The Voice for 5G in the Americas

4G americas

5G Spectrum Recommendations

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EXECUTIVE SUMMARY

The evolution of mobile broadband wireless to the 5th generation is driven by increased capacity demands, improved throughput and additional use cases for wireless access where all things that can be connected will be connected in a seamless fashion. The International Telecommunications Union Radiocommunication Sector (ITU-R), in close collaboration with various stakeholders including the global mobile industry, has embarked on defining the process, timeline and deliverables for the next generation of IMT systems, called IMT-2020, to realize this future vision of mobile broadband communications. To achieve a connected society, 5G services require access to spectrum in a variety of bands to support the multitude of use cases including the need to improve the quality of the service offered and to accommodate much wider channels than those in use today. This white paper describes the drivers behind the spectrum requirements and the need for access to numerous spectrum ranges, the challenges and implications with different frequency ranges, various licensing aspects and potential technology enhancements to enable access to new spectrum.

The 5G spectrum requirements are primarily driven by the combination of expected increases in traffic capacity demands and the support for new use cases that will be enabled by the 5G ecosystem. The 5G technical requirements to support 5G use cases (e.g. peak data rate greater than 10 Gbps, cell edge data rate of 100 Mbps and 1 msec end-to-end latency[1]) could potentially be met in a variety of carrier frequencies. These 5G use cases include enhanced mobile broadband to deliver applications such as high definition video, supported both in very high density (e.g., stadiums) and with ubiquitous coverage. Other categories of 5G use cases include ultra-reliable communications for industry/transport automation, low latency communications applications, and high/medium data rate service for massive Machine Type Communication (MTC) for various applications like e-health, vehicle-to-vehicle (V2V), augmented reality and tactile internet. These and other use cases will further impact the expected increase in spectrum demand.

The suitability to support various use cases depends on the physical characteristics of different frequency bands, ranging from low frequency (~500MHz) to high frequency (>60 GHz). While the lower frequencies have better propagation characteristics for better coverage and thus can support both macro and small cell deployments, the higher frequencies support wider bandwidth carriers (due to potential large spectrum availability at mm-wave bands).

As much of the spectrum, especially in the lower ranges, is currently used by other applications and services, a critical aspect to securing additional spectrum is to leverage new regulatory frameworks involving shared spectrum whenever dedicated licensed spectrum is not feasible. This will help address the need for more spectrum and enable more efficient utilization of the spectrum while still protecting the incumbent services.

Technological advancements underway in the industry leading to 5G is enabled by the emergence of commercially viable semiconductor and antenna array implementations in a variety of spectrum ranges (e.g., in cm- and mm-wave ranges). These advancements are providing access to large contiguous bands of spectrum otherwise inaccessible to mobile systems.

[1] Recommendation ITU-R M.[IMT.Vision], document 5/199, "Framework and overall objectives of the future development of IMT for 2020 and beyond" [adopted in July 2015].

IMT-2000 and IMT-Advanced serve the basis for existing mobile broadband communication systems deployed today. IMT-2020 ("5G") is an extension of the ITU's existing family of global standards. It is expected that the standardization process for IMT-2020 will be completed in the year 2020 timeframe. To coincide with the availability of the IMT-2020 standard is the need for new spectrum with the characteristics described in this paper. Accomplishing the identification of spectrum in the desired timeframe will rely on regulators' cooperation and guidance in the World Radiocommunication Conference (WRC) in the years 2015 (WRC-15) and 2019 (WRC-19) if the vision of a seamlessly connected society of the next decade is to be realized.

1 INTRODUCTION TO 5G

5G is associated with the next step of IMT (i.e., IMT-2020), for which initial planning is currently under way in the ITU. Additionally, a number of other changes in the end-to-end system will be part of 5G evolution, both in the Radio Access Network (RAN) and core network. 5G is the term that is being applied in the market to systems beyond IMT-Advanced (i.e., beyond LTE-Advanced and WMAN-Advanced). In its various white papers on the topic, 4G Americas has stated that while past generations have been identified by a major new technology step, such as the definition of a new air interface, the expectation is that 5G will be approached from an end-to-end system perspective and include major technology steps both in the RAN and core network.

Furthermore, as 4G Americas stated in *4G Americas' Recommendations on 5G Requirements and Solutions*:

> 3G and 4G technologies have mainly focused on the mobile broadband use case, providing enhanced system capacity and offering higher data rates. This focus will clearly continue in the future 5G era, with capacity and data rates being driven by services such as video.
>
> But the future also will be much more than just enhancements to the "conventional" mobile broadband use case. Future wireless networks should offer wireless access to anyone and anything. Thus, in the future, wireless access will go beyond humans and expand to serve any entity that may benefit from being connected. This vision often is referred to as "the Internet of Things (IoT)," "the Networked Society," "Machine-to-Machine communications (M2M)" or "machine-centric communications." North American operators' best customers are no longer humans; they're increasingly machines such as smart utility meters, digital signage and vehicle infotainment systems.[2]

While the technologies that will constitute 5G are still being defined, the drivers for the development of the technology are well understood. The ITU-R has identified three main usage scenarios for 5G:[3]

- Enhanced mobile broadband
- Ultra-reliable and low latency communications
- Massive machine type communications

[2] *4G Americas' Recommendations on 5G Requirements and Solutions*, October 2014.
[3] *Ibid.*

Figure 1.1 illustrates those usage scenarios and some associated applications which will be further explored in Section 2.

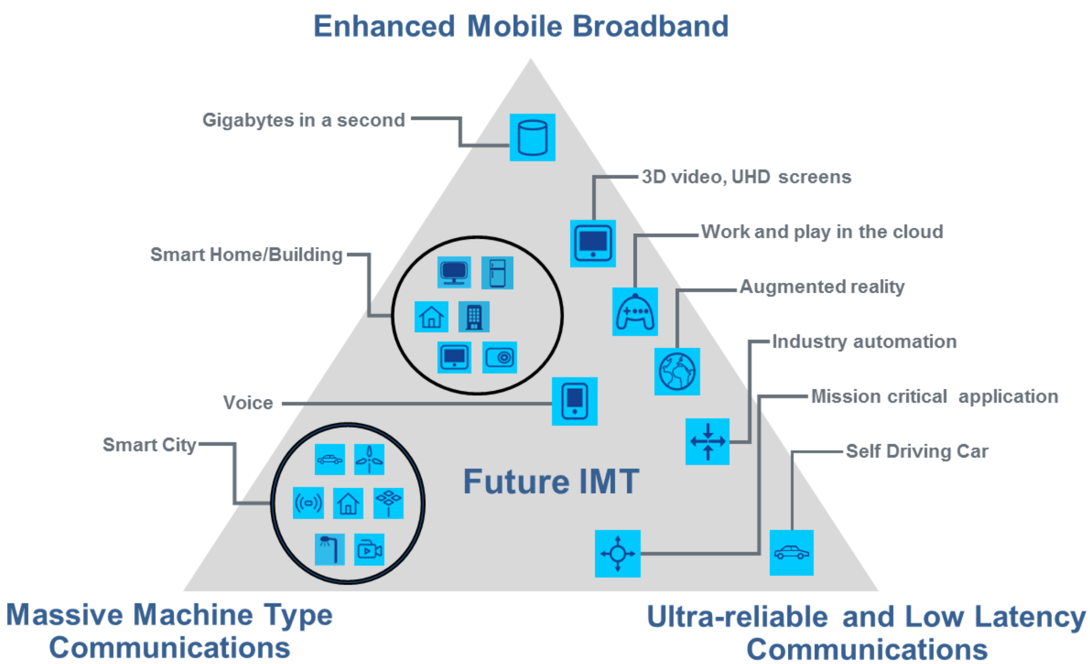

Figure 1.1. Usage Scenarios of IMT for 2020 and beyond.[4]

2 APPLICATIONS DRIVING 5G SPECTRUM REQUIREMENTS

Many factors contribute to the need for additional licensed and in some respects repurposed spectrum to accommodate new or alternative capabilities of wireless systems. These factors include new technological advancements, emergence of new applications and growth in user demand for wireless services.

Technological advancements, such as commercial viability of wideband carriers, have in the past created the need for larger blocks of spectrum. The emergence of applications such as video has also continuously called for radio interface designs with faster connection speeds and even wider channels. Growth in user demand has also put pressure on networks to utilize measures to relieve congestion by various means including access to more spectrum.

This section focuses on how new and emerging applications drive system requirements which in turn have implications on spectrum.

[4]Recommendation ITU-R M.[IMT.Vision], document 5/199, "Framework and overall objectives of the future development of IMT for 2020 and beyond" [adopted in July 2015].

2.1 SUMMARY OF 5G APPLICATIONS REQUIREMENTS

Many applications are envisaged for 5G. These include enhancements to some of the existing 4G use cases as well as some new and emerging applications. High resolution video (4k, 8k), Virtual Reality (VR) and Augmented Reality (AR) for gaming or other purposes, Internet of Things (IoT), wearable devices and mission critical applications for both industrial and commercial purposes are among these new and emerging applications. Figure 1 provides a depiction of these various applications as they relate to the three major usage scenarios described by the ITU and included in Section 1.

To be enabled, these applications each have specific technical requirements that need to be addressed through adequate design of the 5G radio interface(s) and access to appropriate frequency ranges. While some of these applications, such as high resolution video, would require ultra-fast connection speeds, others might need very robust performance and wide reaching range.

Table 2.1 summarizes important implications of various applications on radio interface design and spectrum.

It should be noted that some of the applications in Table 2.1 will be supported by evolved 4G systems with existing spectrum. However, 5G systems will provide additional capabilities and as a result, consideration of required spectrum for 5G should include all applications foreseen for future networks.

Table 2.1. Potential requirements of various 5G applications impacting radio link design (not an exhaustive list).

Usage Scenario	Application	High-level Requirement
Enhanced Mobile Broadband	UHD video (4k, 8k), 3D video (including broadcast services)	Ultra-high speed radio links Low latency (real-time video)
	Virtual Reality	Ultra-high speed radio links Ultra-low latency
	Augmented Reality	Ultra-high speed radio links Low latency
	Tactile Internet	Ultra-low latency
	Cloud gaming	Ultra-high speed radio links Low latency
	Broadband kiosks	Ultra-high speed radio links Short range
	Vehicular (cars, buses, trains, aerial stations, etc.)	Ultra-high speed radio links Short to long range Support for low to high-Doppler environments
Ultra-reliable Communications	Industrial automation	Ultra-high reliability radio links High speed radio links Low to ultra-low latency Short to long range Operation in cluttered environments
	Mission-critical applications e.g. e-health, hazardous environments, rescue missions, etc.	Ultra-high reliability radio links High speed radio links Low to ultra-low latency Short to long range Operation in cluttered environments Ground/obstacle penetration
	Self-driving vehicles	Ultra-high reliability radio links High speed radio links Low to ultra-low latency Short to long range Operation in cluttered environments

		Operation near fast moving obstacles
Massive Machine-Type Communications	Smart home	Operation in cluttered environment Obstacle penetration
	Smart office	Operation in cluttered environment Obstacle penetration High reliability radio links
	Smart city	Short to long range Operation in cluttered environment Operation near fast moving obstacles High reliability radio links Ground/obstacle penetration
	Sensor networks (industrial, commercial, etc.)	Short to long range Operation in cluttered environment Operation near fast moving obstacles Ground/obstacle penetration Mesh networking

2.2 IMPACT ON SPECTRUM NEEDS

The requirements listed in Table 2.1 have potential implications not only on the radio interface design but, more relevantly, to the *type* and *amount* of spectrum needed for optimum operation. To provide an example for factors affecting the amount of spectrum, for instance, ultra-high speed connections in the range of multi-gigabit per second could potentially be achieved through using ultra-wide carrier bandwidths in the order of up to several hundred MHz or more. An example could be fast downloads of 4k/8k video content, which using wide channels and through multi-gigabit speeds, would take seconds. Another example of factors affecting the type of spectrum is the case of ultra-reliable communications for mission critical applications such as public safety, where obstacle and ground penetration for ubiquitous coverage in critical times would require use of lower frequencies such as those in the lower Ultra-High Frequency (UHF) band.

In order to come up with a mapping between applications and required spectrum, Table 2.2 lists potential spectrum-related implications of various high-level requirements for future 5G systems.

Table 2.2. Potential Spectrum-Related Implications of Various 5G Requirements.

High-level Requirement	Potential Spectrum-Related Implications
Ultra-high speed radio links	Ultra-wide carrier bandwidths, e.g. 500 MHz Multi-gigabit fronthaul/backhaul
High speed radio links	Wide carrier bandwidths, e.g. 100 MHz Gigabit fronthaul/backhaul
Support for low to high-Doppler environment	Depends on the throughput requirement
Ultra-low latency	Short range implications
Low latency	Mid-short range implications
Ultra-high reliability radio links	Severe impact of rain and other atmospheric effects on link availability in higher frequencies, e.g. mm-wave, for outdoor operations
High reliability radio links	Impact of rain and other atmospheric effects on link availability in higher frequencies, e.g. mm-wave, for outdoor operations
Short range	Higher frequencies, e.g. mm-wave
Long range	Lower frequencies, e.g. sub-3 GHz
Ground/obstacle penetration	Lower frequencies, e.g. sub-1 GHz
Operation in cluttered environment	Diffraction dominated environment in lower frequencies Reflection dominated environment in higher frequencies
Operation near fast moving obstacles	Frequency-selective fading channels
Mesh networking	High-speed distributed wireless backhaul operating in-band or out-of-band

Arriving at spectrum needs from the information in Tables 2.1 and 2.2 requires consideration of a number of important points including those delineated as follows:

Deployment Environments

Cellular networks do not operate in isolation. There are often systems and services operating in adjacent bands that impact the performance of a cellular system. As a result, the amount of spectrum required to deliver a certain level of guaranteed performance is also related to factors such as interference from adjacent systems.

In addition to adjacent systems and services, there are instances in many geographical areas where there may be multiple network operators. The multi-operator situation has two consequences. First, the national regulatory process needs to provide for the amount of spectrum sufficient to build multiple networks. Secondly, in some cases, especially in the case of unsynchronized TDD operation, adjacent operators could lead to inter-system interference affecting the performance of each network. The amount of spectrum required for proper separation of adjacent cellular networks, including the unsynchronized TDD scenario, should also be taken into account. One way to lower these risks is the establishment of guard bands between various operators and between an operator and adjacent non-cellular services. Detailed spectrum estimation should take into consideration the need for providing adequate isolation between adjacent systems through guard bands.

Frequency Reuse

Modern cellular systems have inherently greater spectral efficiency because, in addition to use of more spectrally efficient technologies, they operate with a frequency reuse of one throughout a deployment area. However, intra- and inter-system interference sometimes make it necessary to use additional carriers, i.e. frequency reuse of greater than one, to provide adequate coverage, quality, and capacity to subscribers. The need for additional carriers as a means to optimize network performance should also be taken into consideration when estimating required spectrum for 5G networks.

Radio Interface Capabilities

Advancements in radio interface design including utilization of antenna techniques such as new and more spectrally efficient modulation schemes, novel multiple access mechanisms, etc., has been pushing the limit towards theoretical boundaries of channel capacity as expressed by the Shannon Theorem. Nonetheless, employing multiple antenna techniques such as massive MIMO and beamforming are among the means through which spectral efficiency of future 5G systems are expected to increase even further. The spectral efficiency expected for 5G radio interfaces should also be taken into account in arriving at spectrum estimates for 5G.

3 IMPORTANCE OF ACCESS TO A VARIETY OF SPECTRUM RESOURCES FOR 5G

This section describes the importance of availability of a variety of spectrum bands in support of 5G for a diverse set of applications, use cases and deployment scenarios with different requirements on performance and therefore spectrum. While certain applications would require highly robust performance over a long distance (a characteristic of lower frequencies), other applications would need very high throughput over shorter distances (a characteristic of higher frequencies). These aspects could be optimally achieved by service providers having access to a variety of bands to deliver a full 5G service.

3.1 ROLE OF LOWER/HIGHER FREQUENCY BANDS

5G entails the next generation of mobile technology that will allow for massively increased connectivity for a networked society, enhanced mobile broadband and the introduction of new modes of communication for very high reliability and service guarantee. It will be a very flexible, heterogeneous system employing numerous technological enhancements that can be configured to provide connectivity simultaneously to a wide range of application types with differing characteristics and requirements. To support these needs, 5G systems will require access to spectrum with the appropriate characteristics.

Several important aspects for regulators to consider as they prepare for 5G include:

- 5G will both interoperate with the evolution of evolved LTE and provide new radio access that will support many new and evolving use cases.
- While recognizing that spectrum below 6 GHz will be critical to building a healthy 5G ecosystem, it is to be noted that higher frequency bands offer real promise for the provision of very high data rates and high system capacity in dense deployments.
- Global harmonization of spectrum resources and technical regulation is highly desirable.
- Wider spectrum allocations enable wider bandwidth signals which, in turn, enable high data rates and shorter transmission intervals, permitting new applications that can provide, for example, very low latency access.
- As the frequency is increased, Non-Line-of-Sight (NLOS) coverage will be increasingly challenging, especially between indoor and outdoor locations and in rural and suburban areas where Line-of-Sight (LOS) is not augmented by reflective paths. LOS coverage will be possible, but obstructions and vegetation will pose difficulties to reception. Diffraction loss will be higher than in traditional cellular bands and will limit coverage in hilly terrain.

3.1.1 BELOW 6 GHZ

As 5G systems develop over time, the mobile spectrum bands below 6 GHz will be valuable to allow the smooth migration from LTE usage to 5G. Again, as time progresses, there will be a continued evolution of LTE for mobile broadband using evolving techniques such as higher-order modulations and carrier aggregation to expand bandwidth capabilities beyond current limitations. Three-carrier aggregation has already been successfully demonstrated using a 3GPP Release 10 (LTE-Advanced) system specification. LTE Releases 12 and 13 specifications will introduce a new LTE-compatible air interface for MTC, capable of low complexity and energy variants for delay-tolerant sensor systems.

These new LTE features can be implemented in mobile bands below 6 GHz in a timely manner and without major spectrum allocation rule changes. As a result, the mobile broadband industry can evolve 4G systems and phase into 5G technologies in bands below 6 GHz, as spectrum is allocated and licensed, and thereby leverage on existing technologies and features.

The continuous increase in data and video traffic makes it essential to increase the amount of spectrum within which these technologies can be deployed and in a way that is compatible with currently allocated bands, so that current and new bands can be used in a complementary manner and in the same devices with comparable technology. New mobile broadband spectrum below 6 GHz can be used together with current mobile broadband spectrum in a well-understood manner. In short, spectrum below 6 GHz can be put to use in the short term to expand the capacity and availability of existing mobile broadband networks.

It should be noted that WRC-15 agenda item 1.1 addresses additional spectrum for mobile broadband. Report ITU-R M.2290 provides the results of studies that estimate the total global spectrum for IMT to be in the range of 1340 (for lower user density settings) to 1960 MHz (for higher user density settings) for the year 2020. For Region 2 (the Americas), the estimated additional (i.e., beyond spectrum already identified) spectrum requirement would be 389-1009 MHz. It is imperative that the short-term needs for mobile broadband be addressed via identification of spectrum for IMT at WRC-15.

3.1.2 ABOVE 6 GHZ

4G Americas believes that the mobile industry is capable of extending mobile services into spectrum bands in the range above 6 GHz to gain additional bandwidth. It is anticipated that 5G systems will largely be used in environments that allow very localized and dense deployment, potentially making Time Division Duplex (TDD) more viable. TDD, in this environment, enables flexible resource allocation which is important in the fluctuating traffic conditions observed in small cell networks. TDD system design also needs to consider synchronization requirements (particularly for indoor deployments) where synchronization between systems can be challenging, as well as air-interface latency requirements. 4G Americas proposes that spectrum license blocks in the order of several hundred MHz per operator be made available, with the stipulation of accommodating multiple operators per band.

The path loss between transmitting and receiving antennas is proportional to the square of the frequency due to a reduction of the aperture as wavelength becomes smaller. Furthermore, penetration loss, diffraction loss, etc., also increase with increasing frequency. The bands between 6 GHz and 30 GHz are important to consider due to propagation reasons. These losses must be compensated by increasing the antenna gain (at the transmitter or receiver) as the frequency is increased. As a result, lower frequencies provide for more uniform coverage in NLOS situations than higher frequencies, which might be important for certain applications such as real-time video. At higher frequencies, one must rely on potential reflections to cover NLOS cases. There are significant studies underway in both industry and academia on characterization of frequencies below and above 30 GHz for 5G applications. These are further described in Section 6.

Due to potential of availability of wider bandwidths, the mm-wave bands above 30 GHz hold promise for providing high peak data rates in specific areas where traffic demands are very high, such as high-definition video communications. For example, such bands could serve high bandwidth data transfers for video services and large data transfers within and between data centers, and for high bandwidth virtual interactive communication between people. It should also be noted that given system trade-offs, techniques such as higher order MIMO could help to achieve this goal in lower bands as well.

Due to the different frequency characteristics described in this section, frequency bands from 6-100 GHz must be considered to support the various 5G applications.

3.1.3 WRC-19

The following guidelines apply to 6 GHz and above:

- Sufficient bandwidths of several GHz should be made available for 5G at WRC-19

- Studies will be needed to determine which bands may be suitable
- The studies should primarily focus on frequency bands with allocation to mobile services in all three regions, however, if all the spectrum requirements are not fulfilled, other alternatives should be considered for allocation
- The studies should consider sharing and coexistence with existing services
- 4G Americas proposes to exclude bands that have an allocation to passive services on a primary basis

3.2 CURRENT GLOBAL STATUS OF SPECTRUM CONSIDERED FOR 5G

Various administrations have started investigation and consideration of potential new bands for 5G. This investigation is similar to industry efforts to characterize new frequency ranges for 5G and the development of technical solutions towards the next generation of mobile broadband cellular systems. Given the need for more bandwidth, these investigations generally have been directed towards opportunities in the 6 GHz to 100 GHz frequency range.

Various administrations' investigation of new frequency bands for 5G around the world are at varying stages. Some regulators, including the FCC, have been investigating spectrum for 5G services by seeking public comments through domestic processes. Others, including the UK Ofcom, have chosen to complement public commenting with pursuing a proposal in the WRC-15 preparation process in their region towards obtaining consensus for consideration of 5G spectrum as part of the set of WRC-19 agenda items.

Table 3.1 summarizes the status of various public proposals as of June 2015.

Table 3.1. Status of Public Proposals for 5G Spectrum Bands Worldwide.

Country	Status/Frequency Ranges	Notes
Australia	Supports WRC-19 agenda item to consider higher bands from among mobile bands. Proposed: 10-10.6, 21.4-23.6, 25.25-27, 31-31.3, 31.8-33.4, 37-40, 40.5-47, 50.4-52.6, 59.3-76, 81-86 GHz	Proposal submitted to APG July 2015 (see note 1).
China	Supports WRC-19 agenda item - no specific proposal is publicly presented at this stage.	Current ranges expressed (May 2015): 25-30, 40-50, 71-76, 81-86 GHz.
Finland	Supports WRC-19 agenda item looking for IMT spectrum between 6 GHz and 100 GHz. Proposed: 8.5-10.6, 13.4-15.2, 15.7-17.3, 19.7-21.2, 24-27.5, 30-31.3, 33.4-36, 37-52.6, 59.3-76, 81-86, 92-100 GHz.	Proposal submitted to CPG. CPG September 2015 will finalize regional views.
Japan	No specific ranges publicly mentioned. Supports a new agenda item to consider identification of frequency bands for IMT in higher frequency ranges for WRC-19.	Initial expression of ranges (2014): 14, 28, 40, 48, 70, 80 GHz

Korea	Supports a future agenda to support wide and contiguous spectrum in the frequency bands below. Proposed: 27.5-29.6, 31.8-33.4, 37-42.5, 45.5-50.2, 50.4-52.6, 66-74 GHz.	Proposal submitted to APG July 2015 (see note 1).
Sweden	Supports a new agenda item in the range 5925 MHz to 100 GHz from among mobile and fixed bands. Proposed: 5.925-7.025, 7.235-7.25, 7.750-8.025, 10-10.45, 10.5-10.68, 12.75-13.25, 14.3-15.35, 17.7-19.7, 21.4-23.6, 24.25-29.5, 31-31.3, 32.3-33.4, 38-47, 47.2-50.2, 50.4-52.6, 55.78-76, 81-86 GHz.	Proposal submitted to CPG. CPG September 2015 will finalize regional views.
United Kingdom	Supports a future agenda item for 'IMT above 6 GHz' focussed on number of identified bands: 10.125-10.225 GHz / 10.475-10.575 GHz; 31.8-33.4 GHz; 40.5-43.5 GHz; 45.5-48.9 GHz; and 66-71 GHz.	Seeking comments, Proposal to CPG. CPG September 2015 will finalize regional views.
United States	The United States has decided on proposing the following ranges to be studied for consideration at WRC-19. 27.5-29.5 GHz, 37-40.5 GHz, 47.2-50.2 GHz, 50.4-52.6 GHz, and 59.3-71 GHz.	FCC NOI Seeking comments on 24.25-24.45 GHz and 25.05-25.25 GHz, 27.5-28.35 GHz, 29.1-29.25 GHz and 31-31.3 GHz, 37.0-38.6 GHz, 38.6-40 GHz, 42.0-42.5 GHz, 57-64 GHz, 64-71 GHz, 71-76 GHz and 81-86 GHz.
Note 1: APG July 2015 agreed on the following ranges: 25.25-25.5, 31.8-33.4, 39-47, 47.2-50.2, 50.4-52.6, 66-76, 81-86 GHz.		

4 LICENSING ASPECTS OF 5G SPECTRUM

This section describes how various licensing regimens could be used to implement and deploy 5G systems.

4.1 LICENSED BANDS

Traditionally, spectrum used for cellular communication has been in licensed bands, where regulatory bodies have granted exclusive rights for an entity to use the spectrum to offer services.

The rules for exclusive rights to use spectrum are different between countries. Some countries/regions set rules on the type of service that will be using the spectrum together with technical rules regarding handling of interference, both internal to the band and for out-of-band interference. In some countries/regions, the exclusive rights also mandate the use of a specific technology, or a set of technologies, that shall be used to offer the service.

The process of gaining exclusive rights also differs depending on specific countries/regions and may involve:

- Public auctions to grant the right to use the spectrum for a service
- Obligations to build the specified services within a defined time frame, and/or
- Reservation of rights granted for a public-service (e.g., Public Safety, Aviation, etc.)

In many cases, there are multiple aspects involved in the process for the regulatory body to grant the rights to use the spectrum band, or part of it, exclusively. Exclusive use licensed spectrum will be a critical element of 5G systems and deployments, to provide a predictable and stable way to determine capacity for deployed networks.

4.2 SHARED LICENSED BANDS

While licensed spectrum provides exclusive rights to use the spectrum and thereby make interference management simpler, it may limit the flexibility of how the spectrum usage may change over time. This has created situations whereby spectrum that has been allocated, and to which exclusive rights have been granted, is under-utilized. The utilization may be geographically concentrated or may only be used for limited periods, while in other geographical areas and time periods, the spectrum is not used at all.

To enable more flexibility and allow for increased utilization, the concept of shared spectrum has been introduced. As such, a defined number of users of the spectrum are granted rights to use the spectrum. This, for example, allows granting use of the spectrum to a second tier user (i.e., “new licensee”), under specific rules to avoid or limit the interference with a higher tier user (i.e., “incumbent licensee”). The right to use the spectrum would be limited to geographic areas where the incumbent licensee of the spectrum does not utilize it for a set period of time.

To enable shared spectrum models, Authorized Shared Access (ASA)/Licensed Shared Access (LSA) regulatory frameworks and supporting technical aspects have been developed. With a central database holding the information on the usage of the spectrum, the second tier user for the spectrum can automatically be granted the rights to use the spectrum in a geographical area for a specified and limited time period.

The shared license model provides 5G systems and deployments with an important flexibility to use spectrum that is under-utilized by other services to provide additional capacity, without interfering with the incumbent.

4.3 UNLICENSED BANDS

Unlicensed/license-exempt bands are spectrum that has been defined for use collectively by an undetermined number of independent users without registration or individual permission.

For unlicensed bands, the regulator establishes rules for how applications, technologies and industries shall use the spectrum that allows applications and users to coexist under limited interference with each other. The rules are defined openly with no limitation on technologies and application other than requirements to avoid harmful interference and reduce risk for interference. With unlicensed spectrum, there is no process for establishing rights for its use, and therefore it may be used by any device that is compliant with usage rules, such as maximum power levels, bandwidth limitations and duty cycles.

The use of unlicensed spectrum is an important complement for all 5G systems and deployments, particularly in small cell deployments.

5 REGIONAL/GLOBAL HARMONIZATION OF 5G SPECTRUM

This section describes the importance of harmonization of 5G spectrum on a regional, and preferably on a global basis, to create economies of scale, reduce overall cost to consumers, and as a result, provide faster adoption and proliferation of the technology. Activities undertaken in various regional organizations working on 5G technology, as well as the role various international and regional entities such as ITU-R, and individual regulators, specifically the FCC, could play in creating harmonization of spectrum around the globe are also described.

5.1 ROLE OF ITU-R AND REGIONAL GROUPS

While technological advancements have paved the way for support of many spectrum bands over time in mobile devices, timely implementation of major technical leaps always benefits from economies of scale created through regional, and preferably global, harmonization of spectrum bands and their conditions of use. Such harmonization reduces overall R&D and deployment costs, which leads to lower costs for consumers, and as a result, provides for faster adoption and proliferation of the technology. In general, radio transceivers are economically viable if they are operated in bandwidths within a few percentages of the center carrier frequency. As a result, bands far apart from each other must be covered with separate radio units within the device, which increases the cost and complexity of the device.

5G systems are no exception. Activities undertaken by various regional organizations and research projects working on 5G technology development will benefit from harmonization of spectrum bands considered by various international (e.g., ITU-R) and regional (e.g., CITEL) organizations.

ITU-R, through its World Radio Conference 2015 (WRC-15) process, could give a significant boost to paving the way for 5G by making timely decisions on the following matters:

- Agreeing on creating an agenda item for WRC-19 on consideration of spectrum for IMT-2020 (5G)
- Agreeing on consideration for studies of a range of frequencies proposed by regional groups from within which a set of globally harmonized bands could be identified for 5G
- Consideration of ranges/bands that could accommodate various use cases and applications envisaged for 5G systems (see Section 2 and Appendix B)

ITU-R could also play a vital role by bringing together the 5G expertise from around the world (standards developing organizations, research entities, regulators and academia) and expertise within ITU-R (Working Party 5D) to complete development of 5G (IMT-2020) standards according to ITU-R-agreed timelines. Developments of such standards need to be accompanied by studies on spectrum matters. ITU-R Working Party 5D, as the focal point of these studies, could bring together technological aspects of 5G with identification of globally harmonized bands for consideration at WRC-19. Figure 5.1 contains the overall ITU-R timeline for development of 5G.

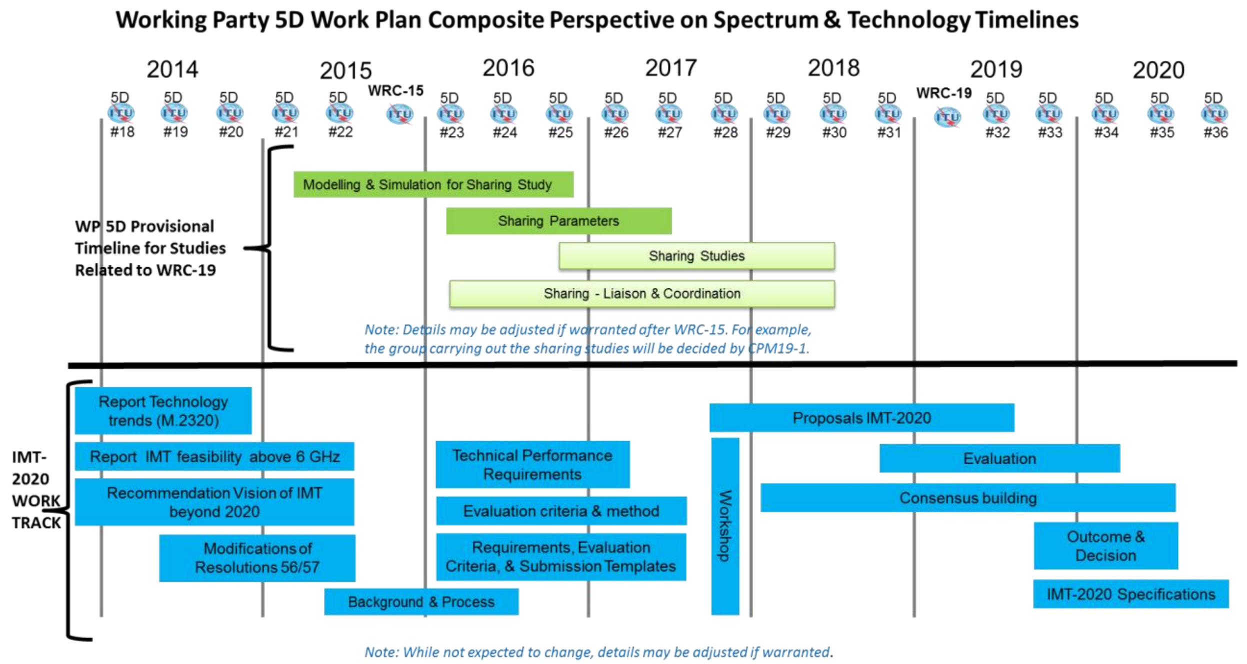

Figure 5.1. ITU-R 5G/IMT-2020 Timeline.

5.2 ROLE OF FCC

The United States Federal Communications Commission (FCC) published a Notice of Inquiry (NOI) in October 2014, in which they sought comments on several bands as potential for 5G. Information sought was on technical matters and licensing options for the following bands:

- 24 GHz Bands: 24.25-24.45 GHz and 25.05-25.25 GHz
- LMDS Band: 27.5-28.35 GHz, 29.1-29.25 GHz, and 31-31.3 GHz
- 39 GHz Band: 38.6-40 GHz
- 37/42 GHz Bands: 37.0-38.6 GHz and 42.0-42.5 GHz
- 60 GHz Bands: 57-64 GHz and 64-71 GHz (extension)
- 70/80 GHz Bands: 71-76 GHz, 81-86 GHz, 92-95 GHz

These bands are graphically shown in Figure 5.2.

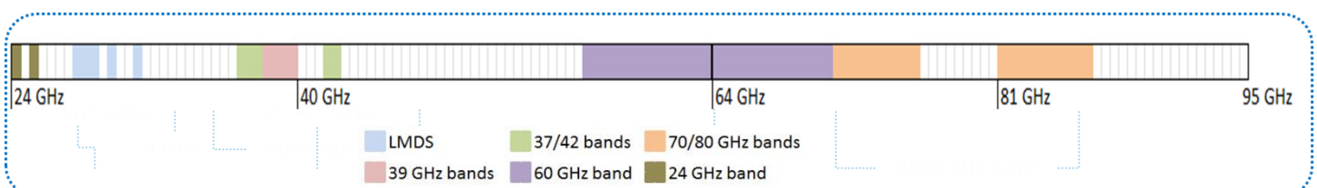

Figure 5.2. Bands Under Investigation in the FCC NOI on 5G.

The FCC was the first regulator around the world who asked specific questions about consideration of suitable spectrum for future mobile broadband systems (i.e., 5G). Since then, other regulators around the world have also approached the subject in the prelude to WRC-15 discussions on a WRC-19 AI for 5G spectrum. The FCC's timely follow up of the NOI through consideration of the following would play a crucial role in setting the stage for the development of 5G in North America and the entire region.

- Engaging with industry through events and workshops to stay at the forefront of 5G technology development
- Consideration of potential service rules for potential 5G bands
- Consideration of licensing options that would facilitate the implementation and deployment of 5G systems in a timely manner, thus increasing the chances of the region becoming the leader in 5G

The United States has decided on proposing the following ranges to be studied for consideration at WRC-19 as potential ranges for 5G spectrum.

- 27.5-29.5 GHz
- 37-40.5 GHz
- 47.2-50.2 GHz
- 50.4-52.6 GHz
- 59.3-71 GHz

The FCC, together with other regulators of the Americas region, could also play a significant role in the international discussions and negotiations before and during WRC-15 for reaching agreement on a set of globally harmonized spectrum bands for 5G.

6 POTENTIAL SOLUTIONS FOR ENABLING ACCESS TO NEW SPECTRUM FOR 5G

This section describes some of the solutions that could potentially be utilized to facilitate and enable access to new spectrum for 5G. These aspects are directly related to technological advancements leading to 5G. For example, commercially viable semiconductor and antenna array implementations at higher bands (e.g., in mm-wave), could make available many opportunities for spectrum otherwise inaccessible to mobile systems. Also, development of interference avoidance and/or protection mechanisms would facilitate better sharing of some of these bands with incumbents.

6.1 PROTECTION OF INCUMBENTS

The commercial mobile market has blossomed under a framework of access to exclusively licensed spectrum. This paradigm is driving the deployment of robust 4G broadband networks across the country and this can continue to be the case for 5G. Therefore, identifying additional spectrum for exclusive licensing must remain the top objective for regulators, even for 5G.

While 4G Americas urges regulators to implement an exclusive licensing regimen in all 5G bands to the greatest extent possible, sharing of spectrum in bands that cannot be cleared in an appropriate timeframe should be considered. For instance sharing with incumbents such as Fixed Satellite Services (FSS), radar, etc., may be possible while ensuring flexibility of technology and use as well as protection of incumbent operations. Therefore, 4G Americas encourages regulators to conduct radio compatibility studies to derive emission and coordination requirements to enable coexistence between 5G and incumbents in the same or adjacent bands.

In addition, 5G can exploit the fact that in some cases, a significant amount of spectrum is used only regionally or intermittently by incumbent users. This can allow for the sharing of spectrum on a territorial or time basis. In this way, regulators could ensure that 5G users could access greater spectrum resources without causing harmful interference to the incumbent user.

To protect incumbents, a mechanism is needed to ensure commercial users will not harmfully interfere with the incumbents. Protection of the incumbents may include:

- Sensing equipment to confirm that spectrum is not currently in use by the primary user and/or a database to track the incumbent spectrum and their usage needs
- A beacon signal transmitted by the incumbent user that can be detected by commercial users in the region who can then adjust their transmissions accordingly
- Proper consideration of fairness (with regard to spectrum access and interference) when multiple technologies are used in the same or adjacent spectrum

The database solution works best for regional sharing where the incumbent uses the spectrum only at fixed locations (like TV channels, FSS stations, or ground based radar). Sensing may be used for time based sharing where and when the incumbent may not be using the spectrum during certain times or if the incumbent user is mobile (e.g., a maritime radar). Industry has developed a trial system utilizing a database repository for spectrum sharing for TD LTE at 2300 MHz[5].

Recently, the FCC released a Report and Order (R&O) for spectrum sharing of 150 MHz of spectrum at 3.55 GHz. This spectrum is currently used by the military, FSS and Wireless Broadband Service.[6] The FCC defined three tiers of users of this spectrum: Tier-1 is the incumbent (primary user), Tier-2 would be Priority Access Licensee and Tier-3 would be for General Authorized Access (the lowest priority).

The FCC has two phases in the rules for the 3550-3650 MHz (US military spectrum). In the first phase, no Environmental Sensing Capability (ESC) is needed; however, the FCC mandates a sizeable exclusion zone, especially along the coast where access to spectrum is minimal. In the second phase, the spectrum can be used within these exclusion zones, once the FCC certifies the sensing capability, provided the spectrum is not currently in-use by the incumbent (US Military) in that area. Even if the military is using the spectrum, it may be using only a small part of the spectrum and not the entire band, therefore spectrum access may still be possible.

In the coming years, the U.S. government has identified 1,000 MHz of federal spectrum that could be made available for commercial use on a shared basis.[7] On June 14, 2013, President Obama issued a memorandum through which the administration seeks to make more spectrum available for commercial use by allowing and encouraging shared access by commercial providers to spectrum that is currently allocated for federal use[8]. In response, the National Telecommunications and Information Administration (NTIA), which manages the federal government's use of spectrum, published a plan that identifies 960 MHz of federal spectrum to be considered for detailed sharing feasibility studies.[9]

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[5] http://networks.nokia.com/news-events/insight-newsletter/articles/5g-under-development-first-live-demo-of-authorized-shared-access.

[6] FCC Report and Order and Second Further Notice of Proposed Rulemaking, In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band. FCC 15-47, April 21, 2015.

[7] President's Council of Advisors on Science and Technology (PCAST) report on "Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth", July 2012.

[8] Memorandum for the Heads of Executive Departments and Agencies, *Expanding America's Leadership in Wireless Innovation* (rel. June 14, 2013), published at 78 Fed. Reg. 37431, June 20, 2013.

[9] http://www.ntia.doc.gov/files/ntia/publications/ntia_5th_interim_progress_report_on_ten-year_timetable_april_2015.pdf.

Some of the groups that have been studying solutions for spectrum sharing include:

- IETF Protocol to Access White Space (PAWS) Databases
- IEEE Dynamic Spectrum Access Networks Standards Committee (DySPAN-SC)
- IEEE 802.11af and 802.22
- ETSI: Reconfigurable Radio Systems (RRS)
- WINN Forum: Spectrum Sharing Committee (SSC)
- 3GPP SA5: Study on OAM support for Licensed Shared Access (LSA)

These are only some of the groups involved in addressing the industry needs of spectrum sharing.

6.2 SEMICONDUCTOR AND ANTENNA TECHNOLOGY

There is a large amount of spectrum available in bands from 6 - 100 GHz, along with new bands below 6 GHz that are attractive resources for 5G wireless mobile communications. Further, in order to meet the 5G requirements of more than 10 Gbps peak rate and 100 Mbps cell edge rate, both improved spectral efficiency over the current LTE-Advanced system and massive Multi-Input Multi-Output (MIMO) using advanced semiconductor and antenna technology will be fundamental to any 5G system design.

The main two techniques for improving system capacity and coverage are beamforming and spatial multiplexing. Beamforming increases the link Signal-to-Noise Ratio (SNR) through the coherent addition of the signal transmitted from the antenna array and thus increases capacity and coverage. Spatial multiplexing increases system capacity by forming multiple parallel spatial channels between the Access Points (AP) and one or more UEs at a time. The use of large scale phased arrays in 5G systems utilizes both of the above techniques to improve coverage, capacity and spectral efficiency in spectrum bands of up to 100 GHz. The use of spatial multiplexing also depends on 5G system bandwidth. As an example, at cm-wave bands where the maximum bandwidth availability is less than 500 MHz, 4 to 8 stream Single User (SU)-MIMO will be required to meet the 5G peak rate requirements, whereas at mm-wave bands a larger bandwidth (e.g., 2 GHz) with 2 stream SU-MIMO can be used.

The difference in wavelength between current cellular bands (e.g., 2 GHz) and cm-wave (3-30 GHz)/mm-wave (30-100 GHz) bands results in an extra 20-30 dB of path loss which is compensated by using large scale phased arrays. Large scale phased arrays are feasible at higher frequency bands since, as the carrier frequency increases, the size of the antenna array correspondingly decreases. As such, it will be feasible from a form-factor point of view to have antenna arrays with hundreds of elements for the higher frequency bands.

Depending upon the band of operation, the hardware architecture for implementing a massive MIMO system will be different. There are three classes of hardware architectures for antenna arrays, namely: i) baseband-oriented architectures; ii) RF-oriented architectures; and iii) hybrid architectures. In the baseband architecture, the beam forming occurs at baseband and there is a single transmit chain feeding each antenna. This type of architecture is well suited for bands below 6 GHz and allows for high flexibility and high performance but with high cost and high power consumption. The Radio Frequency (RF) architecture where each data stream feeds a single transmit chain is suited for mm-wave bands (> 30 GHz) and the beamforming weights are implemented as phase-shifters with limited or no ability to control the gain on each transmit branch. Finally, in the hybrid solution, the transmit beamforming solution is performed both at baseband and RF and will be used in cm-wave bands (6 GHz - 30 GHz). In mm-wave bands, highly integrated Radio Frequency Integrated Circuit (RFIC) solutions providing complete transmitter and receiver chains are clearly desirable to meet the size, cost and power consumption needs of future generations of mm-wave radio products. Although challenges do exist with semiconductors providing the necessary performance in mm-wave bands, advanced semiconductors can already operate in these bands and are continually evolving for future performance improvements.

6.3 PROPAGATION-RELATED IMPAIRMENTS

The principles of propagation of the electromagnetic wave are similar in cm-wave and mm-wave bands. However, the difference in wavelength between the two bands will cause the propagation mechanisms to have some different characteristics. The main differences between cm-wave and mm-wave propagation and interaction mechanisms are the following:

Free space path loss: The Friis transmission law states that the free space path loss grows with the square of the frequency. The reason is that the Friis law assumes the size of the transmitting and receiving antennas are fixed relative to a wavelength and hence the physical antenna aperture size decreases with frequency. The smaller wavelength of mm-wave signals means that more antennas can be fit into the same physical area which then enables greater antenna gain for the same physical area. Therefore, mm-wave propagation is not subject to larger free space loss when the same physical area is used for multiple antennas.

Diffraction: Diffraction loss increases proportionally with frequency and will not be a dominant propagation mechanism for mm-wave frequencies. The cm-wave range below 10GHz diffraction is the main propagation mechanism in NLOS areas. For cm-wave frequencies above 10GHz, diffraction is present, but is not dominating the NLOS propagation. While at mm-wave frequencies, there is no diffraction.

Reflection and scattering: Reflection mechanisms are characterized by specular reflection (e.g., reflections from objects such as walls, vehicles, ground and even people) and diffuse reflection (scattering of the signal energy when encountering an object). The specular reflection transmission mechanism is fairly consistent for all frequencies in the cm-wave and mm-wave bands and hence is the most reliable means of obtaining signals in non-line-of-sight conditions. For scattering, the roughness of materials relative to the wavelength is important. Hence in mm-wave bands, diffuse reflection is enhanced relative to the cm-wave range. The diffuse reflection mechanism could help to extend the coverage range of mm-wave systems due to scattering of the radio wave in a broad range of angles, and thereby reaching the NLOS areas. This topic is now being studied in mm-wave research communities involved in propagation studies.

Material penetration is the amount of energy that is able to be transmitted through an object. Typically, the loss will increase as the frequency is increased and hence some in-building penetration may be possible at the lower part of the cm-wave band but will be difficult, if not impossible, at the higher end of the cm-wave band and in the mm-wave band. While outdoor-to-indoor propagation will be difficult in this frequency range, the increased isolation between indoor and outdoor systems significantly reduces interference.

Oxygen and water absorption, rain loss: The expected maximum supportable range of 100-150 meters makes these losses marginal even at mm-wave bands (no more than 6.0 dB in the very worst case rain events).

Foliage loss: This increases with frequency and will be a detriment in mm-wave and also partially in upper cm-wave band communications. However, this can be overcome with reflections and/or rapid rerouting to a different access point. Also, tight integration of different layers with potential multi-layer-connectivity can guarantee a seamless user experience.

The described principles are being verified in measurement campaigns in different cities and at frequency bands from 6-100 GHz. The evaluation of 5G systems in these frequency bands, and even below 6 GHz, will need a high-confidence channel model which will be available by the mid-2016 time frame. The channel models must properly model frequency dependence of diffraction, diffuse scattering, polarization, delay/angle spreads, blockage and penetration loss.

7 CONCLUSION

According to the ITU, there are expected to be 9.2 billion mobile subscriptions worldwide by the year 2020. This includes population growth and a dramatic increase in subscriptions attributable to M2M and IoT. Many other factors also contribute to the need for new, additional or repurposed spectrum to accommodate new or alternative capabilities of mobile broadband wireless systems. These factors include new technological advancements, emergence of new applications, and growth in user demand for wireless services. For instance, ultra-high speed connections in the range of multi-gigabit per second could potentially be achieved through using ultra-wide carrier bandwidths in the order of several hundred MHz or more.

This paper analyzes various aspects of 5G spectrum requirements and characteristics. Specifically, the following points were discussed:

- As 4G systems evolve and 5G systems develop over time, mobile spectrum bands below 6 GHz will be valuable to allow the smooth migration from 4G LTE usage to 5G.
- Despite challenges, the mobile industry is capable of extending mobile services into spectrum bands in the range above 6 GHz.
- A variety of bands is needed to address both coverage and capacity needs of evolved 4G and 5G systems. Frequencies beyond those traditionally used for cellular systems, especially those above 6 GHz are important to consider. While the lower frequencies have better propagation characteristics for better coverage and thus can support both macro and small cell deployments, higher frequencies can support wider bandwidth carriers (due to large spectrum availability at mm-wave bands) for providing very high peak data rates in specific areas where traffic demands are very high.
- Action is needed by regulators to ensure that new spectrum needs are addressed for the evolution of 4G (WRC-15, agenda item 1.1) and, additionally to address societal needs and for the timely introduction of 5G, to identify new spectrum ranges to be studied in ITU-R (WRC-15, agenda item 10 and WRC-19).

APPENDIX A: ACRONYM LIST

3GPP	3rd Generation Partnership Project
5G	5th Generation
AP	Access Point
AR	Augmented Reality
CITEL	Inter-American Telecommunication Commission
cm-wave	centimeter-waves
ESC	Environmental Sensing Capability

FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FSS	Fixed Satellite Service
IMT	International Mobile Telecommunications
IoT	Internet of Things
ITU	International Telecommunications Union
ITU-R	ITU Radiocommunication Sector
LOS	Line-of-Sight
LMDS	Local Multi-Point Distribution Services
LTE	Long Term Evolution
M2M	Machine-to-Machine
MIMO	Multiple-Input Multiple-Output
mm-wave	millimeter-waves
MTC	Machine-Type Communications
NLOS	Non-Line-of-Sight
NOI	Notice of Inquiry
NTIA	National Telecommunications and Information Administration
PSTN	Public Switched Telephone Network
RAN	Radio Access Network
SNR	Signal-to-Noise Ratio
SU-MIMO	Single User MIMO
TDD	Time Division Duplex
UE	User Equipment
UHD	Ultra-High Definition
UHF	Ultra-High Frequency
VR	Virtual Reality
WRC	World Radiocommunication Conference

APPENDIX B: POTENTIAL 5G APPLICATIONS AND USE CASES

The material below is from the white paper, *4G Americas' Recommendations on 5G Requirements and Solutions*, published in October 2014.

B.1 INTERNET OF THINGS (IoT)

A variety of IoT applications leveraging cellular infrastructure can be envisioned to be prevalent by 2020; opportunities exist from power meters used in Smart Grid to Public Warning Systems utilizing wirelessly connected earthquake/tsunami detection sensors. All such applications can and are beginning to get deployed even on today's cellular networks. However IoT applications are predicted to grow at a much faster pace than perhaps what existing networks and cellular technologies can optimally handle. To support possibly billions of IoT devices, a wireless network infrastructure is needed which is not only highly scalable in terms of its capacity, but can also optimally handle differing service needs of various IoT verticals. Examples of differing service needs include different requirements on mobility, latency, network reliability and resiliency. These diverse set of requirements may require re-architecting key components of the cellular network for example to support mobility on demand whereby mobility is only provided to those devices and services that need it. The following example use cases involving Machine Type Communication (MTC)[10] will become the societal norm in the 2020 timeframe.

B.1.1 SMART GRID AND CRITICAL INFRASTRUCTURE MONITORING

Today's societies depend on a wide array of critical infrastructure to function properly. Malfunction or damage to this infrastructure could result in huge financial impact, quality of living degradation, and even loss of life. The power blackout in Northeastern United States in 2003 was an example of how infrastructure failure can bring an entire region and its economy to a halt. Other examples of such disruption include bridge and building structural failure leading to collapse, water and sewer system malfunctioning, etc. It is therefore important to monitor the "health" of critical infrastructure reliably and cost effectively.

Critical infrastructure monitoring is an expensive undertaking, often requiring service levels achievable only by dedicated wire-line connectivity. For instance, in order to detect a fault in a high-voltage transmission line, and be able to take corrective action to prevent cascading failures, the required communication latency is beyond what current wireless networks can achieve. Similarly, structural monitoring requires the provisioning of a large number of low-data-rate battery-powered wireless sensors and today's wireless networks are not optimized to support this deployment model, both in terms of battery life and cost efficiency. 5G will be designed to support reliable low-latency communications among densely deployed devices that are subject to power constraints and wide-ranging data-rate requirements.

B.1.2 SMART CITIES

Massive urbanization is an ongoing trend around the world which is leading to severe strain on city services, resources, and infrastructure. According to the World Health Organization, by 2030, six out of every ten people will live in a city. Smart-City initiatives aim at improving cost, resource, and process efficiency of cities, while maintaining a high living quality for their rising populations. The following are two potential examples of 5G enabled Smart City use cases:

Smart Transportation: Traffic congestion is becoming a major issue in many urban areas, which lead to productivity loss, environmental pollution, and degradation of quality of life. 5G will enable real-time collection of massive data from vehicles, drivers, pedestrians, road sensors, and cameras to help streamline traffic flow. For example, it can help optimize traffic lights and road usage, direct public transportation to where it is needed most, navigate vehicles to avoid congestion, raise tolls to limit traffic entering a congestion zone, etc.

Smart Building: Urban buildings are major consumers of energy and resources. Streamlining building operations will lead to increased productivity and energy efficiency. For example, 5G connected sensors/actuators can help optimize building temperature, humidity, and lighting based on current activities. They will also enable buildings to detect when hidden pipes and cables need repair, when

[10] Within the industry several different terms are used to describe machine to machine communications, these terms include IoT, M2M, MTC, etc. In this white paper, we use these terms interchangeably.

unauthorized access takes place, when office supplies are running low, and even when garbage bins are full. These allow building management to take appropriate action in a cost effective and timely manner.

Smart Home: Home security and automation applications constitute another M2M service area that is expected to grow significantly in the future. Examples include the transmission of critical home safety alarms and home surveillance video data to commercial monitoring stations.

B.1.3 mHEALTH AND TELEMEDICINE

Telemedicine is a major tool towards improving healthcare access both in remote rural and urban areas. It can help reduce healthcare cost while improving health outcomes. A major enabler in this field is the comprehensive use of cloud-based Electronic Medical Records that would serve as repositories of medical information about individual patients. With 5G, these records, containing high-resolution medical images and video, can be made available to physicians and medical professionals anytime anywhere. Remote, real-time general physician and specialist consultations would also contribute to cost savings, convenience and better and timelier medical outcomes.

A major hurdle in the realization of this scenario is the lack of a wireless infrastructure that would need to handle the voluminous nature of medical images and video with sizes ranging from hundreds of Megabytes to Gigabytes per instance. The increasing use of diagnostic tools such as 3D & 4D Ultrasounds[11], CAT scans & MRIs and the miniaturization of this equipment to a portable/hand-held form factor will lead to even higher demands being placed on wireless networks. In addition, massive improvements in the quality of low-cost mobile displays and application software now available to medical professionals makes this field ripe for massive adoption. Bio-connectivity, the continuous and automatic medical telemetry (temperature, blood pressure, heart-rate, blood glucose, etc.) collection via wearable sensors, is another strong emerging trend that will add to the wireless communications requirements. 5G will enable these and other future medical applications through significant improvements to wireless data throughput and network capacity.

B.1.4 AUTOMOTIVE

Advanced Driver Assistance Systems (ADAS) and Autonomous Vehicles are evolving trends in the automotive space. Together, they bring a number of benefits including better safety, fewer collisions, less congestion, better fuel economy, and even higher productivity for the drivers. 5G wireless technologies supporting high-speed low-latency vehicle-to-vehicle and vehicle-to-infrastructure communications are key enablers of ADAS and Autonomous Vehicles. In addition, today's drivers and passengers are demanding richer infotainment options which are adding to the strain on wireless networks. The following section describes several potential automotive use cases for 5G.

Vehicular Internet/Infotainment: Increasing content consumption by vehicle occupants will greatly contribute to the need for wireless bandwidth and mobile network capacity. Typical infotainment options include video, audio, Internet access, and upcoming applications such as augmented reality and heads up displays. For these applications, vehicle occupants will expect a user experience comparable to the

[11] 4D Ultrasound are ultrasound videos with 3D images where the 4th dimension is time. Most 4D ultrasound videos today are less than 5 frames per second. For greater diagnostic utility they would need to be much higher resolution and about 30 frames per second. For cardiac applications greater than 100 frames per second would be desirable.

levels offered by their home and office networks. The vehicles themselves form another group of Internet users for map, traffic data, and high resolution picture download, and sensor data and image upload.

Pre-Crash Sensing & Mitigation: Collisions not only lead to injury and/or property damage, they also result in time and productivity loss due to traffic congestion. Pre-crash sensing enables vehicles to sense imminent collisions and exchange relevant data among vehicles involved; thus allowing vehicles and drivers to take counter-measures to mitigate the impact of the collision. Pre-crash sensing requires highly reliable and extremely low latency vehicle-to-vehicle communications.

Cooperative Vehicles: Limited highway capacity in many cities often results in severe traffic congestion. Cooperative vehicles make use of Vehicle-to-Vehicle & Vehicle-to-Infrastructure communications to safely operate vehicles as a self-driving car train on a highway in order to improve highway capacity, reduce occurrence of driver error, and achieve better fuel economy. To ensure safety and reliability while operating as a self-driving car train, reliable and very low-latency communications among vehicles and with the infrastructure are needed.

Inter-Vehicle Information Exchange: Peer-to-peer inter-vehicular communication using D2D cellular technology under the guidance of the operator policies can allow vehicles to communicate information related to road safety and traffic congestion directly in a mesh fashion, thus offloading data from the traditional RAN infrastructure. This is just one possible example of the type of information that can be exchanged.

B.1.5 SPORTS AND FITNESS

Fitness-related applications, such as activity and body monitoring applications that track walking, running, and biking activities, metabolic rate, cardiovascular fitness, sleep quality, etc. will constitute a significant vertical market in M2M services. Some of these applications will utilize body or personal area networks to collect biometric information and then use cellular networks to transmit it back to centralized data acquisition sites.

B.2 EXTREME VIDEO AND GAMING APPLICATIONS – INCLUDING AUGMENTED/VIRTUAL REALITY

Future wireless communication systems will support extreme video and gaming applications that use features like augmented and virtual reality. Such immersive multimedia services would require the use of technologies such as 3D audio, 3D video and ultra-high definition formats and codec(s). Examples of such services include:

- Mobile tele-presence with 3D rendering capabilities that will extend well beyond the traditional wire-line office environment.
- Internet gaming, including wirelessly delivered gaming control with high resolution graphics and dynamic management of feedback mechanisms via smartphone to ensure an enhanced, augmented reality gaming environment.
- Adoption of higher resolution devices, head mounted displays and wearables in fields such as emergency services, public safety, telemedicine, smart cities, professional services, retail, etc. is expected to place further demands on mobile networks.

This type of interactive experience will require the network to support much lower latencies and much higher bandwidths than what is possible today.

B.3 EXPLOSIVE INCREASE IN DENSITY OF DATA USAGE

The use cases outlined so far in this section identify some general trends in the industry:

- The number of devices using cellular networks is expected to increase significantly in the coming years. In other words the density of cellular devices (i.e. devices/area) will increase. A large part of this increase will be coming from M2M services.

- Some of the future services will require much higher data rates compared to what is typically achievable today. Examples of such services have been provided in the previous use case on extreme video and Internet gaming.

Concentration of devices using Ultra High Definition (4k & 8k) video and high resolution picture & video-sharing applications occur at event venues, stadiums etc. In addition, significant variations in UL:DL traffic implies a need for air-interface design that can more flexibly assign traffic capacity to the different transmission directions. The effect of these two factors on network traffic will be multiplicative resulting in an explosive increase in data traffic demand per square mile of the coverage area especially in urban environments. Some of this is validated by looking at existing traffic trends where data traffic density in urban environments like sports stadium venues, financial businesses, hospitals, universities, and major transportation corridors has increased dramatically. To handle this surge of data traffic demand by 2020, network capacity would have to be increased by orders of magnitude.

B.4 PUBLIC SAFETY

The US is planning to deploy an LTE Broadband network for Public Safety at 700 MHz to leverage pricing of standardized commercial equipment. Canada is currently evaluating the use of an LTE Broadband network for Public Safety at 700 MHz. It seems natural that future wireless broadband networks will also need to consider public safety in their fundamental design. Some of the “special” public safety needs include:

- **Mission Critical Voice:** Allowing a public safety responder to push a button (push-to-talk) to communicate with other public safety responders. This needs to be extremely reliable, working both on and off network without any delay for dialing phone numbers. The feature needs to allow communication with one or more groups [e.g., local police, regional police, local public safety (e.g., fire, ambulance, etc.)] in real-time. Public safety users must be able to monitor multiple groups simultaneously (scanning communication on different groups) and allow the user to join an on-going group discussion.

- **Broadband Data:** Much of this will be IP traffic from a public safety device to a server (possibly in the cloud). Although this capability can be handled by existing LTE equipment; it is important that 5G consider the following public safety use cases.
    - High-resolution security cameras monitoring public spaces and property with the captured images/video analyzed to alert authorities when incidents occur or persons or interest are detected.
    - Drone or robot based surveillance systems to monitor remote areas.

- Wireless sensors and tracking devices used for intrusion detection, bio and chemical hazard detection, and emergency personnel tracking.

The data generated by these and many other modalities will significantly strain 4G radio link and networks.

Besides these needs specifically for public safety officials, 5G systems will need to support legacy public safety features such as: Public Warning System (PWS), Emergency Calling, Multi-media Emergency Services (MMES), and Lawful Intercept.

To support all such use cases future wireless networks must provide a robust, highly reliable, resilient, and low latency communication infrastructure.

B.5 PSTN SUNSET

The Public Switched Telephone Network (PSTN) sunset in North America is scheduled prior to 2020 and with the general industry trend of migrating towards wireless communication, it is expected that in the 2020 timeframe and beyond, wireless broadband networks will be commonly used in today's PSTN domain. Therefore the 5G Ecosystem must also serve today's land line needs. For 5G networks to be considered a viable replacement to PSTN, they must exhibit the same levels of reliability and robustness. In addition, PSTN services primarily serve stationary customers that do not require support for mobility. The concept of mobility-on-demand that can simplify the packet core and make it scalable should be explored.

B.6 CONTEXT AWARE SERVICES

The past decade has seen a tremendous rise in the use of always on Internet connected devices. The users of such devices are consistently bombarded with information most of which may not be relevant or actionable for them. For the most part existing service models require users of such devices to reach out to the Internet to get the useful information and/or service that they desire. In such a service model amongst other things the user first has to figure out the best match for their request and then find out how to get to it. With the ever increasing amount of available information, it is quite evident that this service model is not scalable. A desired approach is for a service to be context aware and to be able to provide a seamless delivery of the right set of information at the right time using the right means. This approach can also be described as instead of the user going to the Internet and figuring out a way to fulfill its needs, the Internet comes to the user with the right information.

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The mission of 4G Americas is to advocate for and foster the advancement and full capabilities of the LTE mobile broadband technology and its evolution beyond to 5G, throughout the ecosystem's networks, services, applications and wirelessly connected devices in the Americas. 4G Americas, the voice of 5G for the Americas, is invested in leading 5G development for the Americas and maintaining the current global innovation lead in North America with LTE technology. 4G Americas' Board of Governors members include Alcatel-Lucent, América Móvil, AT&T, Cable & Wireless, Cisco, CommScope, Entel, Ericsson, HP, Intel, Mitel, Nokia, Qualcomm, Sprint, T-Mobile US, Inc. and Telefónica.

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