Technological Advisory Council (TAC) Future Game Changing Technologies (FGCT) Working Group Report on 5G Adoption

Version 1.0

7 December 2016

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1 Overview

1.1 Introduction

This overview section provides the report introduction, the mission statement, the scope of work, the methodology for the development of the report, the subgroup membership, and the structure of the report.

1.2 Mission Statement

The FCC Technological Advisory Council (TAC) Future Game Changing Technologies (FGCT) 3Working Group continued its work from 2015. The work proposed for 2016 includes the following:

i. Concentrate on identifying the technical challenges in developing 5G and what can be done to ensure rapid deployment in the U.S. for urban, suburban, and rural markets;

ii. Examine potential new business models and service regimes that could be enabled by future programmable networks. The work group will also address the adoption of dynamic, virtualized networks and the implications for current FCC rules and policies;

iii. Address how the FCC can better anticipate rapid changes in technology and an approach to rules and policies that has the best outcome for the nation.

iv. Finally, the work group will continue its efforts to identify key new and emerging technologies.

1.3 Scope of Work

The scope of this report is to concentrate on identifying the technical challenges in developing 5G and what can be done to ensure rapid deployment in the U.S. for urban, suburban, and rural markets.

1.4 FGCT 5G Subgroup Membership

Table 1.1: FGCT 5G Subgroup Membership

Name	Organization
Brian K. Daly, Co-Chair	AT&T
Charla Rath, Co-Chair	Verizon
Kumar Balachandran	Ericsson
John Barnhill	Genband
Mark Bayliss	Visualink
Nomi Bergman	Brighthouse Networks
Michael Browne	Verizon

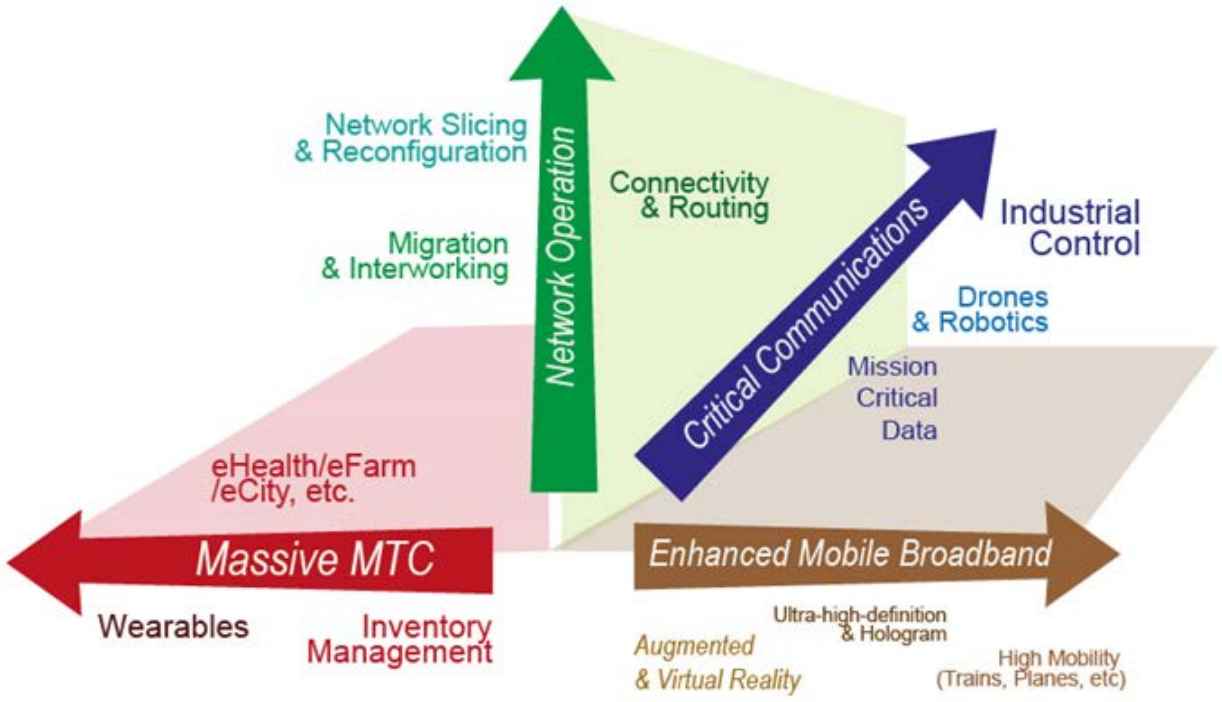
Name	Organization
Lynn Claudy	National Association of Broadcasters (NAB)
Marty Cooper	Dyna LLC
J Pierre de Vries	Silicon Flatirons
Adam Drobot	OpenTechWorks
Jeffrey Foerster	Intel
Dick Green	Liberty Global
Lisa Guess	Juniper Networks
Russ Gyurek	Cisco
Steve Lanning	Viasat
Brian Markwalter	CEA
Lynn Merrill	NTCA
Paul Misener	Amazon
Jack Nasielski	Qualcomm
Ramani Panduragan	XO Communications
Mark Richer	ATSC
Hans-Juergen Schmidke	Facebook
Marvin Sirbu	SGE
Kevin Sparks	Nokia
Paul Steinberg	Motorola Solutions

Also, DeWayne Sennett of AT&T served as Document Editor and Document Manager for the development of this FCC TAC FGCT 5G report.

2 Technical Challenges for Adoption and Deployment of 5G

There are three major motivations for a 5G system as recognized by various industry groups such as 5G Americas, NGMN, ATIS, and 3GPP.[1] These include enhanced Mobile Broadband (eMBB), Ultra Reliable and Low Latency Communication URLLC, and massive machine type communications (also referred to as massive IoT). 3GPP has also defined a fourth building block that is an essential advance in network operations.

[1] Detailed 5G descriptions, definitions, and bibliography can be found in the Appendix B and C.



The development of both the NextGen core network and the New Radio (NR) air interface will occur in all three categories eventually with focus on the first two respectively. In the near term LTE Cat-M and NB-IoT will tackle delay tolerant and high density usage of sensors and actuators for the Internet of Things. Standardization of 5G will therefore introduce new Radio Access Network (RAN) architectures for maximizing spectral efficiency (Cloud RAN, Massive MIMO, etc.) and a Next Generation (NexGen) core network which will be virtualized and support network slicing, low end-to-end latency, diverse and highly varied requirements, flexibility in network design and operations, new RAN-CN Interface, SDN based policy framework for operator policies, access agnostic, and control plane separated from the user plane . In addition, a 5G system including a new air interface based on NR will provide optimized performance for diverse device/application needs, including throughput intensive, latency sensitive, and low power IoT devices. It will also greatly expand the amount of spectrum available for mobile networks, through the expansion of conventional bands, the use of very high frequency bands, and combined use of licensed, unlicensed, and shared spectrum. See Appendix B for a more complete description of 5G architecture and benefits.

While much of the industry and FCC's policy focus around 5G centers on millimeter wave bands, it is understood that many of the principles for a 5G system are being developed are equally applicable to lower frequency bands. Indeed, a large part of the standardization effort must be directed towards creating a roadmap for operators to upgrade existing networks in the current IMT bands to new technologies such as NR. This will involve specification of NR for paired and unpaired spectrum operations, in a wide variety of frequency bands that span existing cellular spectrum as well as new spectrum.

It is very important that coverage not be compromised when deploying infrastructure in new spectrum, or upgrading infrastructure in existing spectrum. The success of 5G for enhanced Mobile Broadband (eMBB) will therefore depend on the improved access to new spectrum in the centimeter-wave and millimeter wave regions of the radio dial; the former is characterized by preferred allocations between 3-6 GHz and 6-30 GHz, and the latter by allocations in the 30-100 GHz region. Such new spectrum assets will address coverage as well as capacity in a way that assures subscribers of a uniform quality of experience.

A challenge for operators in the deployment of 5G includes identifying the migration strategy from the existing deployed system to the new 5G system. 3GPP has identified two main deployment scenarios for 5G (see Appendix B.4 for more details):

- Non-Standalone (NSA) NR deployment - NSA NR in this context implies using LTE as control plane anchor.
- Standalone (SA) NR deployment - SA NR implies full control plane capability for NR.

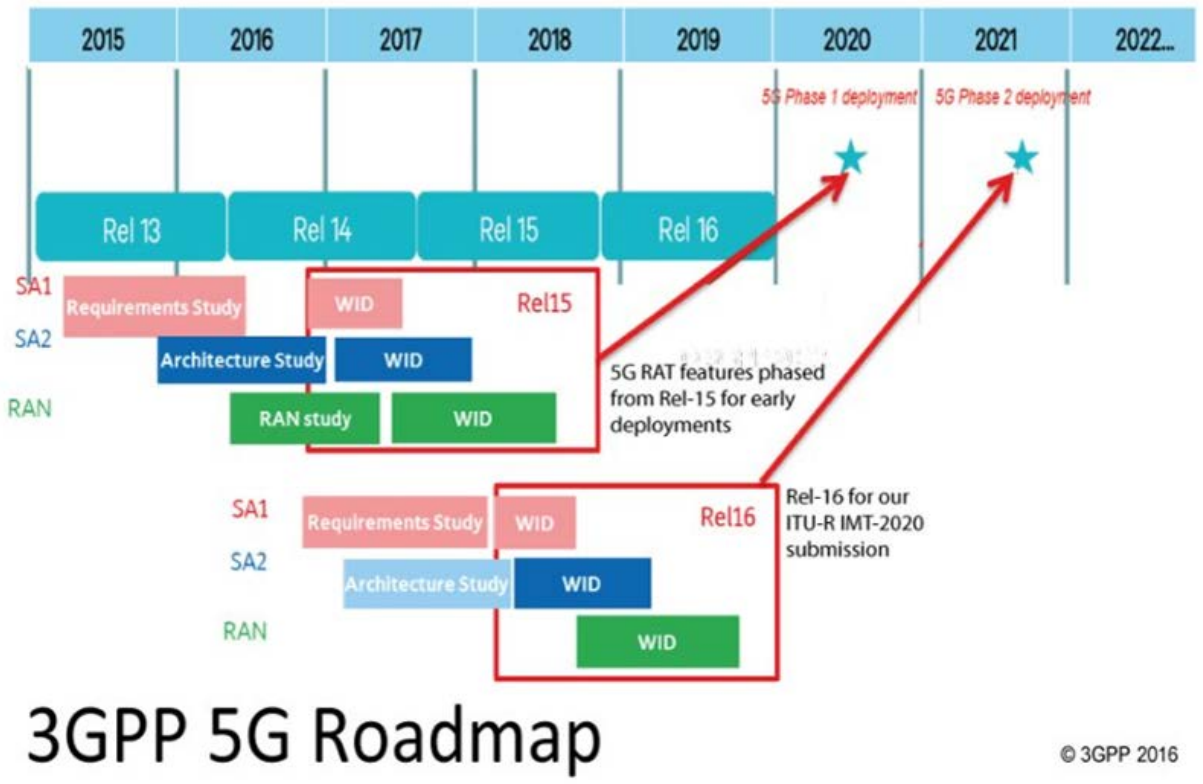
Different architecture options are being evaluated in 3GPP, with decisions as to which option will be standardized will be taken in December 2016 or March 2017. A key requirement for 3GPP is the NR design should be forward compatible at its core so that features can be added in later releases in an optimal way.

The following were affirmed at the September 2016 3GPP plenary meetings:

- There is strong industry interest in completing the Non-Standalone (NSA) version of the New Release specifications on the basis of Architecture Option 3/3a by date to be determined—between December 2017 and March 2018.
    - The stage 3 freeze NSA higher layers will include support for Architecture Option 3/3a.
- There is a strong industry interest in completing the Standalone (SA) Option 2 and Option 4/4a/5/7/7a by the deadline of June 2018.
    - Work on the NSA version shall not delay completion of the SA version.

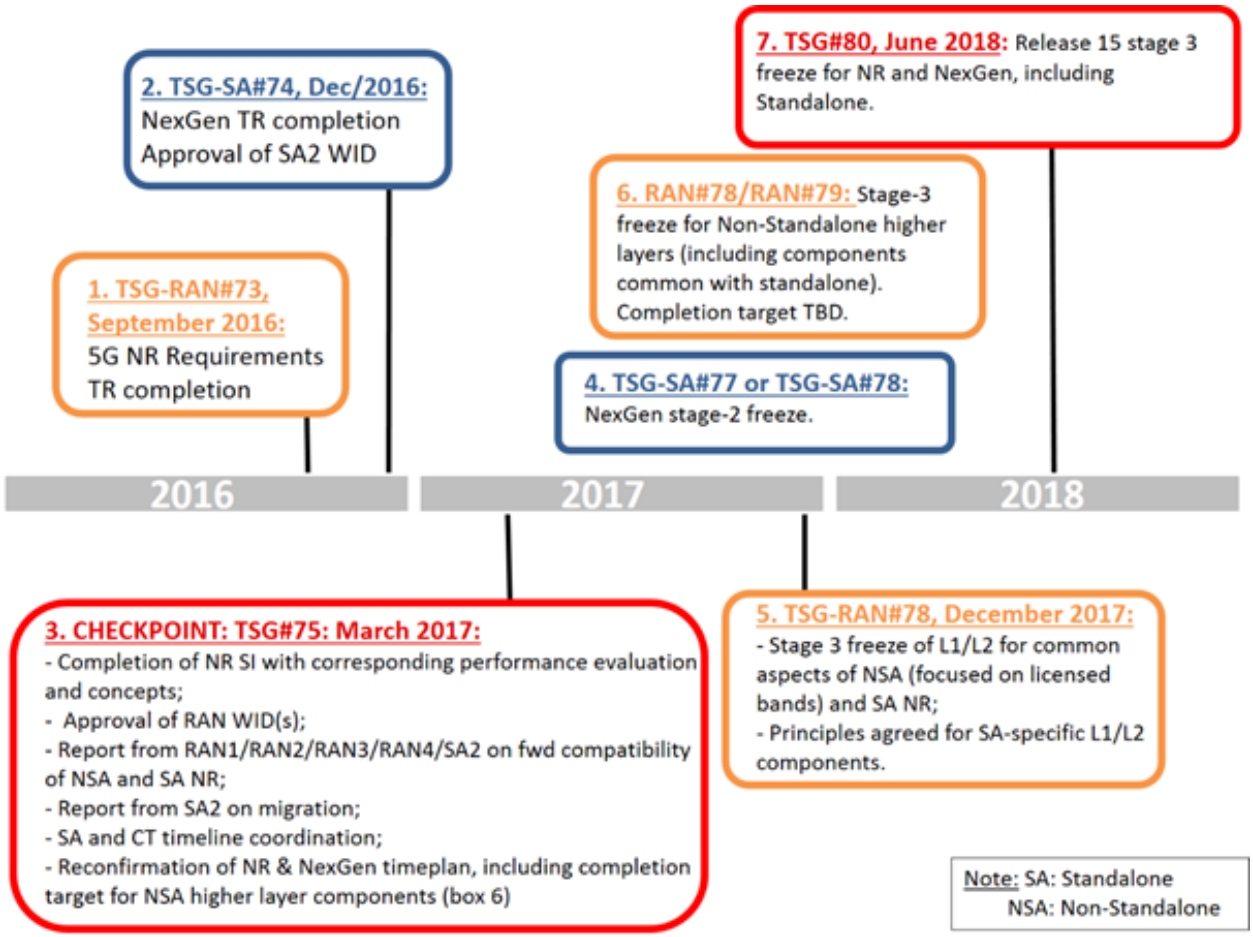
3 Timeline for 5G

The current projected industry timeline for the completion of the 3GPP specifications is show in the following:



3GPP Release 15 will provide the Phase 1 system definition, including all that is needed for deploying a base system. Release 15 Next Generation Architecture will support enhanced mobile broadband and a few other services and features. The flexible function design will allow deployments to use state of the art techniques and it will allow for flexible allocation or distribution of functions and resources within the network. The new architecture allows customization of the slices for different services and characteristics. For example, multiple data sessions per UE that is fully independent from each other and may terminate at different locations in the network. Subsequent releases will provide further features and service capabilities.

In the June 2016 plenary meeting of the 3GPP Technical Specifications Groups (TSG #72), there was an agreement on a detailed workplan for Release-15, the first release of 5G specifications. The plan includes a set of intermediate tasks and check-points (see below) to guide the ongoing studies in the Working Groups. These will get 3GPP in a position to make the next major round of workplan decisions when transitioning from the ongoing studies to the normative phase of the work in December 2016, the start of SA2 normative work on Next Generation (NexGen) architecture and in March 2017, the beginning of the RAN Working Group's specification of the 5G New Radio (NR).

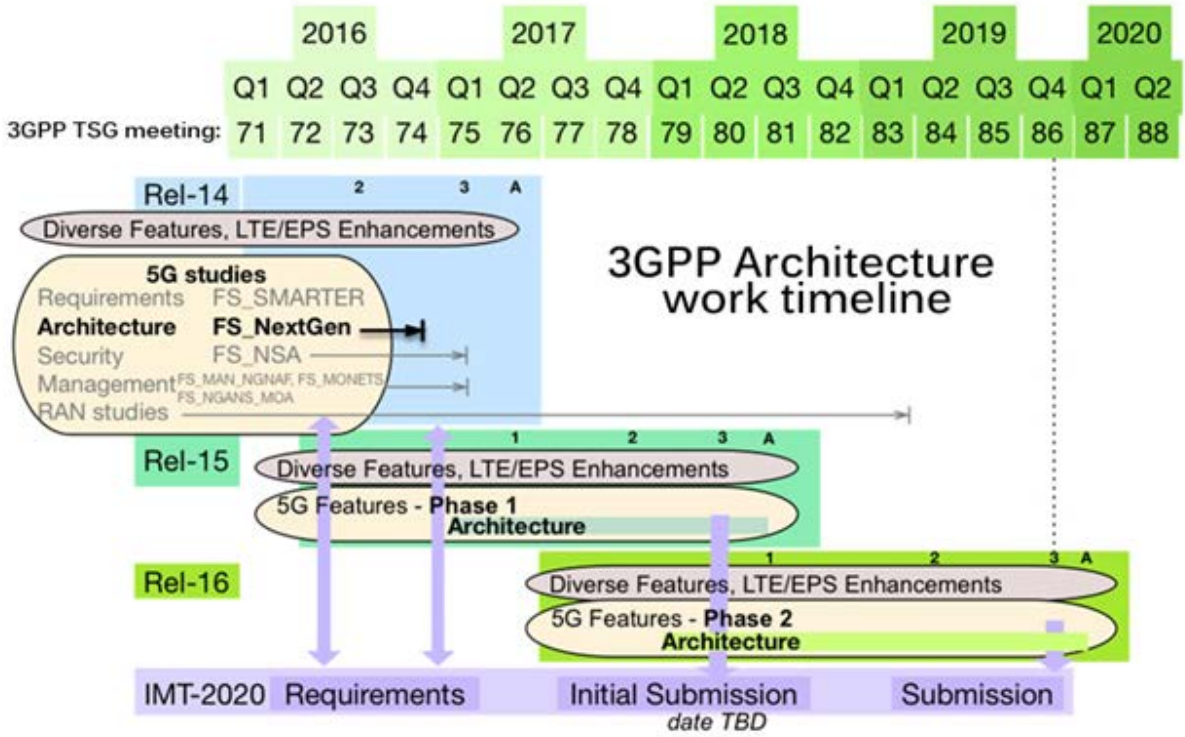


The 3GPP SA1 SMARTER (New Services and Markets Technology Enabler) study, which concluded in June 2016, defined the service requirements in four technical reports:

- TR 22.861 Massive Internet of Things
- TR 22.862 Critical Communications
- TR 22.863 Enhanced Mobile Broadband
- TR 22.864 Network Operation

3GPP SA1 is now starting to consolidate these four TRs into a technical specification, TS 22.261, which are the normative Stage 1 requirements for next generation mobile telecommunications. A draft version expected to be available in December 2016, with normative work targeting completion in March 2017. The TS will guide the work of the Stage 2 and Stage 3 groups in 3GPP.

3GPP SA2 (Architecture) is developing a technical report TR 23.799 on the Architecture and Security for Next Generation System; the target completion is December 2016. A detailed timeline for the 3GPP architecture work has been developed:



3GPP RAN is developing a series of technical reports for the NR. The RAN Working Groups have started evaluating technology solutions for NR. The RAN NR Technical Reports are as follows:

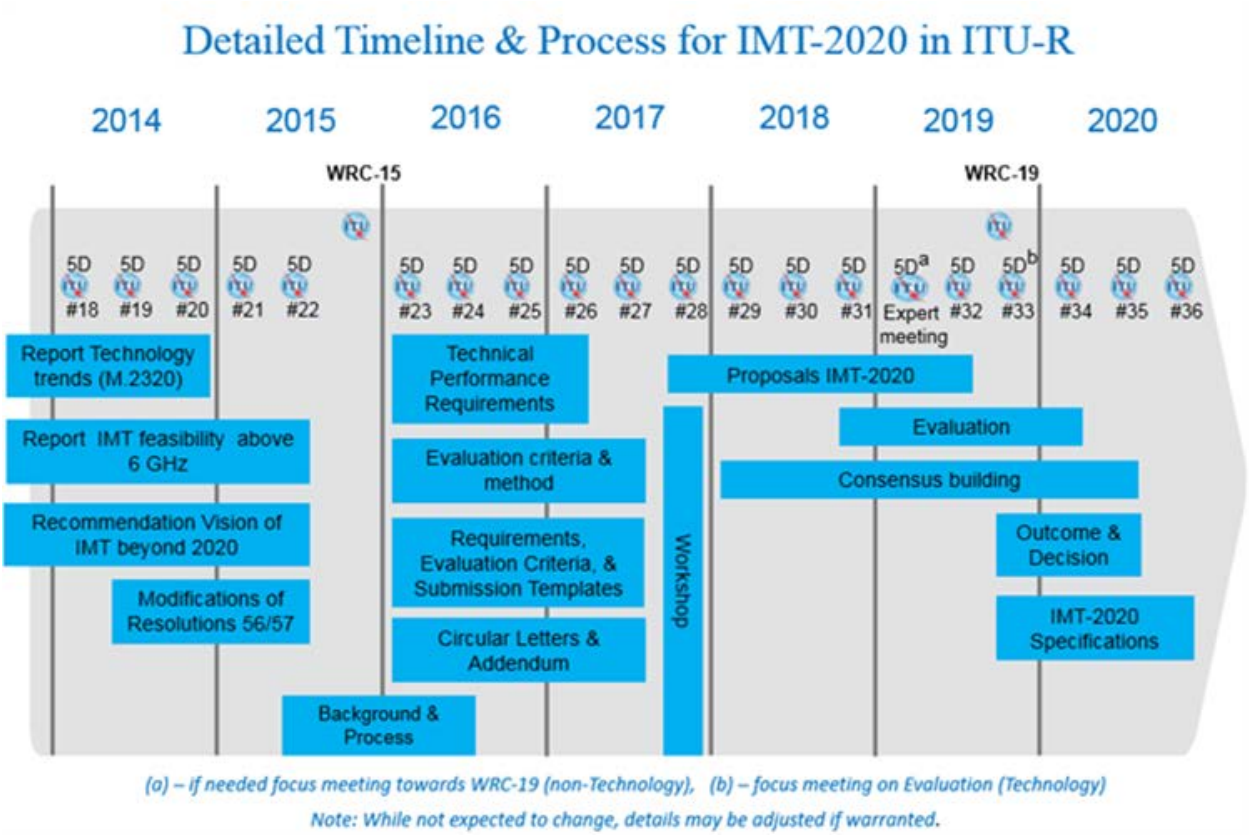
- TR 38.801 Study on New Radio Access Technology: Radio Access Architecture and Interfaces
- TR 38.802 Study on New Radio Access Technology Physical Layer Aspects
  - target completion of June 2017
- TR 38.803 TR for Study on New Radio Access Technology: RF and co-existence aspects
- TR 38.804 TR for Study on New Radio Access Technology Radio Interface Protocol Aspects
- TR 38.900 Study on channel model for frequency spectrum above 6 GHz
  - completed in June 2016
- TR 38.912 Study on New Radio (NR) Access Technology
- TR 38.913 Study on Scenarios and Requirements for Next Generation Access Technologies
  - target completion of December 2016

In early 2012, ITU-R embarked on a program to develop “IMT for 2020 and beyond”, setting the stage for “5G” research activities that are emerging around the world. ITU’s Radiocommunication Sector (ITU-R) has finalized its view of a timeline towards IMT-2020. The

detailed investigation of the key elements of "5G" are already well underway, utilizing the partnership ITU-R has with the mobile broadband industry and the wide range of stakeholders in the "5G" community.

In September 2015, ITU-R has finalized its "Vision" of the "5G" mobile broadband connected society. This view of the horizon for the future of mobile technology will be instrumental in setting the agenda for the World Radiocommunication Conference 2019, where deliberations on additional spectrum are taking place in support of the future growth of IMT.

The framework of standards for International Mobile Telecommunications (IMT), encompassing IMT-2000 and IMT-Advanced, spans the 3G and 4G industry perspectives and will continue to evolve as 5G with IMT-2020.The 3GPP NR specifications will be submitted into the IMT-2020 process; the 3GPP timelines were developed to support bringing the NR into the IMT-2020 process. The following highlights the timeline and process for IMT-2020:



4 Regulatory Actions to Accelerate 5G in US

Rapid deployment of 5G depends on the FCC promoting the innovation building blocks for next generation wireless networks, namely access to spectrum, densified infrastructure, and sufficient backhaul. The FCC has acted in a number of ways to ensure US leadership in 5G, including its recent decision to permit mobile use of certain millimeter wave bands. In addition, the

Commission has taken certain actions that to some degree lessen the burdens and costs of deployment thousands of small cells.

In October 2014, the FCC, acting on a TAC recommendation, launched a Notice of Inquiry to explore prospects for operating mobile radio services in the frequency bands above 24 GHz. In July of this year, the FCC took significant action to encourage 5G development in the US when it adopted this measured approach to millimeter wave spectrum in its "Spectrum Frontiers" Order. However, to ensure a robust 5G deployment, the FCC must continue to balance the incentives for use of mmWave frequency exploitation by similar incentives to use spectrum for where that spectrum performs best. This means encouragement for improvement in speed and capacity at frequencies that have superior propagation, better building penetration, insensitivity to weather, low in band noise or interference levels, and other desirable characteristics. The overall goal is for more efficient and better use of spectrum by using techniques such as: consolidation of spectrum into larger blocks, greater re-use of spectrum through densification, sharing of spectrum in space and time, use of advanced antenna and signal processing technologies, and the use of complementary spectrum for different purposes.

In many bands, the market will drive licensees to this end. An example is the premium that consumers and institutions have placed on mobility that requires the use of spectrum with specific characteristics as contrasted with the complementary use of spectrum for local area networks, access, or for backhaul. But not all spectrum licensees have the flexibility or incentive to respond to the changing consumer needs. To that end, the FCC should continue to promote an approach across all spectrum bands that encourages experimentation and allows the industry to adopt innovative network architectures. In addition, the US government continues to recognize the significant potential benefits of providing the tools for technological innovation, but otherwise relying on industry to invest in and develop 5G. As Chairman Wheeler said in his Spectrum Frontiers statement:

> "With today's Order, we are repeating the proven formula that made the United States the world leader in 4G: one, make spectrum available quickly and in sufficient amounts; two, encourage and protect innovation-driving competition; and three, stay out of the way of market-driven, private sector technological development."

4.1 Extending the Benefits of 5G to All Parts of the US

The FCC should want the benefits of 5G to extend to all parts of the population, and its interest in expanding rural coverage must not diminish as the world moves to implement 5G and deploy very high bandwidth and high capacity networks. Operators have an interest in efficiency: serving the largest number of subscribers with a minimum number of points of presence, or as few base stations as possible. The physics of millimeter wave spectrum impose significant roadblocks to its use to provide rural coverage. If the benefits of eMBB are to reach rural populations, the FCC should address the spectrum needs of such populations through large contiguous allocations of spectrum in lower spectrum bands as well as millimeter wave bands. This would allow an opportunity to improve broadband coverage in less densely populated areas that could mimic the "fiber-like" capacity offered in densely populated urban areas using millimeter wave spectrum. Another reason to make more of the lower band spectrum available is to fill in the gaps in quality of experience in areas where it is not economically viable to deploy millimeter wave radios, which are typically constrained by the limits of propagation in highly

cluttered wide-area environments. Combining high and lower frequency bands will raise end-user quality of experience to an even greater degree than with either solution. Thus, lower band spectrum could help provide a more uniform quality of experience and to fill in coverage gaps in and between targeted millimeter wave deployments.

The portfolio for wide area rural coverage must largely be derived from the mass market – this means cloud-based service and core network components, a transport infrastructure largely based on fiber backhaul and augmented by long-haul microwave links and relays, and cellular infrastructure offering access. A smaller percentage of deployments may rely on satellite backhaul; these will require compromises on latency. The opportunities offered by HAPS will likely take some time to scale up to the same efficiencies as traditional deployment tools. There may also be ample scope for low-earth orbit satellite technologies as a platform to extend coverage to certain sections of the population. The FCC should consider the relative benefits of such alternative approaches with economic factors that may affect the viability, longevity and growth opportunities for any business model. Any new ventures will have to demonstrably overcome the lessons from past adventures in the attempt to extend coverage with equivalent service.

Society benefits from uniformity of opportunity between all communities. The telecommunications industry spans the entire globe. In fact, it is impossible for America to chart a singular course to providing broadband for all and anything done for broadband in America must be applicable to global Internet access. One requirement that is obviously manifested here is in spectrum policy and the guidance that the FCC can provide to the World Radio Conference in harmonizing frequency allocations. Connecting everybody and everything to the Internet is only partially achieved by encouraging economies of scale in telecommunications infrastructure and services businesses. It will be software products and services that will create growth for American industry. The advantage that the FCC has is that the vastness of the country and the diversity of environments offer a sandbox for developing the solutions that will connect the entire world. The FCC should therefore continue to expand the scope of the national broadband plan and enable the creation of a new fabric for the Internet that will eventually connect the entire world to American know-how.

4.2 Other Regulatory and Policy Considerations

The FGCT Sub Working Group did not examine the full range of public policy and societal issues that the rapid deployment of 5G technologies could raise. These include among other things privacy and security, access to healthcare and education, environmental issues, and the full range of services that will define the “smart” community. Privacy and network security alone raise questions about next generation 9-1-1, lawful intercept, wireless emergency alerts, provision of mission critical services, and outage/performance reporting. Obviously there are a number of issues that a future TAC could examine in each of these areas and the TAC should consider these for future exploration.

5 Recommendations for 5G: Actions to Successfully Accelerate 5G Deployment

Accelerating the deployment of 5G in the United States involves progress in multiple technologies; the standardization of those technologies for the global marketplace - primarily in international standards bodies such as 3GPP and the ITU but also in regional standards bodies such as ATIS; increased reliance of solutions based on Open Source; the allocation or re-allocation of scarce resources - such as new and existing spectrum; the melding of 5G with current US infrastructure; and the unique requirements dictated by the distribution of the US population and our geography. In this setting the TAC has identified two priority issues for 5G, and related technologies, addressed below.

Global Standards 5G Watch List

Increasingly global standards drive the viability and economics of technologies such as 5G that depend on acceptance in international markets for scale as well as interoperability and roaming. There are significant and important aspects of standards where attitudes towards solutions differ from region to region. Examples are: CALEA; emergency services such as 911 and text-to-911; authority-to-citizen communications (e.g., Wireless Emergency Alerts), solutions for individuals with disabilities, views on privacy and security; and accommodation of requirements from vertical applications such as vehicular, healthcare, education, and mission critical communications (e.g., law enforcement). Consequently, the TAC recommends that FCC establish and maintain a living 'technology watch list' (including evolving 4G as well as emerging 5G) of priorities and essential needs for the US market, and use that to guide a robust ongoing dialogue with industry to ensure that these needs are met in 5G-related standardization and open source activities. As part of that the FCC should establish:

- Priorities and essential needs watch list that is documented and published with updates as needed.
- Informed by studies, educational, and assessment activities.
- Leverage industry for two-way learning and influence of 5G (and 4G evolution) standards directions.
- Include frequent and regular interaction for timely response to changing standards situations but lightweight enough to be sustainable (suggested frequency of 2-3 times/year).
- Include multi-stakeholder opportunity for other parties to monitor and influence standards.

Spectrum Balance for the 5G Era

Industry investment in widely-deployed advanced networks and experimentation through innovative sharing and unlicensed models are key drivers of efficient use of spectrum and 5G. The FCC can encourage further network efficiencies and investment in advanced networks and thus enable the U.S. to lead the world in next generation technology and 5G deployment by

continuing its balanced approach to spectrum that includes flexible exclusive-use licensing, spectrum sharing, and access to spectrum for unlicensed applications. Given the multi-spectrum, multi-connectivity requirements for meeting 5G scalability and reliability needs, the flexibility for innovative combined usage of different spectrum bands and licensing types is essential; this, in turn, depends on well balanced spectrum availability and growth.

The 5G Sub-Working Group also notes the TAC Spectrum and Receiver Working Group's efforts to quantify the changes in the noise floor and the impact that such an increase may have on existing systems. To the extent that such problems exist today, they will only intensify in a 5G ecosystem, or a highly dense, interconnected network that includes a vast "internet of things."

The FGCT recommends that the FCC continue to:

- Work closely with the Administration and Congress to ensure a flow of spectrum balanced across high, middle, and low spectrum bands for commercial use. In future spectrum allocations, the FCC should encourage state of the art efficient usage for existing services to free up spectrum, and make available large swaths of contiguous spectrum in single bands to support most efficient use going forward.
- Promote flexible-use policies that support experimentation across a range of frequencies and access approaches, including exclusive flexible use licensing, light licensing, sharing, and unlicensed. A balanced approach will ensure the efficient use of spectrum by market participants and the creation of meaningful next generation products and services for wireless consumers.
- Clear the way for market-driven experimentation and deployment in order to advance the development of 5G technologies.

The FCC should conduct and carry out a set of studies, with input from industry and other stakeholders that leads to a balanced spectrum architecture and roadmap fitting the Nation's needs into the 21st Century. It should also allocate resources to promote that architecture as part of its participation in influential standards and open source bodies.

Final Recommendation

Upping the game - the key ingredients for leading in the wireless revolution – ensuring a balance in spectrum allocation for best use, emphasizing the importance of spectrum efficiency, and exerting strong leadership in international standards and open source bodies to advocate positions important to American National interest. FCC should work closely with the Administration and Congress to ensure a flow of spectrum balanced across high, middle, and low spectrum bands for commercial use, and promote flexible-use policies that support experimentation across a range of frequencies and access approaches, including exclusive flexible use licensing, light licensing, sharing, and unlicensed. FCC should establish a 'technology watch list' (evolving 4G and emerging 5G) of priorities for the US market, and used to guide an ongoing dialogue with industry to ensure they are met in standardization and open source activities.

Appendix A: Glossary

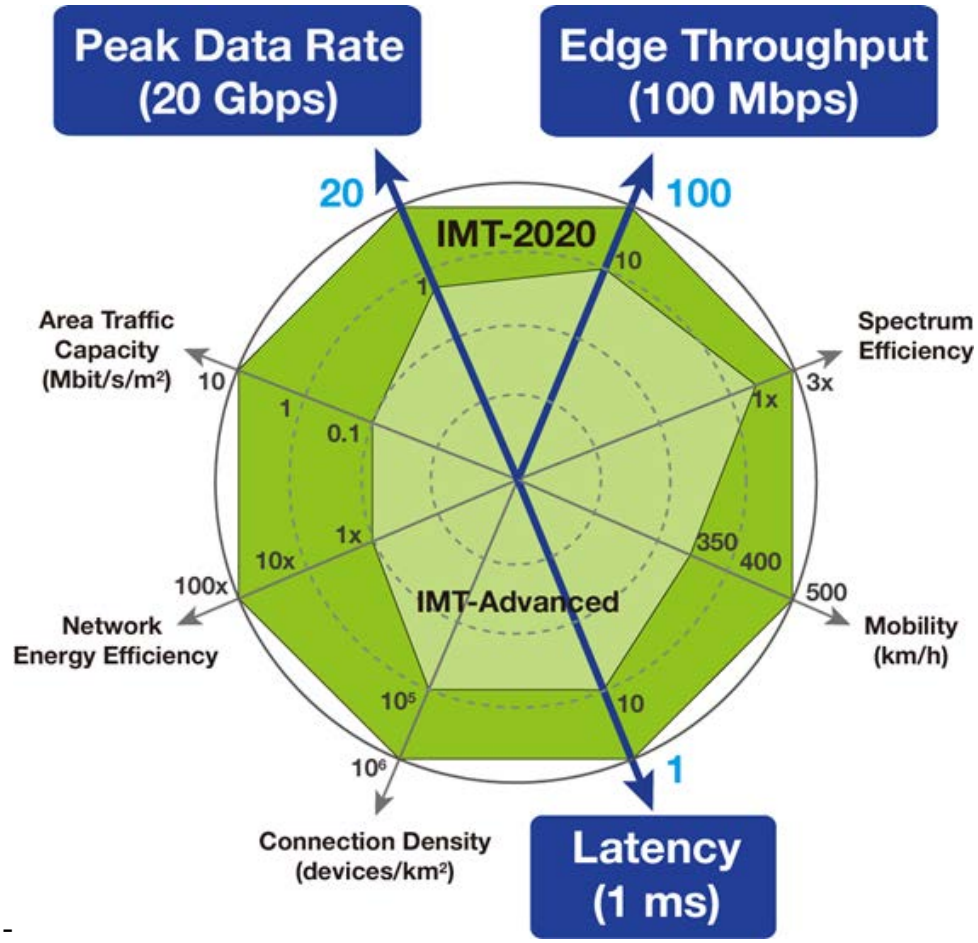
3GPP	Third Generation Partnership Project www.3gpp.org
5G	Fifth Generation
ATIS	Alliance of Telecommunication Industry Solutions www.atis.org
CN	Core Network
CTIA	Cellular Telecommunications Industry Association www.ctia.org
eMBB	Enhanced Mobile Broadband
FCC	Federal Communications Commission www.fcc.gov
FGCT	Future Game Changing Technologies
HAPS	High Altitude Platform Station
IEEE	Institute of Electrical and Electronics Engineers www.ieee.org
IMT	International Mobile Telecommunications
IoT	Internet of Things
ITU	International Telecommunications Union www.itu.int
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
NAB	National Association of Broadcasters www.nab.org
NextGen	Next Generation
NGMN	Next Generation Mobile Networks www.ngmn.org
NR	New Radio
NSA	Non-Standalone
RAN	Radio Access Network
SA	Standalone
SDN	Software Defined Network
TAC	Technological Advisory Council
TR	Technical Report
TS	Technical Specification
UE	User Equipment
URLLC	Ultra Reliable and Low Latency Communication

Appendix B: What is 5G?

The NGMN Whitepaper attempts to define 5G in terms of technology developments and socio-economic transformations, as follows:

> "The fifth generation of mobile technology (5G) is positioned to address the demands and business contexts of 2020 and beyond. It is expected to enable a fully mobile and connected society and to empower socio-economic transformations in countless ways many of which are unimagined today, including those for productivity, sustainability and well-being. The demands of a fully mobile and connected society are characterized by the tremendous growth in connectivity and density/volume of traffic, the required multi-layer densification in enabling this, and the broad range of use cases and business models expected."
>
> "Driven by technology developments and socio-economic transformations, the 5G business context is characterized by changes in customer, technology and operator contexts. It is expected that instant information will be just a touch away, and that everything will be connected."

In September 2015, ITU-R finalized its "Vision" of the "5G" mobile broadband connected society. Recommendation ITU-R M.2083-0 (09/2015) provided the "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond" and defined the technical goals for an IMT-2020 system. The following "spider web" included in that document summarized the goals:


Peak Data Rate
(20 Gbps)
Edge Throughput
(100 Mbps)
20
100
IMT-2020
10
1
Area Traffic
Capacity
(Mbit/s/m²)
10
1
0.1
Spectrum
Efficiency
3x
1x
1x
10x
100x
Network
Energy Efficiency
350
400
500
Mobility
(km/h)
IMT-Advanced
10⁵
10
10⁶
1
Connection Density
(devices/km²)
Latency
(1 ms)

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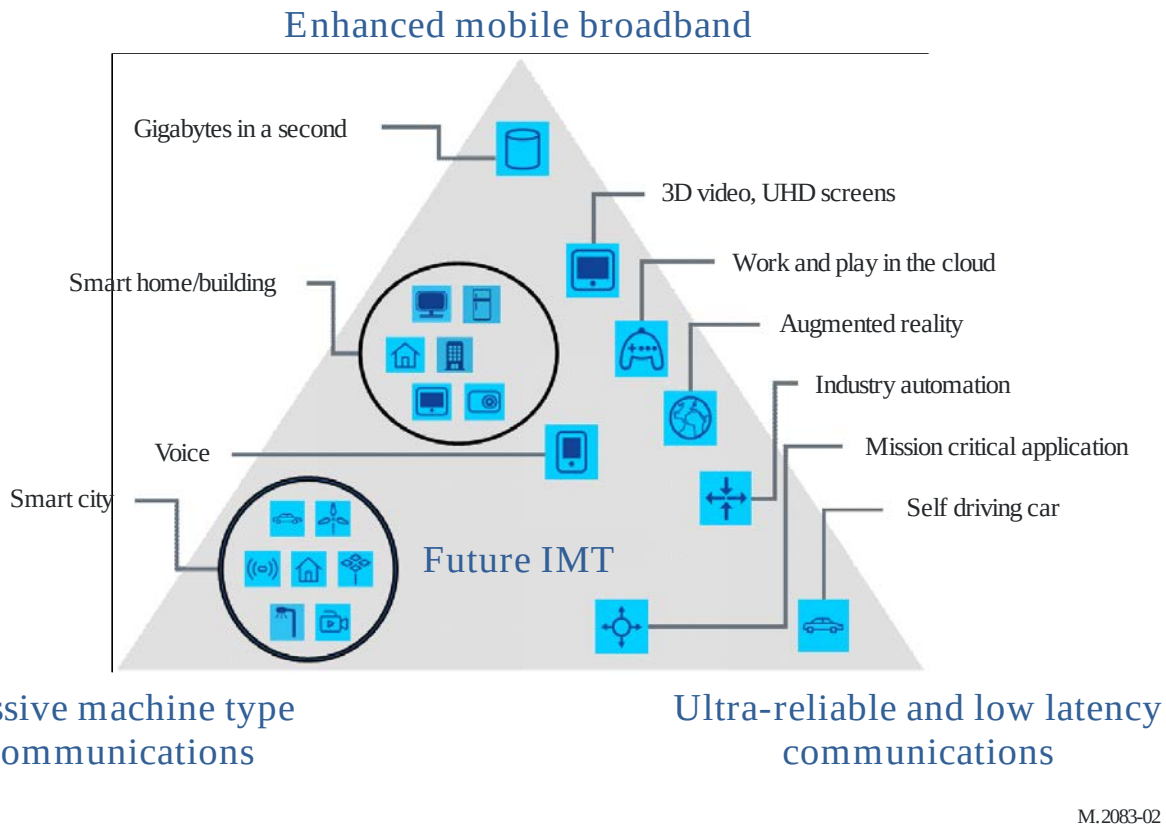
The ITU-R recommendation also defined the envisioned use cases for IMT-2020:



B.1 Architectural Impacts of 5G

5G is a new ecosystem impacting devices, the radio access network, and the core network. Key issues identified in the 3GPP architecture study include:

- Network slicing
- QoS framework
- Mobility management framework
- Session management
- Support for session and service continuity and efficient user plane path
- 3GPP architecture impacts to support network capability exposure and context information awareness
- Policy and Security framework
- NextGen core support for IMS

Network slicing enables the operator to create networks customized to provide optimized solutions for different market scenarios which demands diverse requirements, e.g., in the areas of functionality, performance and isolation. 3GPP is addressing architectural issues such as:

- How to achieve isolation/separation between network slice instances and which levels and types of isolation/separation will be required;
- How and what type of resource and network function sharing can be used between network slice instances;
- How to enable a UE to simultaneously obtain services from one or more specific network slice instances of one operator;
- Which network functions may be included in a specific network slice instance, and which network functions are independent of network slices;
- How to support Network Slicing Roaming scenarios; and
- How to enable operators to use the network slicing concept to efficiently support multiple 3rd parties (e.g., enterprises, service providers, content providers, etc.) that require similar network characteristics.

QoS framework for the system architecture is another technical challenge, i.e., the required functions (in both CP and UP) and a functional split between UE, Access Networks and CN, and any necessary QoS related signaling between those functions. The QoS framework should enable the operator to provide QoS for the wide range of use cases is expected to be fulfilled by the NextGen architecture.

The next generation system is expected to accommodate various use cases, i.e., massive IoT, critical communications, and enhanced mobile broadband, respectively. To allow the 3rd party, UE or Network Functions to access information regarding services provided by the network (e.g., connectivity information, QoS, mobility, etc.) and to dynamically customize the network capability for different diverse use cases within the limits set by the operator, the next generation system should provide suitable access/exchange of network/connectivity information (e.g., via APIs) to the 3rd party, UE and Network Functions. Additionally, to enable service optimizations, the NextGen system should support the combination, collection and exposure of additional context information from/to Network Functions, UE and 3rd parties.

It is well understood that a significant amount of standardization activity for 5G air interfaces such as NR will be devoted to the definition of efficient adaptive beamforming, typically combining MIMO and phased arrays. Beamforming has two significant advantages: 1) array gain allows more efficient transfer of energy between a transmitter and a receiver increasing received signal power; 2) phased arrays also help transmitters and receivers to seek each other out, consequently reducing the unwanted interference to other users in the band. This results in a significant improvement in capacity and/or coverage depending on how performance is traded off between these criteria. In some tailored scenarios being proposed for IMT-2020, the performance advantage of 5G is expected to lead to at least a three-fold increase in capacity over previous generations.

B.2 New Business Models Enabled by 5G

The new technologies, architectures, and greatly expanded capabilities that 5G will bring to mobile networks open many opportunities for the innovation of new business models. Many of these may be use cases that we can't yet imagine, but those we can already anticipate show great promise for end user benefits and economic value creation.

> ***NG Virtual Network Operators*** – Building on SDN/NFV technologies, 5G will allow new forms of virtual network operators, with many models of how much of network functionality is provided by the network operator, by the VNO, or offered by the network operator as a hosted network slice service for (and under the control of) the VNO. This can foster more competition at the service layers and new opportunities for return on network investment.
>
> ***Collaborative Service Delivery*** – Application & content providers can leverage the edge cloud enabled network and greater 5G mobile broadband throughput to deliver bandwidth intensive and/or latency critical new applications (e.g., AR/VR, 4K+ video, …) under many possible different business models: direct to customer w/leased compute/storage/networking, white labeled service offered by the network operator, partner application hosted by the network operator, etc.
>
> ***Network-Enabled Enterprises*** – Enterprises will be able to leverage enhanced 5G service capabilities, network based cloud IaaS and virtual network-aaS functions to offer new types of products and services not previously possible.
>
> ***Massive Scale IoT Vertical Provider*** – Vertical companies and service providers focused on verticals will be able to offer high value IoT applications that depend on very low TCO per devices, due to more simplified devices, more optimized battery life, and lower cost connectivity possible by 5G's optimized support for widely varying service requirements.
>
> ***Mission Critical IoT Vertical Provider*** – Similarly, vertical companies and service providers focused on verticals will be able to offer high value IoT applications that depend on low latency and high reliability, over a broad if not ubiquitous geographical scope.

As these new network capabilities and new types of devices are mashed up, yet unforeseen creative new business models will follow, and 5G ecosystem value creation will accelerate.

B.3 5G in Rural Areas

For purposes here, rural populations can be divided into three user groups: 1) small concentrations of population in hamlets, towns and villages, 2) sparse populations spread over huge areas, and 3) large farms with high data capacity needs and very few users, but very diverse use cases such as precision agriculture.

Terrestrial systems offer the best opportunity for bringing broadband service to rural America because of technological maturity economic feasibility, and the strength of a well-established value chain. Novel infrastructure such as drones and balloons still have no place in the dialogue around Internet access to the unconnected. There is much to be done to develop low operational cost aerial platforms that can remain aloft for long durations and capable of carrying significant

payloads needed, at a minimum, for backhaul, and perhaps also for access services. These are promising areas that are well within the realm of future possibilities.

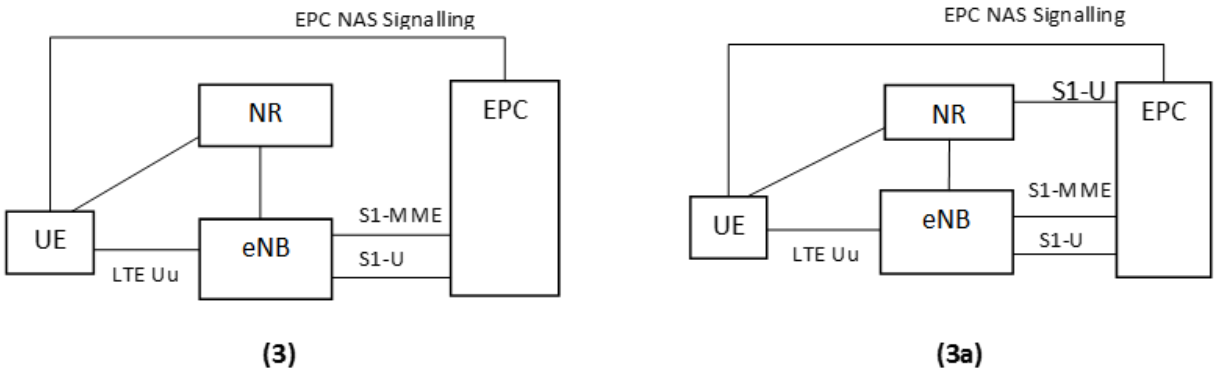
Air-interfaces like LTE are designed for very wide coverage; cell ranges of 100 km are certainly possible, albeit at lower data rates. When this capability is combined with the power of phased array techniques at the transmitter and receiver, cellular networks based on 5G air interfaces may offer a nice method of improving data rates over longer distances. It is unlikely that many populations in the USA will need deployments with cell ranges of the order of 100 km, although wide cell ranges of 30 km or less can certainly be imagined for the purposes of broadband coverage. Beamforming offers a very effective way of providing fixed spot coverage of population centers, and can focus directional arrays towards isolated users as well. However, the needs of sparse populations are not necessarily met easily by long range cellular infrastructure. In this respect, diversity of spectrum assets may play an important role, where low frequency bands below 6 GHz as well as higher frequency bands including, e.g., UMFUS allocations, have a role in a converged approach to providing transport and access services.

A large American farm is a potential IT hub. Apart from human needs such as remote education, entertainment, availability of real-time communication and streaming, and web access, farms are turning out to be highly automated environments with a variety of machine generated traffic ranging from heavy equipment to sensors for soil monitoring, weather monitoring, remote video etc. Similar needs exist in the manufacturing, mining, and oil sectors for monitoring and control of industrial equipment. An interesting question to consider is if there can be a meeting of priorities where distribution chains and common interests between mining industries, manufactories, agribusinesses, farming and broadband telecommunications services can be harnessed to create a tangible revolution for Internet service. Such an approach may be able to create a burgeoning of opportunity in rural communities, with expanded access to digital services, better facilities for remote education, library facilities for higher learning and remote health-care delivery. The development of 5G allows the separation of proprietary concerns between service providers, while the individual priorities of business entities will drive business models towards profitability and overall increase in productivity.

B.4 5G Deployment Options

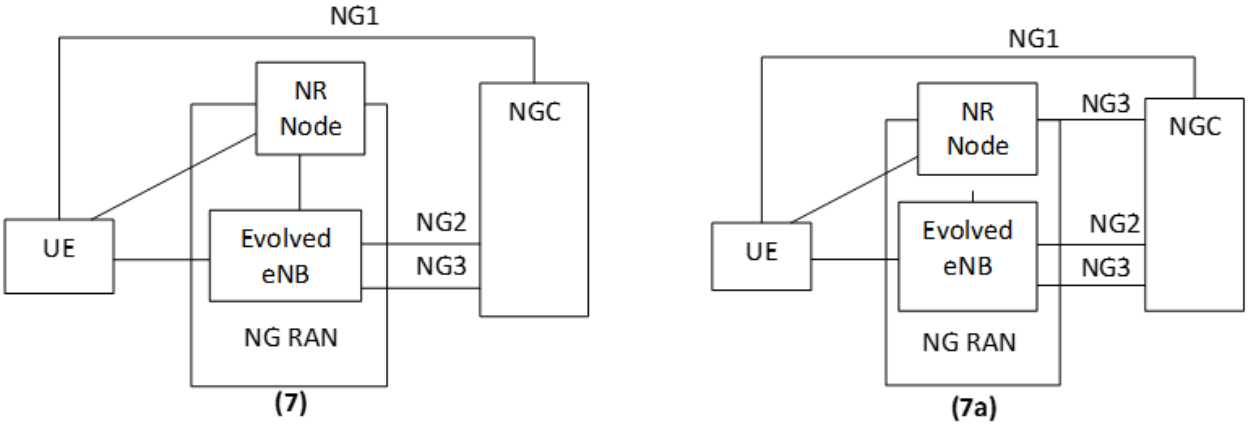
The deployment options for the NR and NexGen Core are identified in 3GPP TR23.799, Study on Architecture for Next Generation System.

Deployment Option 3 - Non-standalone NR in EPS



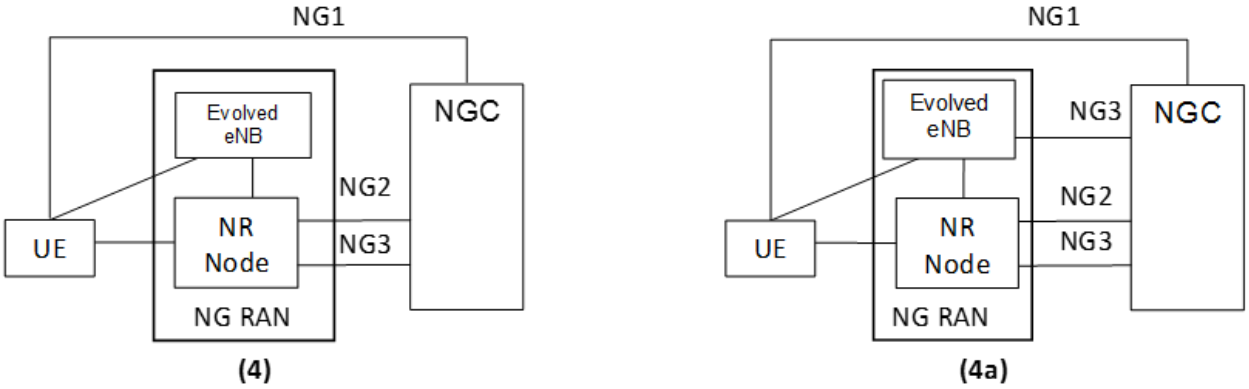
This deployment option is for dual connectivity deployments with E-UTRA as the anchor RAT and NR as the secondary RAT in a non-standalone configuration in EPS.

Deployment Option 7 - Non-Standalone NR in NextGen System



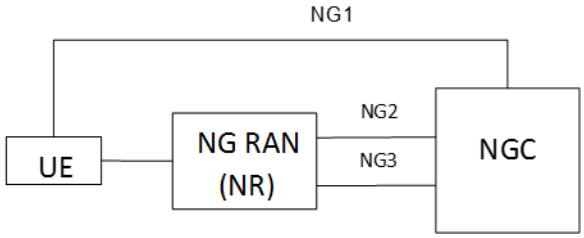
This deployment option is for dual connectivity deployments with Evolved E-UTRA as the anchor RAT and NR as the secondary RAT in a non-standalone configuration in NextGen system.

Deployment Option 4 - Non-Standalone Evolved E-UTRA in NextGen System



This deployment option is a dual connectivity deployment with NR as the anchor RAT and Evolved E-UTRA as the secondary RAT in a non-standalone configuration in NextGen System.

Deployment Option 2 - Standalone NR in NextGen System



This deployment option is for NG RAN with the radio access based on NR in a standalone configuration in NextGen System.

Appendix C: Survey of 5G Activities Glossary

C.1 3GPP

The 3rd Generation Partnership Project (3GPP) was founded in 1998 to develop technical specifications and technical reports for mobile systems. 3GPP has evolved from its initial focus on 3G to 4G LTE and 5G standards setting. To the extent possible, 3GPP works to ensure each release features backwards and forwards compatibility system design. 3GPP comprises seven organizational partners and relies on consensus decision-making. These organizational partners fund and set strategy for 3GPP. The partners also agree to adopt the 3GPP-established standards in their countries. The organizational partners may also invite others to join as "market representation partners" in order to advise 3GPP on relevant wireless market requirements. 3GPP organizational partners are:

- Association of Radio Industries and Businesses (Japan)
- Alliance for Telecommunications Industry Solutions (USA)
- China Communications Standards Association
- The European Telecommunications Standards Institute
- Telecommunications Standards Development Society (India)
- Telecommunications Technology Association (Korea)
- Telecommunication Technology Committee (Japan)

C.2 5G Americas

5G Americas is an industry trade group that represents mobile wireless providers and network vendors operating across the Americas and promotes the seamless evolution of 5G technologies throughout the Americas. 5G Americas offers advice and recommendation to government agencies, regulatory bodies, and technical standards organizations on the appropriate spectrum policies necessary to achieve 5G's full potential. In particular, 5G Americas publishes white papers and research to educate these stakeholders on the recommended steps that will enable plenary interoperability and convergence. The organization also serves as a 3GPP market representation partner and participates on various other international consortia dedicated to the development of 5G standards. 5G Americas encourages technology neutral policies and flexible spectrum use and believes these tenets will support the growth of IoT operations over LTE-Advanced and 5G networks. 5G Americas (formerly known as 4G Americas) has published the following white papers related to 5G:

5G Americas **/ Rysavy Research, "Mobile Broadband Transformation LTE to 5G," 08/2016**

> **Excerpt:** "The mobile industry is in the process of massive transformation, creating vast new capabilities that will benefit businesses and society as a whole. The step from 3G to 4G was dramatic, and the advances the industry is unleashing, initially in LTE and then in 5G, will be even greater. … This paper attempts to capture the scope of what the

industry is developing, beginning with Table 1, which summarizes some of the most important advances."

5G Americas**, "Global Organizations Forge New Frontier of 5G," 07/2016**

Excerpt: "North America, particularly the United States, has long been leading global efforts in the advancements of mobile technologies all the way from analog through 4G, and now into 5G. The U.S. remains a strong player in the vision, definition and development of 5G by ensuring it meets North America's unique marketplace requirements. Public and private investment in research and development (R&D) for 5G has significantly increased to ensure that it develops optimally. U.S. carriers have announced trials and early deployments of 5G technologies, demonstrating a commitment to 5G leadership."

4G Americas**, "5G Technology Evolution Recommendations," 10/2015**

Excerpt: "This paper examines the 5G market drivers, use cases, requirements, regulatory considerations and technology elements. The 5G market drivers and use cases described in Section 2 include the Internet of Things (IoT), extreme video, Public Switched Telephone Network (PSTN) sunset, public safety and context-aware services. Based upon these 5G market drivers and use cases, Section 3 describes the coexistence of the LTE end-to-end ecosystem with 5G, Sections 4 and 5 describe the requirements and regulatory aspects such as low latency, high throughput, mobility on demand, high reliability and resiliency and network flexibility. Section 6 describes potential technologies for 5G, including packet core, RAN and aspects applicable to end-to-end 5G systems. Section 7 discusses the spectrum aspects associated with 5G networks including both licensed and unlicensed spectrum options."

4G Americas**, "5G Spectrum Recommendations," 08/2015**

Excerpt: "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."

4G Americas/Rysavy Research**, "LTE and 5G Innovation: Igniting Mobile Broadband," 08/2015**

Abstract: "The main part of this paper covers exploding demand for wireless services, the path to 5G, supporting technologies and architectures, voice over LTE, Wi-Fi calling, LTE for public safety, options to expand capacity, and spectrum developments. The appendix delves into more technical aspects of the following topics: data throughput, latency, UMTS/WCMA1 , HSPA, HSPA+, LTE, LTE-Advanced, HetNets, Small Cells, self-organizing networks, the evolved packet core, unlicensed spectrum integration, the

IP multimedia subsystem, cloud radio-access networks, broadcast/multicast services, backhaul, UMTS TDD, Time-Division Synchronous Code Division Multiple Access (TD-SCDMA), EDGE, and TV white spaces."

4G Americas**, "Mobile Broadband Evolution Towards 5G: 3GPP Rel-12 & Rel-13 and Beyond," 06/2015**

Excerpt: "This extensive and comprehensive document, similar to past white papers, will help in understanding the future of wireless broadband and how new requirements and technological goals will be achieved. . . . In this white paper, a comprehensive treatment of mobile broadband evolution is presented: global market trends and milestones for LTE and HSPA are documented; and 3GPP standardization progress on both Rel-12 and Rel-13 features are detailed. While Rel-12 continued to build on LTE-Advanced and HSPA+, Rel-13 is in the unique position of being the Release prior to Rel-14 where it is expected that the first set of features addressing IMT-2020 requirements (towards 5G) will be introduced. Rel-13 was initiated with some early approval of higher priority items in June 2014 and is expected to be finalized by early 2016. Features and enhancements are detailed according to LTE-Advanced, HSPA+, and last but not least, Network Services Related enhancements."

4G Americas**, "4G Americas' Recommendations on 5G Requirements and Solutions," 10/2014**

Excerpt: "This paper examines the 5G market drivers, use cases, requirements, regulatory considerations and the technology elements. The 5G market drivers and use cases described in Section 2 include the Internet of Things (IoT), extreme video, PSTN sunset, public safety and context-aware services. Based upon these 5G market drivers and use cases, Sections 3 and 4 describe the requirements and regulatory aspects such as low latency, high throughput, mobility on demand, high reliability and resiliency and network flexibility. Section 5 describes potential technologies for 5G, including packet core, RAN and aspects applicable to end-to-end 5G systems. Section 6 discusses the spectrum aspects associated with 5G networks including both licensed and unlicensed spectrum options."

4G Americas**, "4G Americas' Summary of Global 5G Initiatives," 06/2014**

Excerpt: "This white paper, developed by 4G Americas member companies using publicly available information, is a one-time overview of global 5G initiatives as of the first quarter of 2014. ... This white paper is only focused on the technology evolution of the wireless network."

C.3 5G PPP

The European Union Commission and wireless industry participants in Europe created the 5G Infrastructure Public Private Partnership (5G PPP) to position Europe as a global leader in innovation strategy. 5G PPP promotes next generation wireless infrastructure initiatives that will secure Europe's ability to compete in international markets. 5G PPP working groups analyze and recommend 5G architecture standards and develop consensus proposals to address economic and societal challenges present throughout the European Union. 5G PPP research covers architecture design, network management, and vertical sector use cases. The organization

recommends that requirements for vertical sector use cases should be incorporated in the early phases of the 5G standardization process.

5G ENSURE (5G PPP, European Commission)**, "Deliverable D2.2 Trust Model (draft)," 08/25/16**

> **Excerpt:** "This document takes the first steps towards such a trust model. Firstly we discuss and define terminology. This is essential, as in common speech terminology can be quite muddled but in trust modelling we must be precise. We then review the state of the art in trust modelling, firstly looking at human trust factors (as humans are essential components of 5G network scenarios), understanding how humans make decisions on whether to trust or not when dealing with other humans and when dealing with machines. Secondly we review work on machine trust: machines of course only follow the instructions given to them through their software code by humans, but we review what the options are and the indicators for trustworthiness of other entities, whether they are humans or machines. Finally we look at trust and trustworthiness by design techniques which we recommend for use both during the design of 5G and when changing the design of a 5G deployment by adding or removing elements."

5G ENSURE (5G PPP, European Commission)**, "Deliverable D2.3 Risk Assessment, Mitigation and Requirements (draft)," 08/23/16**

> **Excerpt:** "This document takes the first steps towards the definition of a risk assessment and mitigation methodology to be followed for the specific task of evaluating the 5G security uses cases and architecture. Firstly we discuss and define terminology. This is essential, as common speech terminology can be quite inexact but in risk management we must be precise. We then review the state of the art in risk assessment and mitigation, understanding what existing methodology, or combination of, suits the evaluation of 5G-ENSURE proposed use cases. To understand 5G networks we must first understand the proposed architectural framework and its differences when compared to the previous 4G networks. We therefore introduce the conceptual 5G security framework proposed until the present moment within the 5G-ENSURE project (work ongoing)."

5G PPP **Architecture Working Group, "View on 5G Architecture," 07/2016**

> **Excerpt:** "The current white paper focuses on the produced results after one year research mainly from 16 projects working on the abovementioned domains. During several months, representatives from these projects have worked together to identify the key findings of their projects and capture the commonalities and also the different approaches and trends. Also they have worked to determine the challenges that remain to be overcome so as to meet the 5G requirements. The goal of 5G Architecture Working Group is to use the results captured in this white paper to assist the participating projects achieve a common reference framework. The work of this working group will continue during the following year so as to capture the latest results to be produced by the projects and further elaborate this reference framework."

Euro-5G (European Commission, 5G PPP)**, "The European 5G Annual Journal," 07/2016**

> **Introduction:** "Future European society and economy will strongly rely on 5G infrastructure. The impact will go far beyond existing wireless access networks with the aim for communication services, reachable everywhere, all the time, and faster. 5G is an opportunity for the European ICT sector which is already well positioned in the global R&D race. 5G technologies will be adopted and deployed globally in alignment with developed and emerging markets' needs. The aim of this first edition of the European 5G Annual Journal is to highlight and disseminate the European achievements in the context of global progress in the 5G PPP domain. It presents an analysis of the 5G ecosystem evolution over the past year."

5G PPP**, "Living Document on 5G PPP Use Cases and Performance Evaluation Models," 04/25/2016**

> **Executive Summary:** "This document provides an overview of the use cases and models that were developed for an early evaluation of different 5G radio access network concepts originating from various 5th generation (5G) Public-Private Partnership (5G-PPP) phase 1 projects. It covers 5G scenarios defined from the service perspective, requirements, definitions of key performance indicators (KPIs) and models (e.g., of channel, traffic or user's mobility). Developed use case families are mapped to a corresponding business cases identified in vertical industries. Additionally, performance evaluation approaches are compared with the latest version of performance evaluation framework proposed in Third Generation Partnership Project (3GPP). Since the document contains a comprehensive assessment of the 5G use cases and models originating from 5G-PPP, it can be used to harmonize viewpoints of different projects, while in the same time ensuring that 5G-PPP covers entire 5G research space identified as relevant from the European point of view."

5G PPP**/European Commission, "5G Empowering Vertical Industries," 02/2016**

> **Abstract:** "According to the White Paper, 5G technologies will need to accommodate a wide range of use cases with advanced requirements, especially in terms of latency, resilience, coverage, and bandwidth. 5G will integrate different enabling technologies, including mobile, fixed, satellite and optical. This will, in turn, help create stronger relationships between vendors, operators and verticals. Moreover, 5G will contribute to creating new business value propositions. Last but not least, the White Paper also includes several use cases from vertical sectors and claims that deploying 5G for vertical markets in Europe by 2020 should be seen as a priority."

5G PPP**/European Commission, "5G Vision," 02/2015**

> **Executive Summary:** "Future European society and economy will strongly rely on 5G infrastructure. The impact will go far beyond existing wireless access networks with the aim for communication services, reachable everywhere, all the time, and faster. 5G is an opportunity for the European ICT sector which is already well positioned in the global R&D race. 5G technologies will be adopted and deployed globally in alignment with developed and emerging markets' needs."

C.4 CSMAC

The Commerce Spectrum Management Advisory Committee (CSMAC) advises NTIA on a wide-range of issues related to spectrum policy. CSMAC provides guidance on spectrum initiatives intended to facilitate the U.S. as a leader in innovation, job creation, trade, and national security. It conducts research to gather intelligence on the latest wireless technologies and market trends. CSMAC advances policies that stress flexible and efficient use of spectrum and supports initiatives that mitigate interference resulting from spectrum sharing between commercial entities and federal agencies. The advisory committee features a 5G working group tasked with assessing the technology and standardization challenges associated with 5G spectrum sharing.

CSMAC**, "5G Subcommittee Final Recommendations," 08/2016**

> **Excerpt:** "NTIA Question: What are the technology and standardization challenges unique to 5G that are associated with federal/non-federal spectrum sharing, and what specific roles/actions should NTIA take to address these challenges? The subcommittee has also prepared an extensive report. The report shall be provided in July. The subcommittee also recognizes that some of the recommendations don't have an immediate action involved, but would have an action as 5G is further developed and/or if a specific band is referenced."

C.5 CTIA

CTIA is the leading trade association for U.S. wireless providers, device manufacturers, and suppliers. CTIA advocates for policies that bolster 5G innovation and investment. CTIA and its members recognize more spectrum, continued research and development, and streamlined infrastructure deployment will expedite delivery of 5G services to the wireless market. Furthermore, the association acknowledges millimeter wave spectrum will provide the required large swaths of spectrum needed to power a connected world. The association also hosts its annual Super Mobility expo that showcases the latest wireless innovations from around the world.

Sawanobori, Thomas K. and Paul V. Anuszkiewicz, "High Band Spectrum: The Key to Unlocking the Next Generation of Wireless," CTIA **, 06/13/16**

> **Excerpt:** "With 5G services, innovators are exploring the integration of mobile services with high capacity, speeds, and responsiveness into nearly every aspect of how we work and live. With the benefit of hindsight we can see the full impact of the ubiquitous adoption of mobile phones, and with 5G, we expect the impact to be equally seismic. To meet new demand and maintain U.S. leadership in the next generation of wireless – 5G – policymakers must move quickly to allocate new spectrum. Fortunately, technologies are emerging to open up the next frontier for mobile broadband spectrum: bands above GHz, known as 'high-band' spectrum."

Sawanobori, Thomas K., "The Next Generation of Wireless: 5G Leadership in the U.S.," CTIA, 02/09/2016

> **Excerpt:** "Specifically, this paper explores three key aspects – speed, connection ubiquity, and immediacy – of 5G networks that will transform consumers' wireless experience and enable a fully-connected mobile life. We also provide clear steps policymakers can take to help maintain U.S. wireless leadership and support future 5G investment. In particular, current spectrum planning by the Federal government needs to account for the increased demand that is projected for mobile broadband services; working with stakeholders, the Administration and the FCC must not only keep on track with respect to current efforts, but must also identify new bands capable of being auctioned and develop a timetable for those auctions. Along with smart infrastructure and siting policies, as well as wise R&D investments, more focused spectrum re-allocation planning will be vital to robust development and deployment of 5G in the U.S."

CTIA also has a video blog on 5G which is available at http://www.ctialatest.org/2015/08/18/tech-tuesday-what-is-5g/.

C.6 GSMA

GSMA membership consists of approximately 800 licensed wireless operators across 220 countries using the Global System for Mobile (GSM) technology to provision cellular service. Eligible systems suppliers, roaming hub providers, handset manufacturers, and network vendors receive associate member status. Through its Spectrum Strategy Management Group and Public Policy Committee, GSMA examines complex global spectrum issues and provides technical expertise to industry fora and policymakers. GSMA plans to shape the commercial and regulatory environment for 5G. The association's agenda also places emphasis on identifying appropriate spectrum bands and defining the properties of 5G roaming. Moreover, GSMA organizes the widely attended Mobile World Congress (MWC) series every year. The 2016 MWC Americas conference concentrated on the 5G innovation and standardization required for the future of mobile connectivity.

GSMA, "Unlocking Commercial Opportunities from 4G Evolution to 5G," 03/2016

> **Excerpt:** "Mobile operators can start exploiting commercial opportunities by evolving their 4G network investments between now and 2020 in three areas: 1. Massive IoT and critical IoT, mobilizing vertical industries securely. Conservative estimations suggest that by 2025, the number of IoT devices will be more than double the number of personal communication devices. As the ecosystem grows, it will become clear that IoT is about more than connectivity, as this will only realize a small portion of addressable mobile revenues. 2. Optimized services, making real-time communications real A particular class of services earmarked in the available 5G literature for receiving a boost in usage are broadcast services. Operators could offer distributed content delivery network broadcasting, e.g., software updates or in-app advertisements, delivering live coverage of sports or music events. Where feasible, operators can become active distributors of infotainment services and directly monetize this opportunity. 3. Mobile broadband, the perception of infinite bandwidth Mobile broadband is the core business of operators

aimed at the mass market and operators' data revenues have soared in recent years. Customers and operators are already demanding faster and more reliable access in the pre-5G era."

GSMA**, "Understanding 5G: Perspectives on Future Technological Advancements in Mobile," 12/2014**

> **Excerpt:** "5G offers enormous potential for both consumers and industry. As well as the prospect of being considerably faster than existing technologies, 5G holds the promise of applications with high social and economic value, leading to a 'hyperconnected society' in which mobile will play an ever more important role in people's lives. The GSMA will work for its members and with its partners to shape 5G As the association representing the mobile industry, the GSMA will play a significant role in shaping the strategic, commercial and regulatory development of the 5G ecosystem. This will include areas such as the definition of roaming and interconnect in 5G, and the identification and alignment of suitable spectrum bands. Once a stable definition of 5G is reached, the GSMA will work with its members to identify and develop commercially viable 5G applications. This paper focuses on 5G as it has developed so far, and the areas of technological innovation needed to deliver the 5G vision."

C.7 IEEE

With over 425,000 members, the Institute of Electrical and Electronics Engineers (IEEE) established 45 technical committees under its direction that are dedicated to standards development and scientific research in the engineering and technology fields. IEEE has released over 1,600 standards and publishes more than 160 journals. The IEEE Standards Association administers consensus-based standards through an open development process. IEEE is investigating the costs and benefits of creating 5G network access and radio specifications that comply with ITU's IMT-2020 and 5G plans. In October 2016, IEEE sent a formal request to 3GPP to collaborate on the development of 5G standards.

IEEE 5G Kickoff Workshop

IEEE 5G Summit

> http://www.5gsummit.org/

Rappaport, Theodore S. et.al., "Investigation of Prediction Accuracy, Sensitivity, and Parameter Stability of Large-Scale Propagation Path Loss Models for 5G Wireless Communications," IEEE Transactions On Vehicular Technology**, 05/2016**

> **Abstract:** "This paper compares three candidate large-scale propagation path loss models for use over the entire microwave and millimeter-wave (mmWave) radio spectrum: the alpha–beta– gamma (ABG) model, the close-in (CI) free-space reference distance model, and the CI model with a frequency-weighted path loss exponent (CIF). Each of these models has been recently studied for use in standards bodies such as 3rd Generation

Partnership Project (3GPP) and for use in the design of fifth generation wireless systems in urban macrocell, urban microcell, and indoor office and shopping mall scenarios. Here, we compare the accuracy and sensitivity of these models using measured data from 30 propagation measurement data sets from 2 to 73 GHz over distances ranging from 4 to 1238 m. A series of sensitivity analyses of the three models shows that the four parameter ABG model under predicts path loss when relatively close to the transmitter, and over predicts path loss far from the transmitter, and that the physically based two-parameter CI model and three-parameter CIF model offer computational simplicity, have very similar goodness of fit (i.e., the shadow fading standard deviation), exhibit more stable model parameter behavior across frequencies and distances, and yield smaller prediction error in sensitivity tests across distances and frequencies, when compared to the four-parameter ABG model. Results show the CI model with a 1-m reference distance is suitable for outdoor environments, while the CIF model is more appropriate for indoor modeling. The CI and CIF models are easily implemented in existing 3GPP models by making a very subtle modification—by replacing a floating non-physically based constant with a frequency-dependent constant that represents free-space path loss in the first meter of propagation. This paper shows this subtle change does not change the mathematical form of existing ITU/3GPP models and offers much easier analysis, intuitive appeal, better model parameter stability, and better accuracy in sensitivity tests over a vast range of microwave and mmWave frequencies, scenarios, and distances, while using a simpler model with fewer parameters."

IEEE**, "Towards 5G Software-Defined Ecosystems," 07/15/2016**

Abstract: "Techno-economic drivers are creating the conditions for a radical change of paradigm in the design and operation of future telecommunications infrastructures. In fact, SDN, NFV, Cloud and Edge-Fog Computing are converging together into a single systemic transformation termed "Softwarization" that will find concrete exploitations in 5G systems. The IEEE SDN Initiative1 has elaborated a vision, an evolutionary path and some techno-economic scenarios of this transformation: specifically, the major technical challenges, business sustainability and policy issues have been investigated. This white paper presents: 1) an overview on the main techno-economic drivers steering the "Softwarization" of telecommunications; 2) an introduction to the Open Mobile Edge Cloud vision (covered in a companion white paper); 3) the main technical challenges in terms of operations, security and policy; 4) an analysis of the potential role of open source software; 5) some use case proposals for proof-of-concepts; and 6) a short description of the main socio-economic impacts being produced by "Softwarization". Along these directions, IEEE SDN is also developing of an open catalogue of software platforms, toolkits, and functionalities aiming at a step-by-step development and aggregation of test-beds/field-trials on SDNNFV-5G. This will prepare the ground for developing new ICT ecosystems, thereby improving the quality of life and facilitating the development of the new digital economy."

C.8 ITU

The International Telecommunication Union (ITU) is authorized by the United Nations to oversee spectrum allocation and the development of technical standards for information and

communications technologies. ITU membership spans across 193 countries and encompass academia and nearly 800 private firms. The ITU will establish detailed technical performance requirements for 5G and prepare use cases that qualify for IMT-2020 (International Mobile Telecommunication system). The ITU works to remove harmful interference between operators in different countries and recommends initiatives that promote efficient use of spectrum bands.

International Telecommunication Union**, "IMT Vision – Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond," 09/2015**

> **Abstract:** "This Recommendation defines the framework and overall objectives of the future development of International Mobile Telecommunications (IMT) for 2020 and beyond in light of the roles that IMT could play to better serve the needs of the networked society, for both developed and developing countries, in the future. In this Recommendation, the framework of the future development of IMT for 2020 and beyond, including a broad variety of capabilities associated with envisaged usage scenarios, is described in detail. Furthermore, this Recommendation addresses the objectives of the future development of IMT for 2020 and beyond, which includes further enhancement of existing IMT and the development of IMT-2020. It should be noted that this Recommendation is defined considering the development of IMT to date based on Recommendation ITU-R M.1645."

C.9 NGMN

Next Generation Mobile Networks Alliance (NGMN) endeavors to enhance the mobile broadband experience with the deployment of 5G and the development of LTE-Advanced. NGMN represents the interests of international mobile providers, and its membership consists of network operators that serve more than 60% of customers throughout the world. NGMN's primary goal is to ensure standards for next generation infrastructure meet network operators and consumers' needs. The alliance collaborates with standards setting bodies and offers guidance on technical requirements and network management methods proposed for global 5G operations. NGMN will conduct trials with vertical industry stakeholders to test the viability of 5G uses cases.

Next Generation Mobile Networks Ltd.**, "NGMN Briefing Paper: Future IMT Spectrum Goals For ITU WRC-15," 02/2015**

> **Excerpt:** "The new capabilities that 5G is expected to deliver, and the increasing demand for network capacity by consumers, will require additional spectrum, beyond that currently available to mobile operators or expected to be identified by WRC-15. Some of these capabilities will require very wide channel bandwidths that can only be accommodated in bands above 6GHz. NGMN therefore welcomes the proposals by several regional groups to include additional spectrum bands/ranges to be studied for IMT2 on the agenda of WRC-19."

Next Generation Mobile Networks Ltd., **"NGMN 5G White Paper," 02/17/2015**

> **Excerpt:** "[I]n 5G, there is a need to push the envelope of performance to provide, where needed, for example, much greater throughput, much lower latency, ultra-high reliability, much higher connectivity density, and higher mobility range. This enhanced performance is expected to be provided along with the capability to control a highly heterogeneous environment, and capability to, among others, ensure security and trust, identity, and privacy. While extending the performance envelope of mobile networks, 5G should include by design embedded flexibility to optimize the network usage, while accommodating a wide range of use cases, business and partnership models. The 5G architecture should include modular network functions that could be deployed and scaled on demand, to accommodate various use cases in an agile and cost efficient manner. . . . Enabling 5G use cases and business models require the allocation of additional spectrum for mobile broadband and needs to be supported by flexible spectrum management capabilities. In addition, an IPR eco-system needs to be developed to further enable innovation and unlock the potential associated with some of the use cases described in this paper. NGMN and other stakeholders/partners will work together towards delivering globally and commercially available 5G solutions by 2020. This process will require a process of collaboration in the industry through existing standards development organizations (SDOs), or potentially new collaboration forms like open source."

C.10 Other

Adler, Richard, "Preparing for a 5G World," The Aspen Institute**, 2016**

> **Excerpt:** "In the advancement of improvements to mobile communications, policymakers will need to respond to the burgeoning increase in demand for mobile services with significant investments in research, building new and improved infrastructure, accessing and sharing new swaths of spectrum, and in expanding the accessibility of 5G technologies. The ideas and recommendations of this report highlight the technological possibilities and policy options to achieve the necessary improvements that 5G will offer to American society."

Alcatel Lucent**, "5G is Coming. Are You Prepared?" 11/2015**

> **Excerpt:** "This strategic white paper describes the drivers and requirements for 5G and provides a vision of what the 5G network will look like. A time line to 5G is also presented, based on standardization activities that are under way as well as when mobile operators are expected to deploy 5G networks. This paper also lets mobile operators know what they can do today to prepare for the 5G of tomorrow."

Alliance for Telecommunications Industry Solutions**, "ATIS—A Critical Force in Shaping 5G to Meet Service Providers' Market Needs," 03/2016**

> **Abstract:** "From the development of an overarching vision to the delivery of specific requirements, ATIS plays a pivotal role in the communications industry's advancement of the concept, objectives and capabilities for 5G systems. . . . Both incremental and innovative perspectives are crucially important in terms of positioning network operators to leverage 5G to advance their business models. In 2016, ATIS is fast-tracking its work

to develop detailed 5G specifications. ATIS is defining the industry requirements that will direct 5G's eventual technical capabilities and provide the basis for all subsequent 5G standardization. How will the new 5G radio access technologies work? How will the 5G transition take place? What will Quality of Experience mean in a future in which communications technology is even more deeply embedded into the social fabric than it is today? This briefing provides insight into these questions, and covers some of the areas in which ATIS is working to ensure 5G's success."

Alliance for Telecommunications Industry Solutions**, "5G Reimagined: A North American Perspective," 11/2015**

Abstract: "The purpose of this white paper is to understand, define, and advance North American requirements for 5G. Deployment scenarios and use cases for 5G networks are analyzed from a North American perspective. These use cases include both traditional and more disruptive service scenarios. The scope of the use cases is not limited to narrowly defined mobile network, and includes interactions with other components. The white paper identifies unique characteristics of the North American network and regulatory requirements. Although the focus is on the North American market, it is considered in a global context to leverage synergies wherever possible, and to only identify new requirements where necessary."

Anritsu**, "Physical Layer Measurement for Next-Generation 5G/IoT Wired Communications," 2016**

Abstract: "Development of 5G mobile communications technology is progressing, targeting commercial rollout in 2020. Moreover, the 2020 Tokyo Summer Olympics seem likely to mark the start of ultra-HD 4K and 8K video streaming services. As well as Cloud Computing, attention is increasingly focusing on new applications and businesses, such as the Internet of Things (IoT) and Machine to Machine (M2M), linking people and things via wireless communications. Against this background of increasing demand for ever-faster data communications speeds, this paper introduces the next generation of high-speed wired communications standards and describes physical-layer measurement techniques targeting 5G/IoT."

Anritsu**, "In-Building Propagation Measurements for The Coming Fifth-Generation Mobile Communication Technologies (5G)," 2016**

Abstract: "Spectrum regulators, world-wide, are recognizing the need to open up new spectrum to support the rapidly growing use of high speed data. In July, 2016, the US FCC opened up nearly 11 GHz of spectrum in the mmWave frequency range. Specifically; 27.5 to 28.35 GHz, 37 to 38.6 GHz. 38.6 to 40 GHz, and 64 to 71 GHz. Users will expect their devices, with this new spectrum, to function similarly to their current devices. New Machine-to-Machine (M2M) devices will need to work in closets and cabinets inside buildings. While outdoor propagation of this mmWave spectrum is well known, few studies have been done in-building. Anritsu is a leader in mmWave measurement test equipment and offers the MG369xC Series Signal Generators and MS2720T Series of portable spectrum analyzers covering the new 5G frequencies to 40 GHz. This white paper outlines procedures to make mmWave in-building propagation predictions and measurements."

Anritsu**, "5G Standardization Status in 3GPP," 2016**

> **Summary:** "3GPP is scheduled to standardize the 5G specification. Similar to 3G and 4G cases, it will submit IMT-2020 specifications based on ITU-R recommendations. Part of the 5G specification is to be operational within 2020. In this article, the probable schedule of 3GPP and some of the new technology has been described."

Anritsu**, "5G Technologies & Test Challenges," 2016**

> **Excerpt:** "The 5G network will be more than a new air interface, more than an expansion to mmW bands, and will require new technologies and measurement tools across the whole network infra-structure. The access network architecture based on C-RAN, and the core network based on SDN/NFV, will require new inter-connect technologies, new network physical layer/transport layer connectivity, and enhanced monitoring / service assurance tools to ensure that the new services and new use cases can be realized and deployed effectively using the 5G set of technologies. So the industry is developing the new inter-connect and transport technologies to deliver this, and the test and monitoring tools to validate and ensure the quality of customer experience."

Bari, Farooq, "5G: System and Core Aspects," AT&T Presentation**, 2015**

> **Excerpt:** "In order to achieve the level of scalability and flexibility required by industry drivers and significantly reduce the cost per Gigabyte and the cost per connection, 5G networks must utilize concepts such as SDN, Cloud Computing and Network Function Virtualization (NfV). The packet core forms a critical component of an end to end 5G system. To fulfill operational needs of operators an access agnostic packet core that is largely decoupled from radio access technology dependencies is required."

Brake, Doug, "5G and Next Generation Wireless: Implications for Policy and Competition," ITIF**, 06/2016**

> **Excerpt:** "Industry, academia, and governments around the world are pouring a tremendous amount of effort into developing next generation wireless networks. And rightly so: 5G represents a unique opportunity to step back and rethink a new network, one that incorporates recent technological advancements to radically extend wireless capacity and adaptability. With 5G we will move beyond networks that are purpose-built for mobile broadband alone, toward systems that connect far more different types of devices at much higher speeds."

Brown, Gabriel, "Heavy Reading White Paper: Exploring 5G New Radio: Use Cases, Capabilities & Timeline," *Heavy Reading***/Qualcomm, 09/2016**

> **Excerpt:** "This white paper explores the key features of 5G NR, as understood at this stage of development. It addresses the capabilities NR will use to support diverse performance requirements at a low operational cost, with a focus on nearer-term deployment of enhanced mobile broadband (eMBB), and on how to make 5G NR wireless links indistinguishable from wireline broadband. It also discusses NR features that will enable innovative services and help insert 5G into new industrial value chains."

Brown, Gabriel, "Exploring the Potential of mmWave for 5G Mobile Access," *Heavy Reading*/**Qualcomm, 06/2016**

> **Abstract:** "This white paper discusses the role of mmWave in future 5G networks. It investigates why mmWave is attractive to operators, provides a status update on technology development, discusses field testing activity around the world, and investigates how to mobilize mmWave using advanced antenna processing technologies. In the final section, it examines proposed deployment options."

Cisco**, "Cisco 5G Vision Series: Vertical Value Creation," 06/2016**

> **Abstract:** "5G networks must be designed with new capabilities addressing the needs of new vertical markets. Current mobile standards lack well-defined interfaces to the service layer. Without them, expensive, proprietary solutions are required. For vertical use cases such as the Internet of Things (IoT) and machine-to-machine (M2M) interface, which are expected to be a major focus of 5G networks, more than basic connectivity is required. Enablement platforms and vertical applications must also be supported. These new capabilities will be crucial to 5G value-added services addressing verticals. This white paper in the Cisco 5G Vision Series explores 5G value-added service requirements, capabilities, and architectures."

Cisco**, "The Cisco 5G Strategy Series: Packet Core, Transport, and Identity Management," 06/2016**

> **Abstract:** "Among the current standards recommendations for the fifth-generation (5G) mobile network are exciting technologies and architectures that promise more flexibility and agility, less complexity, and higher performance while lowering an operator's total cost of ownership. This paper in the Cisco 5G Strategy Series includes an overview of general architectural design principles for 5G; a look at the evolution of flexible mobile services; and descriptions of service function chaining, the 5G core architecture, network transport protocols, and fixed-mobile convergence (FMC) in a 5G network."

Cisco**, "Cisco 5G Vision Series: Licensed, Unlicensed, and Access-Independent Networks," 05/2016**

> **Abstract:** "A very important capability of evolving mobile networks is the need to integrate and/or aggregate different radio access technologies (RATs) that span both licensed and unlicensed spectrum across 3GPP technologies such as fourth-generation long-term evolution (4G LTE) and fifth-generation (5G) mobile standards, IEEE technologies such as Wi-Fi, and Internet of Things (IoT) technologies such as long-range access (LoRA). This paper reviews different approaches to integration and aggregation and weighs their relative efficiencies and value as the industry evolves to 5G. Cisco engineers are working toward a common plug-in framework for all kinds of access technologies in the 5G core."

Cisco**, "Cisco 5G Vision Series: Laying the Foundation for New Technologies, Use Cases, and Business Models," 04/2016**

> **Abstract:** "The fifth generation (5G) of mobile networking standards is in the early stages of development. Cisco is actively engaged in defining its requirements and leading engagements to address how 4G LTE networks will gracefully evolve to 5G by 2020.

This white paper describes the primary drivers for the creation of 5G, the technologies proposed by the industry for inclusion in 5G standards, and the expected timeline for 5G completion and rollout. Also included are an overview of Cisco's vision for 5G technologies and examples of Cisco engagements meant to evolve current 2G/3G/4G mobile networks based on the new 5G technologies across the RAN, the mobile core, and the next-generation Internet. Other papers in this series go into greater detail about RAN evolution, mobile core evolution, and the next-generation Internet evolution in the context of 5G standards."

Cisco**, "5G Vision Series: Small Cell Evolution," 04/2016**

Abstract: "With spiraling traffic volumes experienced by mobile networks around the world, small cell radio access network (RAN) has been proposed as the way to accommodate billions of users with a myriad of devices and demanding applications. With the coming of fifth generation (5G) networks, several small cell architectures and technologies have been proposed to reengineer the small cell environment that has yet to proliferate in 3G and 4G networks. This paper in the Cisco® 5G Vision Series examines these proposals."

Daly, Brian, "5G: Turning a Vision into Reality", AT&T Presentation**, 5G North America, November 2016**

Excerpt: "New capabilities of 5G will allow for new business modeling for vertical industries by offering mobility, flexibility, security, reliability and interoperability. Evolution to 5G will enable rapidly growing, diverse services for both human and machine communications. Official technology standard enables smoother roll-out experience and helps get 5G technologies to businesses and consumers faster. The evolution to 5G will spur innovation, making cities more livable, secure, efficient, and responsive to citizens' needs."

Ericsson**, "Opportunities in 5G: The View From Eight Industries," 09/6/16**

Abstract: "5G technology will provide an innovation platform enabling emergent technologies such as the Internet of Things (IoT) to become integral parts of our economy and lifestyle. To learn more about the opportunities that 5G will create, Ericsson commissioned a detailed survey of more than 650 decision-makers from eight key industries. The survey sought to understand how industries use communications technology today, how they expect to apply next-generation mobile technology (5G), which use cases are likely to dominate in their industry, and what business reasons will drive them to move to 5G."

Ericsson**, "Number Theories: What 100 Operators Really Think About 5G," 06/14/16**

Summary: "By 2021, it is estimated that there will be 28 billion connected devices – more than 15 billion of them machine-to-machine (M2M) and consumer electronic devices. Only by utilizing 5G will operators be able to keep up with future demand. Standardization efforts for 5G have begun and are expected to be completed by 2018. Many operators are already taking steps toward 5G. Ericsson recently commissioned an in-depth survey of 100 global operators (including COOs, CTOs, CIOs, heads of network operations, network innovation and network development) to see what expectations they have for 5G. They told us of their plans for adoption and expected use cases."

Ericsson**, "5G Radio Access," 04/2016**

> **Abstract:** "The capabilities of 5G wireless access must extend far beyond previous generations of mobile communication. Examples of these capabilities include very high data rates, very low latency, ultra-high reliability, energy efficiency and extreme device densities, and will be realized by the development of LTE in combination with new radio-access technologies. Key technology components include extension to higher frequency bands, access/backhaul integration, device-to-device communication, flexible duplex, flexible spectrum usage, multi-antenna transmission, ultra-lean design, and user/control separation."

Ericsson**, "5G Security," 06/2015**

> **Excerpt:** "5G systems are the next step in the evolution of mobile communication. As a fundamental enabler of the Networked Society, 5G networks need to provide capabilities not only for voice and data communication as we know it today, but also for new use cases and new industries, and for a multitude of devices and applications to connect society at large. Research and standardization have started in many technology areas of fundamental importance for 5G (such as cloud and the Internet of Things). These efforts have achieved various degrees of maturity, although the definition of 5G mobile networks has not yet reached standardization phase in the 3GPP. The evolution of LTE is a vital part of 5G. However, 5G will include the evolution of all parts of the network, such as core and management systems, as well as all protocol layers ranging from radio to applications. As a result, security is potentially affected everywhere. Current 4G cellular systems provide a high level of security and trustworthiness for users and operators. Second generation (GSM) systems were the first to have standardized, built-in security functions, which then evolved through 3G and now 4G networks. Although the security designs of previous and current systems have provided a platform of undisputed socioeconomic success, with the number of global mobile subscriptions exceeding 7 billion in 2014, 5G introduces many new aspects that require the following important questions to be addressed: Are there fundamentally new security requirements, and if so, how should they be identified? Can 5G security be a carbon copy of 4G security? Are previous design approaches still valid?"

Ericsson**, "5G Energy Performance," 04/2015**

> **Excerpt:** "High energy performance targeting reduced network energy consumption is a critical requirement of 5G. It enables reduced total cost of ownership, facilitates the extension of network connectivity to remote areas, and provides network access in a sustainable and more resource-efficient way. Key technologies to achieve this include ultra-lean design, advanced beamforming techniques, and separation of user-data and system-control planes on the radio interface, as well as virtualized network functionality and cloud technologies. This paper also defines two design principles on which 5G systems with high energy performance should be built."

European Technology Platform for Communications Networks and Services, Joint White Paper, "5G: Challenges, Research Priorities, and Recommendations," NetWorld2020 ETP**, 09/2014**

> **Excerpt:** "The Advanced 5G Infrastructure, defined as the ubiquitous ultra-broadband network that will carry the Future Internet, is not only an evolution of current generations, but a revolution in the ICT field that will enable highly efficient, ultra-reliable, dependable, secure, privacy preserving and delay critical services to everyone and everything. Fully immersive experience, enriched by context information and realized as an 'All as a Service', will be the main drivers for a massive adoption of the new technology components and market uptake. This calls for a complete redesign of the architecture, services and service capabilities of the new infrastructures, and a re-thinking of interfaces, access and non-access protocols and related procedures, functions, and advanced algorithms, for authorization, authentication, establishment, maintenance and reconfiguration of ICT services and any type of resource among cyber-physical entities, especially at the edge. Several challenges need to be addressed to meet and exceed the expected key performance indicators, in terms of throughput (1000x more in aggregate and 10x more at link level), service-level latency (1ms for tactile Internet and below 5ms for 2-8K change in view, at 30-50Mb/s), energy efficiency (90% less consumption for the same service compared to 2010 levels), coverage (global and seamless experience), battery lifetime (10x longer), QoS, manageability, etc. Moreover, the advanced 5G infrastructure needs to be highly flexible in order to meet foreseen as well as unknown requirements, in alignment with current and future stakeholders' expectations, while optimizing the total cost of ownership in various deployment contexts in Europe and beyond. This calls for the integration of various access technologies."

Fettweis, Gerhard and Alamouti, Siavash, "5G: Personal Mobile Internet beyond What Cellular Did to Telephony," *IEEE Communication Magazine***, 02/2014**

> **Abstract:** "Cellular technology has dramatically changed our society and the way we communicate. First it impacted voice telephony, and then has been making inroads into data access, applications, and services. However, today potential capabilities of the Internet have not yet been fully exploited by cellular systems. With the advent of 5G we will have the opportunity to leapfrog beyond current Internet capabilities."

***Fierce Wireless*/Cisco, F5 and** InterDigital**, "The 5G Vision: Preparing for the Next Stage in Wireless Networks," 05/2016**

> **Abstract:** "Hopes are sky-high for what 5G may enable, from 20 Gbps speeds to extremely low latency to connections for billions of IoT new devices. But there are still many unknowns. This Fierce Wireless eBook sponsored by Cisco, F5 and InterDigital, aims to address some of the unknowns."

Forbes Insights**/Huawei, "The Mobile Industrial Revolution," 06/2016**

> **Excerpt:** "The introduction of 5G networks in the next five to 10 years is expected to create huge opportunities to build enterprise value in a range of industries, profoundly affecting business operations, P&L economics, asset valuations and revenue models. Forward-looking organizations are already anticipating the impact of this technology, and are creating long-term plans to realize value, gain shareholder buy-in and deliver

innovation. To gain more insight into this crucial development, Forbes Insights conducted a global survey of more than 1,000 senior executives."

Global Mobile Suppliers Association/Ericsson, Huawei and Qualcomm, "The Road to 5G: Drivers, Applications, Requirements and Technical Development," 11/2015

Excerpt: "We forecast that there will be around 10-15 early 5G networks (exhibiting at least one aspect of network-performance-enhancing technology beyond LTE-Advanced), which will become quickly fully 5G once the standardization process is completed from 2020. By 2025, we forecast that there will be over 270 networks worldwide where there are local or regional areas with full 5G capability. We believe the industry needs to focus between now and 2020 on seeking consensus on approaches to concurrent LTE-Advanced development and 5G radio interface research – in particular demonstrating how assets can be reused. It must also begin to build compelling 5G business models in some specific application areas, focusing on those areas where LTE evolution does not 'cut the mustard'."

Hu, Yun Chao, Milan Patel, Dario Sabella, Nurit Sprecher and Valerie Young, "Mobile Edge Computing: A Key Technology Towards 5G," European Telecommunications Standards Institute, 09/2015

Excerpt: "The objectives of this white paper are to introduce the concept of Mobile Edge Computing and the related key market drivers, and to discuss the business and technical benefits of Mobile Edge Computing. A few examples of service scenarios that can benefit from the technology and possible deployment scenarios are presented. The white paper explains what is being standardized and how innovation can be stimulated through using a standardized API. It outlines the specifications being produced by the Industry Specification Group on MEC."

Huawei**, "5G Opening Up New Business Opportunities," 08/2016**

Excerpt: "Society and industry are undergoing a digital transformation, and it is apparent that existing mobile networks will not be able to satisfy future communication needs. New technology is required. According to a 5G white paper newly released by Forbes, over 80% of executives believe that 5G, a new generation of mobile broadband (MBB) network, has the potential to provide a range of benefits. Industrial managers have begun to realize that MBB networks provide a path and platform for the upgrade and transformation of multiple aspects of their operations. The connection platform enabled by 5G network infrastructure must be leveraged to release the full potential of digitalization."

Huawei**, "5G Network Architecture – A High Level View – Huawei White Paper," 07/27/2016**

Abstract: "In the 5G era, a single network infrastructure can meet diversified service requirements. A Cloud-Native E2E network architecture featuring agile, automatic, and intelligent operation is described in this Huawei white paper."

Huawei**, "5G Security: Forward Thinking Huawei White Paper," 12/2015**

Excerpt: "In the 5G context, users may already have some perception of provided security level based on experience with earlier generations. To provide continuity of

perceived security, it is important that security and privacy features that exist in earlier generations are also present in 5G, although the actual technical security mechanisms may be different. On the other hand, it is clear that it is not sufficient just to provide the same security features as in the legacy systems because there may be new security requirements and challenges. 5G systems are going to be service-oriented. This implies there will be a special emphasis on security and privacy requirements that stem from the angle of services."

Huawei**, "5G: New Air Interface and Radio Access Virtualization," 04/2015**

> **Excerpt:** "To adequately support the development of mobile Internet and IoT, 5G networks will increasingly become the primary means of network access for person-to-person and person-to-machine connectivity. This means that 5G will need to match the diversity of service requirements and service characteristics. Examples include extreme broadband, ultra-low latency, massive connection and ultra-high reliability etc., along with the ability to accommodate various use cases. The strong requirement of a service oriented network to provide better user experience in a flexible, efficient way is raised."

Huawei**, "5G: A Technology Vision," 02/2014**

> **Excerpt:** "5G wireless networks will support 1,000-fold gains in capacity, connections for at least 100 billion devices, and a 10 Gb/s individual user experience capable of extremely low latency and response times. Deployment of these networks will emerge between 2020 and 2030. 5G radio access will be built upon both new radio access technologies (RAT) and evolved existing wireless technologies (LTE, HSPA, GSM and WiFi). Breakthroughs in wireless network innovation will also drive economic and societal growth in entirely new ways. 5G will realize networks capable of providing zero-distance connectivity between people and connected machines."

Industry White Paper **(Contributors: Aalto University, BUPT, CMCC, Nokia, NTT DOCOMO, New York University, Ericsson, Qualcomm, Huawei, Samsung, INTEL, University of Bristol, KT Corporation, University of Southern California) "5G Channel Model for Bands Up to 100 GHz," 12/06/2015**

> **Excerpt:** "This white paper presents a preliminary overview of the 5G channel models for bands up to 100 GHz. These have been derived based on extensive measurement and ray tracing results across a multitude of bands."

InterDigital/**Mobile World Live, "How Will The Olympics Shape 5G?" 10/2016**

> **Snapshot:** "With the recent finish of the 2016 Olympics in Rio de Janeiro, there is huge interest in how the 2018 Winter Olympics and 2020 Summer Games will be the launchpad for the latest generation of mobile technology – 5G. A new whitepaper from InterDigital and Mobile World Live cuts through the hype to address:
>
> – why the 2018 Winter Olympics in South Korea is highly unlikely to support true 5G
> – the challenges facing operators – and device vendors – in hitting these ambitious deadlines
> – the visionary new services 5G technology could enable at the Games
> – the companies leading the way to a 5G future
> – why there is such urgency behind these Olympic efforts"

International Wireless Industry Consortium**, "Evolutionary & Disruptive Visions Towards UltraHigh Capacity Networks," 04/02/2014**

> **Excerpt:** "This paper provides a summary of factors that will influence the next generation of cellular systems which can also be termed as 5G systems. Specifically, the following conclusions are drawn. Future wireless networks will likely need to address several critical performance areas which include: 1. Cost 2. Traffic density 3. Latency 4. Reliability including availability, connection retention, and redundancy of network elements 5. Multi-operator and heterogeneous networks 6. Multicast/broadcast requirements 7. Security 8. The need to serve a variety of devices 9. Reduced battery consumption 10. High density usage 11. Various traffic patterns 12. Coverage improvements."

IMT-2020 **(5G) Promotion Group, "5G Vision and Requirements," 05/2014**

> **Excerpt:** "5G will penetrate into every element of future society and create an all-dimensional, user-centered information ecosystem. 5G will break through the limitation of time and space to enable an immersive and interactive user experience. 5G will also shorten the distance between human and things and implement seamless integration to achieve an easy and smart interconnection between people and all things. 5G will provide users with fiber-like access data rate and "zero" latency user experience. 5G will be capable of connecting 100 billion devices. 5G will be able to deliver a consistent experience across a variety of scenarios including the cases of ultra-high traffic volume density, ultra-high connection density, and ultra-high mobility. 5G will also be able to provide intelligent optimization based on services and users awareness, and will improve energy and cost efficiency by over a hundred of times, enabling us all to realize the vision of 5G – 'Information a finger away, everything in touch.'"

Kohlenberger, Jim, "Mobilizing America: Accelerating Next Generation Wireless Opportunities Everywhere," Mobile Future**, 09/08/2015**

> **Excerpt:** "Thanks to pragmatic policy choices, a vibrant innovation ecosystem and massive private sector investment, the U.S. leads the mobile world today with an estimated half of all 4G LTE connections on earth. Yet a heated global race already is underway to claim the next-generation 5G crown. Ubiquitous, advanced mobility is central to our future competitiveness and national prosperity. It has now become imperative that the United States begin to develop a comprehensive strategy to 'Mobilize America' in order to ensure continued U.S. leadership of an increasingly connected, capable and transformational wireless world."

Luo, Fa Long, "Signal Processing Techniques for 5G: An Overview," ZTE**, 2015**

> **Abstract:** "This paper gives an outline of the algorithms and implementation of the main signal processing techniques being developed for 5G wireless communication. The first part contains a review and comparison of six orthogonal and non-orthogonal waveform-generation and modulation schemes: generalized frequency-division multiplexing (GFDM), filter-bank multicarrier (FBMC), universal filtered multicarrier (UFMC), bi-orthogonal frequency-division multiplexing (BFDM), sparse-code multiple-access (SCMA), and non-orthogonal multiple access (NOMA). The second part discusses spatial signal processing algorithms and implementations for massive multiple-input multiple-

output (massive-MIMO), 3D beamforming and diversity, and orbital angular momentum (OAM) based multiplexing. The last part gives an overview of signal processing aspects of other emerging techniques in 5G, such as millimeter-wave, cloud radio access networks, full duplex mode, and digital radio-frequency processing."

archetti, Nicola, "Towards 5th Generation Wireless Communication Systems," ZTE, 2015

Abstract: "This paper introduces the general landscape of next-generation wireless communication systems (5G), including the impetus and requirements of 5G and the candidate technologies that might help 5G achieve its goals. The following areas, which the author considers particularly relevant, are discussed: detection of and access to free spectrum over bands of a heterogeneous nature, extreme densification of networks (massive base station deployments), extreme increase in the number of antennas in base station arrays and their interaction with a novel waveform, integration of both wireless and optical sides of telecom networks, and study of wireless networks from the perspective of complex systems science. The author discusses recent research conducted by his team in each of these research areas."

Martinez, Gina, Shufang Li, and Chi Zhou "An Optimal Lifetime Utility Routing for 5G and Energy-Harvesting Wireless Networks," ZTE, 2015

Abstract: "Harvesting energy from environmental sources such as solar and wind can mitigate or solve the limited-energy problem in wireless sensor networks. In this paper, we propose an energy-harvest-aware route-selection method that incorporates harvest availability properties and energy storage capacity limits into the routing decisions. The harvest-aware routing problem is formulated as a linear program with a utility-based objective function that balances the two conflicting routing objectives of maximum total and maximum minimum residual network energy. The simulation results show that doing so achieves a longer network lifetime, defined as the time-to-first-node-death in the network. Additionally, most existing energy-harvesting routing algorithms route each traffic flow independently from each other. The LP formulation allows for a joint optimization of multiple traffic flows. Better residual energy statistics are also achieved by such joint consideration compared to independent optimization of each commodity."

Mastrangelo, Teresa, "5G: A Network Transformation Imperative," *Heavy Reading*/Intel, 12/2015

Abstract: "This white paper explores the necessity of network transformation in support of 5G networks and services, including its requirements, applications and challenges. In addition, it examines the enabling technologies and strategies that facilitate the 5G vision. It concludes by describing how Intel is well positioned to play a leading role in the future 5G network – from the device to the data center – demonstrating Intel's ecosystem and solution leadership to accelerate the adoption of NFV and SDN."

METIS II**, "5G RAN Architecture and Functional Design," 03/08/16**

Abstract: "This white-paper summarizes the initial views and considerations of METIS-II on the 5G RAN architecture and functional design. It starts by listing the main service types that are considered for 5G, namely extreme mobile broadband (xMBB), massive machine-type communications (mMTC) and ultra-reliable machine-type communications (uMTC), as well as the five specific use cases towards which METIS-II is performing the

5G RAN design, and which typical represent a mixture of services. It further describes the key requirements on the 5G RAN architecture that have been identified and derived from the diverse service and use case needs, and explicitly elaborates on the requirements posed by the notion of Network Slicing in 5G."

METIS**, "Deliverable D5.3. Description of the Spectrum Needs and Usage Principles," 08/29/2014**

Abstract: "This document explains the expected spectrum scenarios, the resulting spectrum needs, methodology for evaluating this, suitable spectrum bands to address the needs, principles for using them and KPIs to evaluate potential technical solutions, and the technology components. The deliverable further contains the techno economic analysis of expected spectrum usage for future 5G systems. The foreseen functional architecture of spectrum usage for 5G systems is described, and the related Technical Components are linked with the KPIs that will enable their evaluation."

NetWorld 2020**, "Pervasive Mobile Virtual Services," 07/2016**

Excerpt: "In 5G and beyond networks, the first fundamental change is the availability of processing and storage as core services provided by the network itself. We can compare this next generation network with a distributed computer, where a dedicated operating system controls the distributed virtual infrastructure, offering a common interface to applications. However, the definition of a reference architecture for next generation networks is challenging due to the required Key Performance Indicators (KPIs), which go from the transport of massive volume of data, to the capacity to connect trillions of devices. Current research projects are tackling several challenges towards a 5G network standard, but there are plenty of research activities still pending."

NetWorld 2020**, "Service Level Awareness and Open Multi-Service Internetworking," 06/09/16**

Excerpt: "The value creation of the current Internet is substantial and growing, both directly and indirectly. It constitutes a fundamental building block for many businesses. The basic Internet access service constitutes the dominant business for an increasing number of telecommunication companies (Telcos) and Internet Service Providers (ISPs). The current Internet is very efficient in IP packet transport and very suitable for elastic applications, which can adapt to the varying network conditions and are not highly demanding in terms of network performance. However, the visions and expectations for the future and the 5G networks go far beyond what the Internet can support today. The shortcomings of the IP backbone inter-domain networking (internetworking) solution as of today should get more attention."

NTT DOCOMO**, "DOCOMO 5G White Paper," 07/2014**

Excerpt: "[T]he anticipated challenges of the future are so tremendous that there is a vastly increased need for a new mobile communications system with even further enhanced capabilities, namely a fifth generation (5G) system. Envisioning the development of a 5G system, NTT DOCOMO…started studies on future radio access (FRA) as early as 2010. The aim is to identify the future needs and requirements of 2020 and beyond and identify the right system concept and radio access technologies to

address them. Today, several experimental trials with world-leading vendors are ongoing."

Nokia Networks**, "5G Radio Access System Design Aspects," 09/23/2016**

Excerpt: "To meet demand, Nokia envisions 5G as a system providing scalable and flexible services with a virtually zero latency gigabit experience when and where it matters. In addition, 5G will provide at least a ten-fold improvement in the user experience over 4G, with higher peak data rates, improved "everywhere" data rates and a ten-fold reduction in latency. 5G mobile communications will have a wider range of use cases and related applications including video streaming, augmented reality, different ways of data sharing and various forms of machine type applications, including vehicular safety, different sensors and real-time control. Starting with trials in 2016 and the deployment of first use cases in 2017, the full 5G system will be introduced in 2019/20 and will be in use well beyond 2030. 5G also needs the flexibility to support future applications that are not yet fully understood or even known."

Nokia Networks**, "Multi-Layer and Cloud-Ready Radio Evolution Towards 5G," 09/14/2016**

Abstract: "Networks are on the threshold of a transformation driven by the demands of the Internet of Things (IoT) and the advent of 5G technologies that will create new services and applications. These will require seamless, fast, scalable and ultra-reliable access that can only be delivered by a 'Network of Networks'. Unfortunately, simply evolving current radio access network (RAN) architectures will not meet the new requirements in a sufficiently agile and cost-effective way. So, what is the solution? Will distributed or centralized architectures be needed? What are the advantages and drawbacks of purpose-built platforms versus cloud-based solutions? How can operators start today to prepare effectively for the transformation that will be needed? These are key questions that operators face and can start to address straight away. This white paper describes Nokia's vision for a multi-layer and cloud-ready RAN architecture and aims to help operators identify the challenges and how to solve them, as well as the opportunities open to operators."

Nokia Networks**, "Dynamic End-To-End Network Slicing For 5G," 09/09/2016**

Abstract: "To address very diverse requirements, 5G network architectures must shift from the current network of entities to a network of capabilities. Network models must shift from the current network for connectivity to a network for services model. Dynamic network slicing offers an effective way to enable this shift and partition a single common 5G infrastructure into multiple logical end-to-end networks. It provides the service agility needed to address diverse: Users (people and machines). Use cases. Requirements for latency, throughput, and availability. With dynamic network slicing, operators can establish different deployments, architectural flavors, and performance levels for each use case or service group. And they can run all network implementations simultaneously in parallel. This paper outlines the dynamic network slicing concept. It explains how the concept can be used to create different network slices on the same 5G network by leveraging: Software-defined networking (SDN). Network function virtualization (NFV). End-to-end orchestration. Network applications. Analytics."

Nokia Networks**, "5G for Mission Critical Communication: Nokia White Paper," 06/20/2016**

> **Abstract:** "Mobile networks must meet new demands as human communications changes from click and wait/background traffic, to interactive, real-time, haptic communication, and introduction of critical machine-to-machine type communications. The networks must provide significantly reduced end-to-end latency and higher reliability than is achievable today. Ultra-reliability is vital for safety. Low latency is crucial to ensure applications are usable and interactive whether human-to-human, human-to-machine or machine-to-machine communication. This Nokia white paper outlines the needs for ultra-reliability and virtual zero latency communication as well as the solutions to build 5G networks."

Nokia Networks**, "5G Masterplan – Five Keys To Create The New Communications Era," 02/2016**

> **Excerpt:** "Nokia Networks has identified five key aspects that describe the transformation of today's communications to the 5G era. Together these five areas outline how 5G will come about, what it will be, the way it will be built and how it will affect all our lives. Possibilities defines the new demands that 5G must support and the new opportunities it will create. Versatile radio explores the different radio access technologies that will combine to provide ultra-flexible connectivity. System of systems sets out the network architecture that will be needed, how it will support the new demands and provide the great experiences and solid security that people and industries will expect."

Nokia Networks**, "5G Use Cases and Requirements," 07/2014**

> **Summary:** "The number of use cases for a next generation mobile communications system will grow rapidly and the scenarios will place much more diverse requirements on the system. In this White Paper we have outlined the use cases and requirements for 5G but also the key design principles – flexibility and reliability. The future may seem far ahead but the phase for defining the requirements is now and what's more, any new technology or system that we design for 5G needs to be future proof and last at least until 2030. 5G will come and even though we are still in an exploratory phase, Nokia is already setting out what 5G will deliver and how it will deliver it."

Nokia Networks**, "Looking Ahead To 5G," 05/2014**

> **Summary:** "5G is on its way and rather than being another 'next generation' it will be a better integration of old and new technologies. This integration of different systems will enable more stringent requirements in some areas to be met, relaxed needs in others, with a focus on keeping overall costs and energy dissipation low. The combination of evolution and revolution, wide and local area, big and small cells and different carrier frequencies will enable a fully scalable service experience on demand, where people and machines will enjoy a virtual zero latency gigabit experience when and where it matters."

Qualcomm**, "Paving the Path to Narrowband 5G with LTE Internet of Things," 07/2016**

> **Abstract:** "NB-IoT also establishes the foundation for Narrowband 5G, which will bring even more opportunities for the Internet of Things. 5G will enhance massive IoT with new capabilities such as Resource Spread Multiple Access (RSMA) for grant-free transmissions, and multi-hop mesh to further extend coverage. 5G will also enable new

services, such as mission-critical control, with many innovative use cases in robotics, aviation, healthcare, industrial control, and vehicles, where enhancement dimensions such as sub-1ms latency, ultra-high reliability, and availability are required (but not simultaneously needed for all services). All in all, connecting the Internet of Things will be an integral part of 5G – a unified, more capable connectivity platform for the next decade and beyond."

Qualcomm**, "5G - Vision For The Next Generation Of Connectivity," 03/2015**

Excerpt: "Generational shifts in the world of technology capture the imagination, and promising the opportunity to push the envelope and do things in entirely new ways. The story of 5G is no different, it will be a transformational force that enables new services, connects new industries, and empowers new user experiences for the next decade—and beyond. 5G promises to deliver much more than just higher data rates and more capacity. It targets new kinds of ultra-reliable, mission-critical services. Examples include, applications that will allow doctors to remotely control medical procedures or give consumers new levels of control over their homes or cars, and beyond. 5G aims to effectively connect virtually everything—from simple sensors to complex robots, all while further enhancing traditional mobile broadband service. That means next generation of applications, services and use cases will have extreme variation in requirements. To meet this challenge, 5G will require a whole new user-centric design that can scale and adapt to billions of connected things, provide new ways of connecting everything, and enhance cost and energy efficiency."

Radio Access and Spectrum/FP7**, "5G Radio Network Architecture," 02/28/2014**

Abstract: "This white paper is an outcome of the Radio Access and Spectrum cluster projects funded by the European Commission under the Seventh Framework Programme in the area of Future Networks. It presents a view from the European research community on the architecture aspects of 5G mobile and wireless communication systems."

Rohde & Schwarz**, "5G Waveform Candidates: Rohde & Schwarz White Paper," 06/20/2016**

Abstract: "Enhanced Mobile Broadband, Massive Machine Type Communication, Ultra-reliable and low latency communication have been identified as the requirements to be supported by the 5th Generation of Mobile Communication – 5G. 5G is being extensively discussed in the wireless industry especially around the need for a new airlink. A great deal of research and pre-development is being conducted worldwide, including an analysis of the waveforms and access principles that are the basis for current LTE and LTE-Advanced networks. In this application note R&S discuss potential 5G waveform candidates, list their advantages and disadvantages and compare them to Orthogonal Frequency Division Multiplexing (OFDM), which is used in LTE/LTE-Advanced."

Rysavy, Peter/Channel Partners, "IoT & 5G: Wait or Move?" Rysavy Research**, 10/2016**

Introduction: "IOT and 5G, two of the hottest trends in technology, are combining to transform our future by interconnecting everything: humans, cars, appliances, utilities, transportation infrastructures, mailboxes, light switches and anything else that might benefit from an intelligent connection. Expected 5G IoT capabilities include multiyear modem battery life, support for 1 million devices per square kilometer and low-cost

modems. But before you recommend that customers develop Internet of Things initiatives around 5G capabilities, know that, despite all the excitement and press being generated about 5G, operators will not begin deploying it in earnest until the 2020 time frame. Before then, companies may pilot pre-5G technologies in limited areas, but efforts will emphasize consumer broadband service to fixed locations, not IoT. Fortunately, IoT improvements in 4G LTE are occurring at a steady pace, meaning IoT wireless connectivity options will continually improve even before 5G. In many ways, 4G is setting the stage and providing a foundation for 5G. In this Report we'll cover 4G and 5G IoT capabilities, the implications of radio spectrum allocation on the IoT and time frames for various features."

Samsung Electronics Co., Ltd**., "5G Vision," 02/2015**

Abstract: "Samsung envisions the fifth Generation (5G) mobile communication era to be the beginning of a full scale Internet of Things (IoT). Billions of connected devices autonomously interconnect with one another while ensuring personal privacy. The unprecedented latencies offered by 5G Networks will enable users to indulge in gigabit speed immersive services regardless of geographical and time dependent factors. This white paper introduces you to future services, key requirements, and enabling technologies that will herald in the 5G era that is expected to revolutionize the way we experience mobile services."

SK Telecom**, "SK Telecom 5G White Paper," 10/22/2014**

Excerpt: "This document will outline how SK Telecom views and conceives 5G in general, which includes background behind the technological evolution to 5G and requirements, vision, architecture, major enabling technologies, potential frequencies and services and future direction of the telecommunications network development."

TechUK**/Future Technologies Network, "5G Innovation Opportunities- A Discussion Paper," 08/2015**

Excerpt: "The purpose of this paper is to alert interested parties to the UK's excellent capabilities in 5G, to identify the key technical challenges that must be overcome, and to stimulate the change needed to make the UK a true 5G powerhouse - by helping UK technology companies to play a valuable role in contributing to the development of key facets of 5G technology and applications as well as in the roll out and exploitation of 5G networks. It can be done. Investment of time and money in this sector does not just have huge business benefits. Socioeconomically too, when we all have more to do and less to do it with, we can still look after our ageing population, help local Government leverage the changes that are coming to provide their services ever more intelligently, and even improve remote learning to foster the key skills where they are currently lacking."

Telecommunications Industry Association/InterDigital**, "5G Operator Survey," 07/2015**

Abstract: "Within the next two decades, it is predicted that every person, industry, and service provider will be using 5G systems. The fifth generation wireless standard is expected to underpin new technology deployments as well as future technologies that at this time can only be imagined. This paper provides valuable insight into the network operators' view of the 5G revolution."

University of Surrey**, "5G Whitepaper: The Flat Distributed Cloud (FDC) 5G Architecture Revolution," 01/2016**

> **Excerpt:** "This 5GIC whitepaper proposes a disruptive change in architecture for next generation cellular networking that enables a user experience that is perceived as always sufficient for their current context. In order to meet this perception the network is designed so as to always make best use of the resources available at the time of each new communications request applicable to the context of the user at the time."

West, Darrell, "How 5G Technology Enables the Health Internet of Things," Brookings**, 07/14/2016**

> **Excerpt:** "In this paper, Darrell West discusses the unique capabilities of the 5G era, explores applications of IoT technology in medicine, and recommends policies for making these new care delivery systems a reality. 5G technology has the potential to increase patient access to treatment options, reduce hospital visits, and create a flexible network of telehealth, in addition to reducing overall medical costs."

Yuan, Yifei and Xiaowu Zhao, "5G: Vision, Scenarios and Enabling Technologies," ZTE**, 2015**

> **Abstract:** "This paper presents the authors' vision for 5G wireless systems, which are expected to be standardized around 2020 (IMT-2020). In the future, ubiquitous service will be the key requirement from an end-user's prospective, and 5G networks will need to support a vast mesh of human-to-human, human-to-machine, and machine-to-machine connections. Moreover, 5G will need to support these connections in an energy-efficient manner. Various 5G enabling technologies have been extensively discussed. These technologies aim to increase radio link efficiency, expand operating bandwidths, and increase cell density. With these technologies, 5G systems can accommodate a massive volume of traffic and a massive number of connections, which is fundamental to providing ubiquitous services. Another aspect of 5G technology is the transition to an intelligent cloud that coordinates network access and enables flatter architecture."

C.11 Commercial Initiatives

A list of 5G commercial initiatives, including brief descriptions on pages 36-37 of the U.S. national carriers' 5G efforts, can be found in the 5G Americas paper, "Global Organizations Forge New Frontier of 5G," 07/2016.

http://www.4gamericas.org/files/8914/6774/6748/Global_Organizations_Forge_New_Frontier_of_5G_Final.pdf