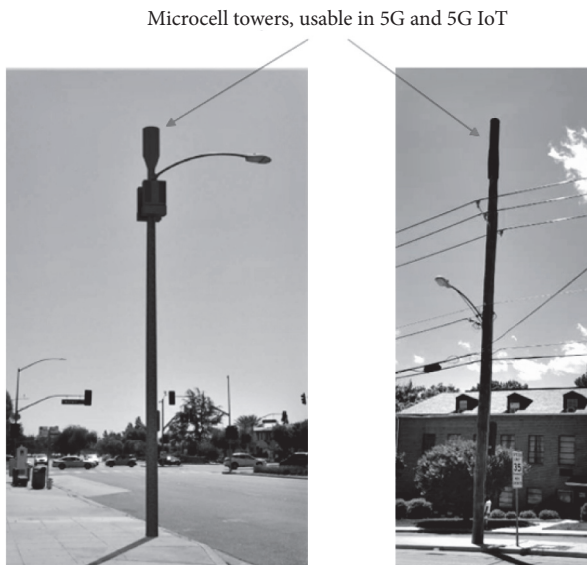


FIGURE 12: Microcell towers (these for 4G, but a lot more for 5G). (non-copyrighted material from FCC-related filings [91]).

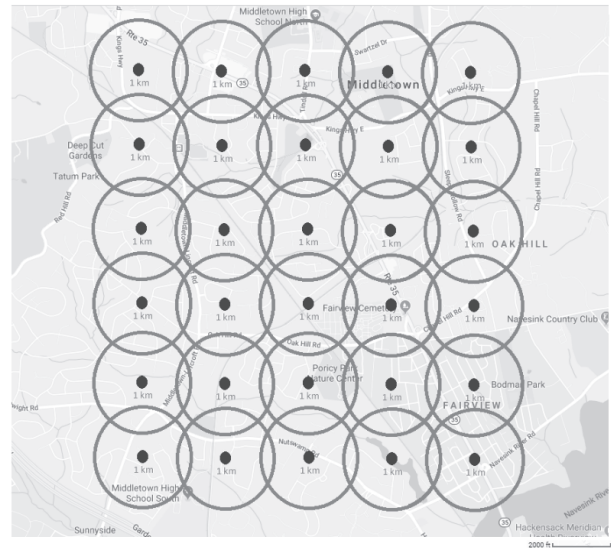


FIGURE 13: Microcells for 5G/5G IoT.

- (xi) 5G mmWave Channel Model Alliance (NIST initiated, North America based)
 - (xii) mmMAGIC (Millimetre-Wave Based Mobile Radio Access Network for Fifth Generation Integrated Communications) (Europe based)
 - (xiii) IMT-2020 5G promotion association (China based)
- (also including firms and academic centers such as, but not limited to AT&T, Nokia, Ericsson, Huawei, Intel/Fraunhofer

HHI, NTT DOCOMO, Qualcomm, CATT, ETRI, ITRI/CCU, ZTE, Aalto University, and CMCC.)

Diffraction loss (DL) and frequency drop (FD) are just two of the path quality issues to be addressed. Although greater gain antennas will likely be used to overcome path loss, diffuse scattering from various surfaces may introduce large signal variations over travel distances of just a few centimeters, with fade depths of up to 20 dB as a receiver moved by a few centimeters. These large variations of the channel must be taken into consideration for reliable design

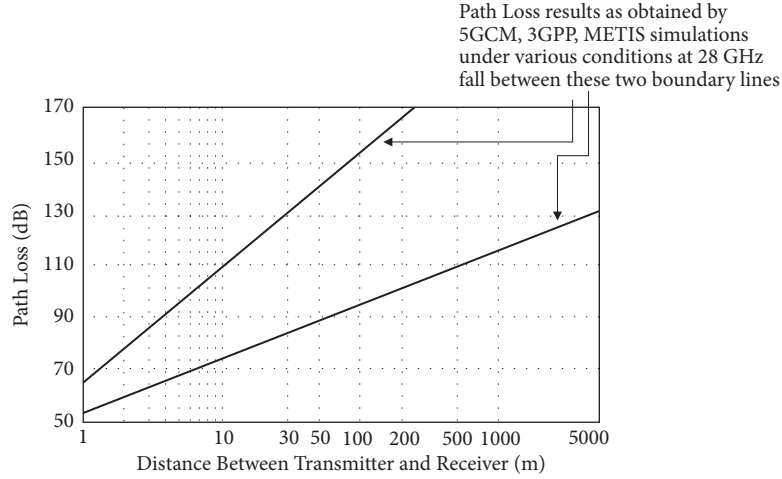


FIGURE 14: Path Loss simulations for 5G by various entities.

of channel performance, including beam-forming/tracking algorithms, link adaptation schemes, and state feedback algorithms. Furthermore, multipath interference from coincident signals can give rise to critical small-scale variations in the channel frequency response. In particular, wave reflection from rough surfaces will cause high depolarization. For LOS environment Rician fading of multipath components, exponential decaying trends and quick decorrelation in the range of 2.5 wavelengths have been demonstrated. Furthermore, received power of wideband mmWave signals has a stationary value for slight receiver movements but average power can change by 25 dB as the mobile transitions around a building corner from NLOS to LOS in an UMi setting. Additionally, human body blockage causes more than 40 dB of fading at the mmWave frequencies. Figure 14 depicts the path loss according to various simulations for 5G by various stakeholder entities.

The main parameter of the radio propagation model is the Path Loss Exponent (PLE), which is an attenuation exponent for the received signal. PLE has a significant impact on the quality of the transmission links. In the far field region of the transmitter, if $PL(d_0)$ is the path loss measured in dB at a distance d_0 from the transmitter, then the loss in signal power expected when moving from distance d_0 to d ($d > d_0$) is [88–90] is

$$PL_{d_0 \rightarrow d} (dB) = PL(d_0) + 10n \log_{10} \left(\frac{d}{d_0} \right) + \chi \quad (1)$$

$$d_f \leq d_0 \leq d$$

where

$PL(d_0)$ = Path Loss in dB at a distance d_0

n = PLE

χ = A zero-mean Gaussian distributed random variable with standard deviation σ . (This is utilized only when there is a shadowing effect; if there is no shadowing effect, then this random variable is taken to be zero.)

See Figure 15. Usually PLE is considered to be known upfront but in most instances PLE needs to be assessed for the case at hand. It is advisable to estimate the PLE as accurately as possible for the given environment. PLE estimation is achieved by comparing the observed values over a sample of measurements to the theoretical values. Obstacles absorb signals, thus treating the PLE as a constant is not an accurate representation of the real environments, both indoors and outdoors (for example treating PLE as a constant which may cause serious positioning errors in complicated indoor environments [88]). Usually to model real environments the shadowing effects cannot be overlooked, by taking the PLE as a constant (a straight-line slope). To capture a shadowing effect a zero-mean Gaussian random variable with standard deviation σ is added to the equation. Here the PLE (slope) and the standard deviation of the random variable should be known precisely for a better modeling.

Table 5 provides theoretical performance equations developed by 3GPP and ETSI for outdoor channel performance [81]. As pragmatic working parameters, one has the following:

- (i) PLE values are in the 1.9 and 2.2 range for LOS and at the 28 GHz and 60 GHz bands; PLE is approximately 4.5 and 4.2 range for NLOS in the 28 GHz and 60 GHz bands.
- (ii) Rain attenuation of 2–20 dB/km can be anticipated for rain events ranging from light rain (12.5 mm/hr) to downpours (50 mm/hr) at 60 GHz (higher for tropical events). For 200-meter cells, the attenuation will be around 0.2 dB for 5mm/hr rain at 28 GHz and 0.9 dB for 25mm/hr rain at 28 GHz. The attenuation will be around 0.5 dB for 5mm/hr rain at 60 GHz and 2 dB for 25mm/hr rain at 60 GHz.
- (iii) Atmospheric absorption of 1–10 dB/km occurs at the mmWave frequencies. For 200-meter cells the absorption will be 0.04 dB at 28 GHz and 3.2 dB at 60 GHz.

TABLE 5: Path Loss Equations for mmWave 5G/5G IoT.

Scenario	LOS/NLOS	Pathloss [dB], (f_c is in GHz and d is in meters)	Shadow fading std [dB]	Applicability range, antenna height default values
UMi - Street Canyon	LOS	$PL_{UMi-LOS} = \begin{cases} PL_1 & 10m \leq d_{2D} \leq d'_{BP} \\ PL_2 & d'_{BP} \leq d_{2D} \leq 5km, \end{cases} \quad \text{see note 1}$ $PL_1 = 32.4 + 21 \log_{10}(d_{3D}) + 20 \log_{10}(f_c)$ $PL_2 = 32.4 + 40 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) - 9.5 \log_{10}((d'_{BP})^2 + (h_{BS} - h_{UT})^2)$	$\sigma_{SF} = 4$	$1.5m \leq h_{UT} \leq 22.5m$ $h_{BS} = 10m$
	NLOS	$PL_{UMi-NLOS} = \max(PL_{UMi-LOS}, PL'_{UMi-NLOS}) \quad \text{for } 10m \leq d_{2D} \leq 5km$ $PL'_{UMi-NLOS} = 35.3 \log_{10}(d_{3D}) + 22.4 + 21.3 \log_{10}(f_c) - 0.3(h_{UT} - 1.5)$ <p>Optional PL = $32.4 + 20 \log_{10}(f_c) + 31.9 \log_{10}(d_{3D})$</p>	$\sigma_{SF} = 7.82$	$1.5m \leq h_{UT} \leq 22.5m$ $h_{BS} = 10m$
InH - Office	LOS	$PL_{InH-LOS} = 32.4 + 17.3 \log_{10}(d_{3D}) + 20 \log_{10}(f_c)$	$\sigma_{SF} = 3$	$1m \leq d_{3D} \leq 100m$
	NLOS	$PL_{InH-NLOS} = \max(PL_{InH-LOS}, PL'_{InH-NLOS})$ $PL'_{InH-NLOS} = 38.3 \log_{10}(d_{3D}) + 17.30 + 24.9 \log_{10}(f_c)$ <p>Optional</p>	$\sigma_{SF} = 8.03$	$1m \leq d_{3D} \leq 86m$
		$PL'_{InH-NLOS} = 32.4 + 20 \log_{10}(f_c) + 31.9 \log_{10}(d_{3D})$	$\sigma_{SF} = 8.29$	$1m \leq d_{3D} \leq 86m$

Note 1: Breakpoint distance $d'_{BP} = 4h'_{BS}h'_{UT}f_c/c$, where f_c is the centre frequency in Hz, $c = 3.0 \times 10^8$ m/s is the propagation velocity in free space, and h'_{BS} and h'_{UT} are the effective antenna heights at the BS and the UT, respectively. The effective antenna heights h'_{BS} and h'_{UT} are computed as follows: $h'_{BS} = h_{BS} - h_E$, $h'_{UT} = h_{UT} - h_E$, where h_{BS} and h_{UT} are the actual antenna heights, and h_E is the effective environment height. For UMi $h_E = 1.0m$. For Uma $h_E = 1m$ with a probability equal to $1/(1 + C(d_{2D}, h_{UT}))$ and chosen from a discrete uniform distribution uniform $(12, 15, \dots, (h_{UT}-1.5))$ otherwise. With $C(d_{2D}, h_{UT})$ given by $C(d_{2D}, h_{UT}) = \{0, h_{UT} < 13m; ((h_{UT} - 13)/10)^{1.5}g(d_{2D}), 13m \leq h_{UT} \leq 23m\}$ where $g(d_{2D}) = \{0, d_{2D} \leq 18m; (5/4)(d_{2D}/100)^3 \exp(-d_{2D}/150), 18m < d_{2D}\}$

3GPP TR 38.901 version 14.0.0 Release 14
ETSI TR 138 901 V14.0.0 (2017-05).

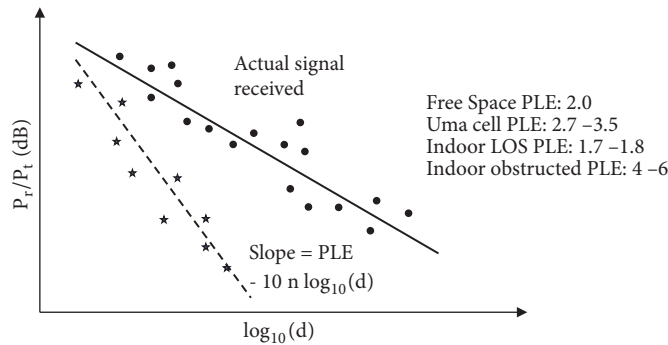


FIGURE 15: PLE.

Penetration into buildings is an issue for mmWave communication, this being a lesser concern for contemporary sub 1 GHz systems and even systems operating up to 6 GHz. O2I (Outdoor-to- Indoor) losses have to be taken into account. Actual measurements (e.g., at 38 GHz) demonstrated a penetration loss of 40 dB for brick pillars, 37 dB for a glass door, and 25 dB for a tinted glass window (indoor clear glass and drywall only had 3.6 and 6.8 dB of loss) [76]. This is why DASs are expected to be important for 5G in general and 5G IoT in particular.

3GPP and ETSI propose that the pathloss incorporating O2I building penetration loss be modelled as in the following [81]:

$$PL = PL_b + PL_{tw} + PL_{in} + N(0, \sigma_p^2) \quad (2)$$

where

PL_b is the basic outdoor path loss where d_{3D} is replaced by $d_{3D-out} + d_{3D-in}$

PL_{tw} is the building penetration loss through the external wall,

PL_{in} is the inside loss dependent on the depth into the building, and

σ_p is the standard deviation for the penetration loss

PL_{tw} is characterized as:

$$PL_{tw} = PL_{npi} - 10 \log_{10} \sum_{i=1}^N (p_i \times 10^{L_{material,i}/-10}) \quad (3)$$

where

PL_{npi} is an additional loss is added to the external wall loss to account for non-perpendicular incidence

$L_{material,i} = a_{material,i} + b_{material,i} \cdot f$, is the penetration loss of material i , example values below

Material	Penetration loss [dB]
Standard multi-pane glass	$L_{glass} = 2 + 0.2f$
IRR glass	$L_{IRRglass} = 23 + 0.3f$
Concrete	$L_{concrete} = 5 + 4f$
Wood	$L_{wood} = 4.85 + 0.12f$

Note: f is in GHz

p_i is proportion of i -th materials, where $\sum_{i=1}^N p_i = 1$; and N is the number of materials.

3GPP TR 38.901 version 14.0.0 Release 14

ETSI TR 138 901 V14.0.0 (2017-05)

In consideration of these propagation characteristics, many municipalities in the U.S. are concerned about the possible massive proliferation of small cells needed to support 5G. For example, a filing to the FCC was made in the U.S. late in 2018 by a consortium of towns known as the Communities and Special Districts Coalition in response to the Commission's September 5, 2018, Draft Declaratory Ruling and 3rd Report and Order where the FCC asserted the

claim that "small cell" deployment is a federal undertaking; furthermore the filing states that "*the massive deployment envisioned by the Commission raises substantial questions as to whether the Commission is in a position to assert that deployment is safe, given that its radio frequency emissions rules were based on technologies and deployment patterns that the Commission declares obsolete in this Order*" [74, 91]. Furthermore, it is unclear, according to the filing, what is the size of the equipment needed to support a small cell, since it could vary from a "pizza box" system to several racks that equate to 56 "pizza boxes" [91]. Although small cells will indeed need to be deployed to properly support 5G, caution is advocated. S&P Global Market Intelligence estimates that small-cell deployments reach approximately 850,000 in the U.S. by 2025 (with approximately 700,000 already deployed in 2019), with about 30% of small cell installations being outdoors; the same projection forecasts a total of 8.4 million small cells world-wide, with some regions of the world experiencing much higher deployments rates than in the U.S., e.g., doubling the 2019 numbers by the year 2025. These data show that placement within buildings is a common alternative (there will be more in-building systems than outdoor systems) [75].

4. 5G DAS for Indoor IoT Applications

The previous section discussed propagation issues at the higher frequencies. However, even the sub-6 GHz bands have issues penetrating buildings with the new building materials and infrared reflecting (IRR) glass. Indoor solutions are needed for IoT even at standard 3G/4G LTE frequencies and much more so at mmWave if cellular-based (5G) IoT transmission services for in-building applications are contemplated; outdoor 5G IoT applications do not.

Although it is in principle possible to support multiple access technologies in an IoT sensor (chipset), end-point IoT devices tend to have low complexity in order to achieve an established target price point and on-board power (battery) budget. Therefore a (large) number of applications will have devices that have a single implemented wireless uplink. It follows that -- either because of the goal of mobility support (for example, a wearable that works seamlessly indoors and in open spaces around town) or because of the designer's goal to utilize a single, consistent IoT nodal and access technology -- an all-sites wireless service for a Smart City application, is preferred. DASs may support such a goal (while city-wide Wi-Fi and/or Sigfox/LoRa could be an alternative, the ubiquity, standardization and cost-effectiveness of 5G cellular and IoT services, may well favor the latter in the future).

4.1. DAS Networks. A DAS is network of a (large) number of (small) (indoor or on-location) antennas connected to a common cellular source via fiber optic channel, providing cellular/wireless service within a given structure. DAS (sometimes also called in-building cellular) refers to the technology that enables the distribution and rebroadcasting of cellular, LTE, AWS, 5G and other RF frequencies within a building or confined/defined structural environment. While DAS is often used in large urban office buildings, DAS can also be used in

open spaces such as campuses, conference centers, stadiums, hospitals, airports, train stations, tunnels, hotels, cruise ships, and so on. DASs can and will support cellular-based IoT (e.g., LTE-M, NB-IoT, and 5G IoT.) Elements of a DAS include (see Figure 16):

- (i) (Small) Broadband antennas and amplifiers in the indoor space (typically one or more per floor) that shape the coverage. These antennas typically cover the entire spectrum of the cellular service (for/from multiple service providers;
- (ii) Coax or fiberoptic cabling to connect the structure antennas to a local Base Station;
- (iii) Remote Radio Head, a local Base Station, (“small cell”), typically in the basement; and,
- (iv) Fiberoptic connection to an aggregation point (typically in a carrier colocation space) (or the use of an outdoor donor antenna to a specific cellular provider). The former supports carrier-neutral applications, the latter typically supports only one carrier. Physical connectivity from the colocation space to each of the wireless providers is needed, typically in the form of fiber connectivity or other telecom service. Business relationships with the wireless providers are needed.

Current typical drivers include the fact that during anticipated peak times (whether in a building or in some public venue as a stadium) users will experience: coverage deficiencies, blocked connections, reduced data speeds, among other service deficiencies. Current systems support CDMA, EVDO, GSM, HSPA, UMTS, among others. Future systems will support 5G and become even more prevalent.

Given the mmWave transmission issues mentioned above (the small cells, the directionality, the free space loss and other attenuation factors) DASs will likely play a big role in 5G, both for regular voice and data services and for IoT. The large number of “small cells” cited earlier (8.4 million in 2025, with about 70% of these being considered to be indoors) supports the thesis that DASs will play a pivotal role in the future. They will be a key element of Smart City IoT support, especially for in-building sensors. As was shown in Figure 2, while a number of applications could use a Wi-Fi (or related) access technology with networked connection to the cloud, or a Sigfox/LoRa related solutions (these, however, being vendor proprietary), Smart City IoT service implementers may prefer to use a cellular service such as LTE-M or NB-IoT in the immediate future and 5G IoT as it becomes available, allowing a seamless and single-technology solution city-wide. In some cases, for example in smaller/older buildings and/or in suburbia and/or for buildings very close to a 5G cell tower, a direct 5G IoT connection may suffice. But for high-density urban and smart building applications, the use of DASs seems inevitable.

4.2. DAS Design. A single, carrier-neutral, consolidated system is often sought: a carrier-neutral system avoids multiplicity of antenna distribution, and sharing allows more coverage and higher capacity. A carrier-neutral DAS supports an end-use system, for example a smartphone, regardless of

which service provider the user is subscribed to. It would be rather expensive for a building owner to deploy a carrier-neutral DAS that supports a single building, unless it would be a very large building, campus, or installation. With carrier-neutral DAS arrangements the ownership of system is shifted from the building owner, or a specific cellular carrier to a third-party system provider, or a DAS integrator. Figure 17 depicts a typical carrier-neutral arrangement. Obtaining wireless carrier permission and coordinating between different wireless carriers is a key planning undertaking of any successful DAS rollout. Three scenarios are shown:

- (i) Scenario/Approach S1: The DAS integrator/provider wires up a remote building or space and drops a fiber link into an existing colo rack at an existing carrier-neutral provider, thus sharing all the Base Station Hotel (BSH) colo equipment and interfaces to the various wireless providers.
- (ii) Scenario/Approach S2: The DAS integrator/provider must build out the requisite base station equipment in the colo (the colo provider only provides power, rack space, HVAC, and so on). The DAS integrator/provider must also build interfaces to the wireless providers and secure business arrangements with them. The DAS integrator/provider builds out the remote buildings or venues.
- (iii) Scenario/Approach S3: The DAS integrator/provider must build out the requisite base station equipment in the colo, but the DAS integrator/provider can make use of existing interfaces and equipment to the various wireless providers. The DAS integrator/provider builds out the remote buildings or venues.

A less desirable approach is to use “donor antennas” (also shown in Figures 16 and 17). These antennas are installed on the roof of a building and are pointed at “donor” cell towers. Typically, a single cellular vendor is supported. The in-building arrangement is similar to that of a carrier-neutral arrangement, except that there typically will not be a remote base station: a combination of fiber optic cable, coaxial cable and in-building antennas is used to amplify and distribute those signals within a given space; coordination with the given carrier is still needed to make sure that the concentrated traffic is accepted by the provider.

5. 5G Deployment Snapshot

5.1. 5G Cellular Services. According to GSMA 5G is on track to account for 15% (1.4 billion) of global mobile connections by 2025. By early 2019, according to GSMA, eleven worldwide operators had announced initial 5G service launches and seven other operators had activated 5G base stations with commercial services to follow in the near future [92]. Select cities worldwide will have 5G by the end of 2019. See Table 6 for a summary of near-term 5G service-deployment activities. However, 4G services are expected to continue well past 2025: 4G will account for 59% of the connections, 3G for 20% of the connections, and 2G 5% of the connection (3G and 2G

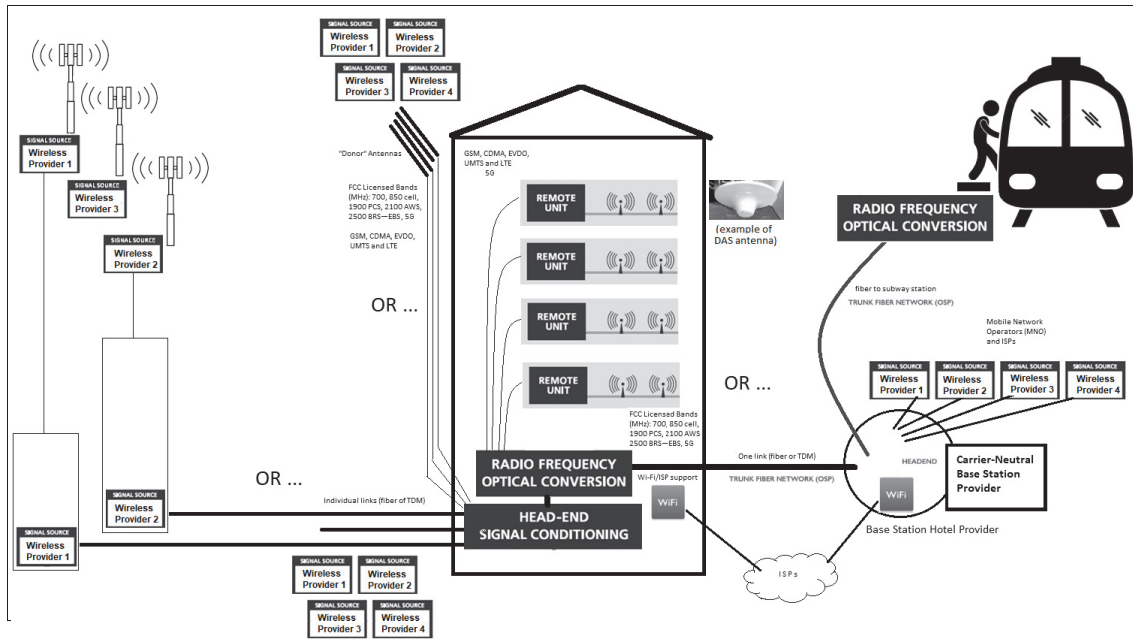


FIGURE 16: Elements of a DAS.

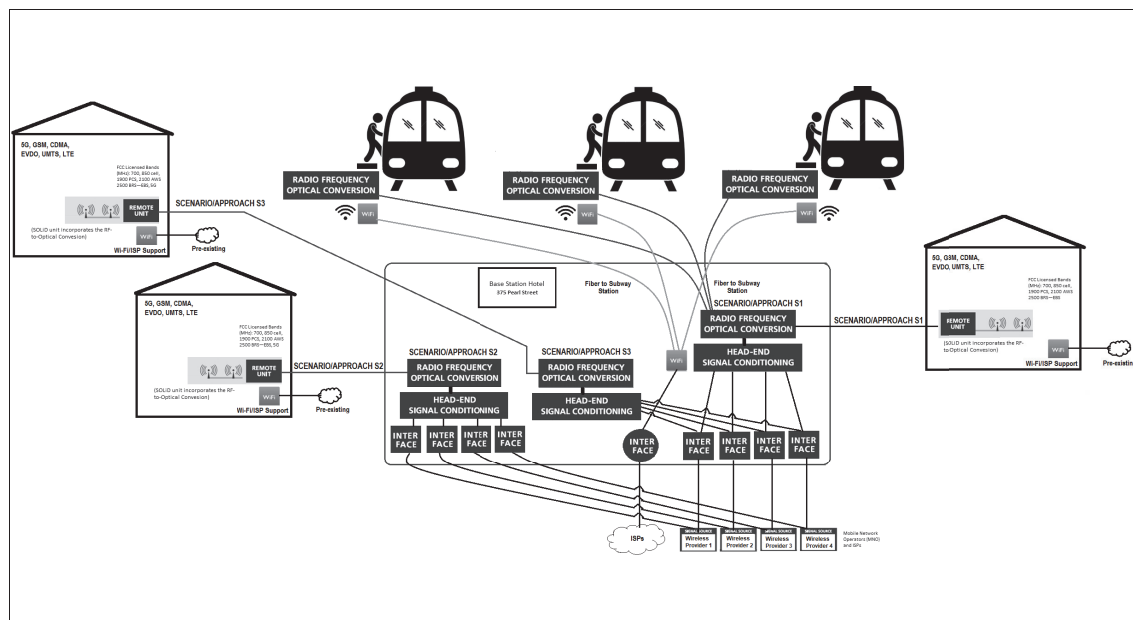


FIGURE 17: Carrier-neutral DAS.

are trending down through this period while 4G will continue to grow, but settle at around 60% by 2023 -- 5G is penetrating at approximate linear rate of CAGR around 1.5-2%). Also, according to GSMA 2019 will see 5G launches accelerate and devices hit the market: 16 major markets worldwide will start to offer commercial 5G networks in 2019, following on from the first 5G launches in South Korea and the U.S. in 2018, as follows [28]:

(i) Q4 2018: South Korea, U.S.

(ii) Q1 2019: Bahrain, Czech Republic, Estonia, Finland, Saudi Arabia, Switzerland

(iii) Q2 2019: Australia, Qatar

(iv) Q3 2019: Austria, China, Hong Kong, Kuwait, Spain, UAE

(v) Q4 2019: Portugal, UK

As of Q2 2019, there were 303 rollouts of 5G mobile networks across 294 locations worldwide, operated by 20 mobile

TABLE 6: Summary of near-term 5G service-deployment activities (2019 view).

Country or Region	Near-term 5G Activities
South Korea	Korea Telecom rolled out a trial 5G network in support of the 2018 Winter Olympics in Seoul, South Korea covering events in several cities. It has also launched a VR/AR games platform supported from the cloud over 5G. SK Telecom has acquired spectrum in the 3.5 GHz and 28 GHz frequencies in preparation of deploying 5G.
China	China plans early implementations of 5G. The GSMA estimates that by 2025 China will represent 40 percent of global 5G connections. According to the GSMA, with 460 million projected users China is expected to become the world's largest 5G market by 2025, higher than Europe's 205 million and the United States' 187 million combined. China's three major mobile operators - China Mobile, China Unicom and China Telecom - are rolling out trial operations of 5G systems in several cities, and all three aim to fully commercialize the technology by 2020 [66].
India	5G trials are contemplated by late 2019 and early deployments may happen late in 2020.
Japan	NTT DoCoMo demonstrated an advanced security service based on 5G network technology for use in the 2020 Olympics.
United States	Migration from the 4G networks should be relatively simple. The FCC has been making several new bands available as noted elsewhere. Verizon has been aggressive in its advertisement campaigns about its introduction of 5G-related services.
Europe	T-Mobile is preparing for the rollout of 5G in 2020, starting in the Netherlands. Some fear that Europe risks falling behind other regions because of restrictive regulation and weak investments; less than half of the countries in Europe have actually allocated spectrum for 5G [67].

carriers [93]. In the U.S., 21 deployments were documented, of which five were in Texas, four in California, two each in North Carolina and Florida, and one each in Oklahoma, Minnesota, Illinois, Indiana, Kentucky, Tennessee, Georgia, and Louisiana (some of these, such as the AT&T 5G network in Louisville, KY, had "Limited Availability" at that time.)

5.2. MmWave Spectrum. Regarding frequency bands 3GPP is initially focusing on 24 GHz to 43 GHz mmWave spectrum (Release 15.) Other ongoing 5G work relates to NSA and SA configurations Massive MIMO, beamforming, and LTE interoperability. 3GPP Release 16 (2019) aims at full compliance to IMT-2020 (e.g., supporting 1 GHz channels) and other spectrum capabilities (e.g., spectrum sharing, additional bands, and URLCC).

In the U.S., among other possible candidates, the FCC is making available new frequency bands for 5G use under its rubric of "Spectrum Frontiers proceeding", of which three have been instituted in the recent past. With the "July 2016 Order", the FCC designated the 27.5-28.35 GHz (known as the "28 GHz band"), 37-38.6 GHz (known as the "37 GHz band"), and 38.6-40 GHz (known as the "39 GHz band") bands for flexible mobile and fixed commercial use, and designated the 64-71 GHz band for unlicensed use (to supplement 57-64 GHz which had been made available for unlicensed use at an earlier time.) While the FCC has yet to auction any of the new Upper Microwave Flexible Use Service or (UMFUS) spectrum, in 2017, with a *Second Report and Order*, a *Memorandum Opinion and Order* it designated an additional 1700 megahertz of mmWave spectrum for licensed flexible commercial wireless fixed and mobile use. The 1700 MHz spectrum covered the 24.25-24.45, 24.75-25.25, and 47.2-48.2 GHz bands (the first two known collectively as the "24 GHz" bands, and the third, known as the "47 GHz" band). Therefore, the spectrum at 24.25-24.45 GHz is now allocated for non-Federal fixed and mobile services on a

co-primary basis, and the spectrum at 24.75-25.25 GHz for non-Federal fixed, mobile, and fixed-satellite (FSS) services on a co-primary basis [94].

In terms of rollouts, in the U.S., the spectra at 27.5 – 28.35 GHz and 37 – 40 GHz may see preliminary commercial deployments in 2019; in Korea, the spectrum at 26.5 – 29.5 GHz is similarly expected to see commercial deployments in 2019; and the EU expects commercial deployments for the 24.25 – 27.5 GHz spectrum starting around 2020.

In addition to the radio access for the end-user device, there is also interest in Backhaul and now also in Fronthaul. Backhaul mechanisms are mechanisms to connect the wireless network to the wired network by backhauling traffic from dispersed cell sites to Mobile Switching Offices (MSOs). These links typically are either traditional transmission systems (such as SONET or point-to-point microwave at various operating bands), or they are Ethernet-over-Fiber links (e.g., 1 GbE or 10 GbE). A UMa site has Baseband Unit (BBU) that processes user and control data, which is in turn connected to a Radio Unit (RU) to generate radio signals transmitted over the air via the tower-mounted antennas.

Fronthaul is related to a new type of Radio Access Network (RAN) architecture that is comprised of centralized baseband controllers and standalone radio heads installed at remote UMa or UMi sites possibly many miles away. In the fronthaul model the BBU and RU equipment is located further away from each other than is the case in the backhaul model. The RU equipment (now referred to as a Remote Radio Head [RRH]) is still located at the cell site, but the BBU is relocated to centralized location where it supports multiple RRHs. See Figure 18. The optical links that interconnect the newly centralized BBU and the multiple RRHs is referred to as fronthaul. The use of fronthaul-based C-RAN (Cloud-RAN) architectures typically improves the cell edge performance. Backhaul and fronthaul are key use cases for mmWave spectrum and will play a role in 5G and 5G IoT.

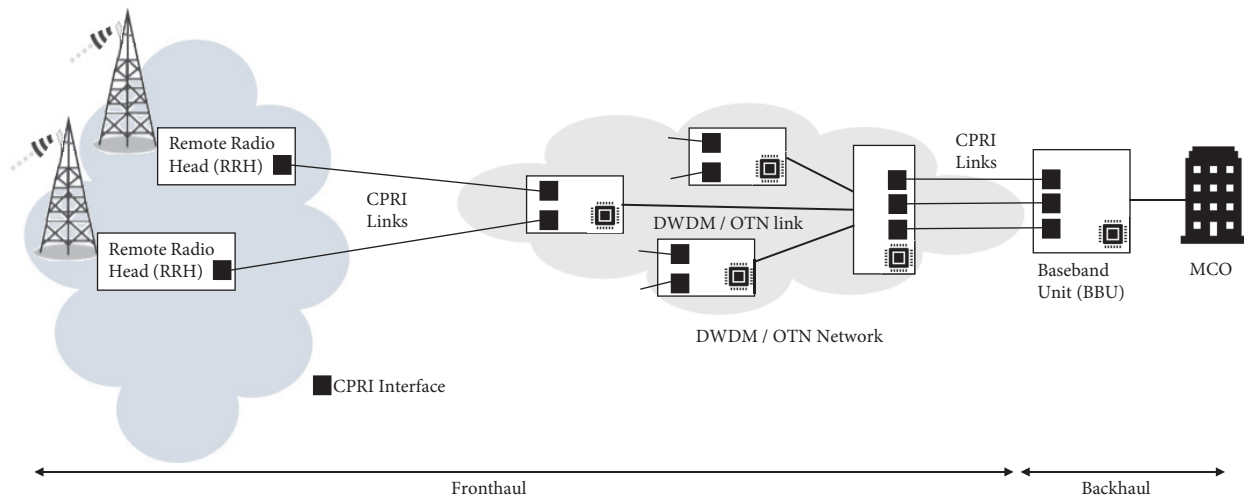


FIGURE 18: Fronthaul and Backhaul.

A consortium of wireless equipment vendors standardized the Common Public Radio Interface (CPRI) protocol that runs over these fronthaul links a few years ago; more recently, a newer eCPRI 1.0 interface has been defined; additionally, work is underway to defining a more detailed interface. The tight performance requirements of CPRI/eCPRI -- capacity, distance, and latency -- drive towards fiber connectivity such as DWDM (or more specifically OTN [Optical Transport Network]) systems between centralized BBUs and the RRHs. Ethernet-based solutions have existed for a number of years using mmWave spectrum. Work is underway in 3GPP to define backhauling solutions using the same spectrum as access. Work is also underway to define new fronthaul interfaces also utilizing mmWave spectrum.

5.3. 5G IoT Services. Global IoT revenue are expected to increase at an annual rate of 23% to 2025 to reach \$1.1 trillion (up from 267 B in 2018). As discussed in the next section, near term “5G IoT” really equate to NB-IoT and LTE-M capabilities. At the end of 2018, there were 83 commercial deployments of LTE-M and NB-IoT worldwide. However, pure connectivity will become increasingly commoditized, making it difficult for operators to compete on the data transmission alone, declining from 9% of total IoT revenue in 2018 to 5% in 2025. Service providers must develop new strategies and business models beyond connectivity services. Applications, platforms and services (e.g., cloud data analytics and IoT security) are the major growth areas of IoT; this segment will be approximately 70% of the market in 2025. Professional services (e.g., consulting, systems integration, also including managed services) will increase in share and will be approximately 25% of the market in 2025 [28].

6. Current Alternatives and Convergence to 5G

5G IoT will need to compete with other technologies, both of the cellular type (e.g., NB-IoT and LTE-M) as well as the non-cellular type (although NB-IoT and LTE-M are now considered “part of the 5G world”). The economics and

availability of these “legacy” networks in various parts of the world may be such that a level of inertia, frustrating a full migration to truly-novel 5G IoT services, will take hold. Clearly, in principle, 5G is better positioned for city/region-wide applications as contrasted with building or campus applications.

From an end-user perspective, design and implementation questions center around the following issues, which 5G IoT technology must be able to address successfully:

- (i) Availability of equipment;
- (ii) Availability of service (geographic coverage in the area of interest);
- (iii) Support of required technical details (latency, bandwidth, packet loss, and so on);
- (iv) Support of mobility (where needed, e.g., wearables, crowdsensing, Vehicle to Vehicle and Vehicle to Infrastructure applications, to name a few);
- (v) Adequate reliability (where needed, e.g., physical security, process control, Vehicle to Vehicle and Vehicle to Infrastructure applications, to name a few);
- (vi) Scalability support (functional and geographic/numerical expansion of the application)
- (vii) Initial and recurring cost of the equipment; and
- (viii) Initial and recurring cost of the service.

Recent acceptability and economics of NB-IoT and LTE-M can serve as a proxy for the near-term commercial success of 5G IoT in particular and truly-novel 5G IoT services in general. Some developers have looked at cellular services for city-wide or region-wide IoT coverage; in some instances, for example, for national truck transportation a combination of Low Earth Orbit (LEO) satellite service and cellular services have and are being used. A current drawback is the cost of the requisite (miniaturized) modems and the cost of the cellular service. New services such as NB-IoT and LTE Cat-M1 (an LTE-based 3GPP-sponsored alternative to NB-IoT,

also known as LTE-M) are short term attempts to address the cost and resource issues. In particular, NB-IoT is seen as providing a pathway to 5G IoT. 5G and truly-novel 5G IoT are the target solutions.

6.1. NB-IoT. As noted earlier, NB-IoT is a licensed low power LPWAN technology designed to coexist with existing LTE specifications and providing cellular-level QoS connectivity for IoT devices. NB-IoT was standardized by 3GPP in LTE Release 13, *but it does not operate in the LTE context per se* [95–97]. NB-IoT has attracted support from Qualcomm, Ericsson and Huawei, among many other vendors and service providers. NB-IoT (also known as LTE Cat-NB1) is based on a Direct Sequence Spread Spectrum (DSSS) modulation in a 200 kHz channel. There are several underutilized 200-kHz GSM spectrum channels, as well as other possible bands such as guard bands. NB-IoT is intended as an alternative to LoRa and Sigfox. This technology can optimize sunken financial investments by service providers and can shorten the service deployment rollout timetable for IoT services, since NB-IoT uses existing cellular infrastructure. NB-IoT service goals include: (i) low complexity end-nodes, (ii) device cost less than \$5, (iii) a device battery life expected to last for 10 years if it transmits 200 bytes of data per day, and (iv) uplink latency less than 10s (thus not a true real-time service). NB-IoT operates on 900-1800 MHz frequency bands with coverage of up to about 20 miles; it supports data rates of up to 250 Kbps for uplink and 230 Kbps for downlink communications [98–101]. NB-IoT can be implemented in a number of ways: (i) in standalone non-cellular licensed bands; (ii) in unused 200 kHz bands in the context of GSM or CDMA; and (iii) in LTE environments where base stations can allocate a resource block to NB-IoT transmissions. Since NB-IoT offers low cost for the device and for the service, it is a good choice for large-scale distributed deployment in Smart Cities and smart grid applications.

As illustrative commercial examples, in 2018 T-Mobile announced a North American NB-IoT plan that costs just \$6 a year – one tenth of Verizon’s Cat-M plans– for up to 12 MB per connected device, and several NB-IoT modules based on Qualcomm® MDM9206 LTE IoT modem that are certified for use on T-Mobile’s network. T-Mobile, in conjunction with Qualcomm and Ericsson conducted the first trial NB-IoT in the U.S. in 2017 across multiple sites; T-Mobile and the City of Las Vegas also announced a partnership to deploy IoT technology throughout the city. For applications that require more bandwidth and voice, T-Mobile offers Cat-1 IoT Access Packs [102, 103]. NB-IoT consumes minimal power: while most IoT end-nodes save power when they are quiescent, when the node and the modem are running and handling all the signal processing, the systems with simpler waveform (such NB-IoT) consume less overall power. Additionally, chipsets that support a single protocol (such as NB-IoT) are cheaper compared to a chipset that supports multiple protocols. Furthermore, *prima facie*, NB-IoT may provide deeper building penetration than LTE-M.

6.2. LTE-M. LTE-M is a power-efficient system, where two innovations support battery efficiency: LTE eDRX (Extended

Discontinuous Reception) and LTE PSM (Power Saving Mode). LTE-M allows the upload of 10 bytes of data a day (LTE-M messages are fairly short compared to NB-IoT messages), but also allows access to Mbps rates. Therefore, LTE-M can support several use cases. In the U.S., major carriers such as Verizon and AT&T offer LTE-M services (as noted, Verizon has announced support for NB-IoT -- T-Mobile and Sprint appears to lean in the NB-IoT direction) [104]. Worldwide geographies with GSM deployments will likely offer NB-IoT in the short term. Figure 19 depicts some of the IoT compatibility mechanisms to be incorporated into 5G in terms of band and bandwidth; however, the transmission frequencies will be wildly different.

In summary, LTE-M supports low nodal complexity, high nodal density, low nodal power consumption, low latency and extended geographic coverage, while allowing service operators the reuse of the LTE installed base. NB-IoT aims at improved indoor coverage, high nodal density for low throughput devices, low delay sensitivity, low node cost, low nodal power consumption and simplified network architecture. NB-IoT and LTE-M are currently providing mobile IoT solutions for smart cities, smart logistics, and smart metering, but only in small deployments to date (as of early 2018, there were 43 commercial NB-IoT and LTE-M networks worldwide [105]). As noted, the commercial success of NB-IoT and LTE-M can serve as a proxy for the eventual success of 5G IoT in a smart city context (compared with non-cellular LPWAN solutions).

NB-IoT, LTE-M and LTE are 4G standards, but advocates claim that they remain integral parts of early releases of 5G. Proponents make the case that “*enterprises deploying either NB-IoT or LTE-M are futureproofing their IoT projects because when 5G rollouts become commonplace these two Mobile IoT standards will continue into foreseeable 5G releases (from 3GPP Release 15 on)*” [102]. In the context of 3GPP Rel 15, it appears, in fact, that NB-IoT and LTE-M will be included as 5G mobile standards. In 2018 the GSMA asserted that “*NB-IoT and LTE-M, as deployed today, are part of the 5G family; with the dawn of the 5G era [...] both NB-IoT and LTE-M technologies are an integral part of 5G, and that 5G from the LPWA perspective, is already here today*” [105]. Including these technologies as initial 5G IoT standards will motivate service providers and vendors to support these implementations for IoT deployments as an evolutionary strategy to 5G. 3GPP Release 16 (targeted for the end of 2019) is considered to be the “second 5G standard” and thereafter transmitted to the ITU for consideration as a global standard. Among other functionality and capabilities, Release 16 is expected to add standards for connected cars and smart factories (notably, automobile companies have formed the 5G Automotive Association to assist 3GPP to set autonomous vehicle standards, such as 5G cellular vehicle-to-everything [C-V2X]).

7. Conclusion

This paper discussed a number of issues related to 5G-based IoT applications, particularly in Smart Cities environments,

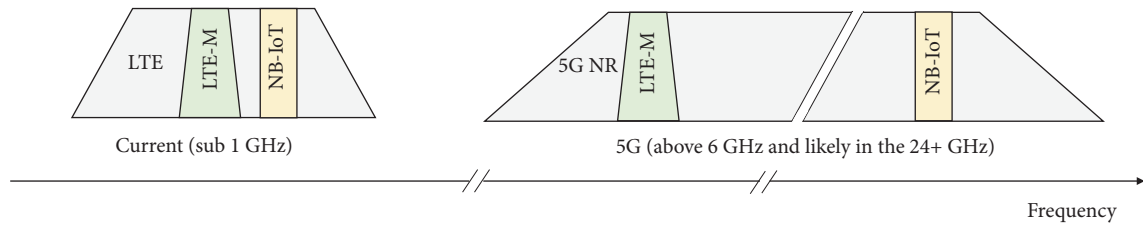


FIGURE 19: Support of LTE-M and NB-IoT under 5G.

including the need for small cells, the transmission issues at the millimeter wave frequencies, building penetration issues, the need for DAS, and the near term introduction of pre-5G IoT technologies such as NB-IoT and LTE-M, these being possible proxies for 5G IoT deployment.

A firm definition of 5G IoT has still to emerge, although a large number of use cases have been described by various industry entities. Both 3GPP NB-IoT and LTE-M technologies are seen at this juncture as integral to 5G services: these 4G technologies are expected to continue under full support in 5G networks for the immediate future. However, IoT/Smart City applications that require high bandwidth will need implementations of eMBB and mmWave frequencies.

Some controversy existed at press time about the development of 5G equipment, in the context of origin-of-manufacturing and the possible intrinsic risk related to cybersecurity [106]. If these issues are not satisfactorily resolved, some delay in the broad early deployment of 5G may result. However, the expectation is that these issues will work themselves out over time.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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