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Exhibit Number:	Cal Advocates-
Commissioner:	C. Rechtschaffen
Admin. Law Judge:	K. J. Bemesderfer
Cal Advocates Project Mgr.:	Shelly Lyser
Cal Advocates Expert Witness:	Cameron Reed

PUBLIC ADVOCATES OFFICE

Public Advocates Office

California Public Utilities Commission

Supporting Exhibits to the Public Advocates Office Testimony on Fifth Generation Wireless Service for the Proposed Transfer of Control of Sprint to T-Mobile

- PUBLIC -

San Francisco, California
January 7, 2019

A.18-07-011 AND **A.18-07-012** THE PUBLIC ADVOCATES OFFICE TESTIMONY EXHIBIT INDEX ON 5G WIRELESS SERVICE

Exhibit #	**Document Name**	Public Information	Contains **Confidential** T-Mobile Information	Contains **Confidential** Sprint Information
CR-1	International Technical Union – Radiocommunication Sector (ITU-R) Recommendation M.2083	X		
CR-2	Sprint Response to Cal Advocates Data Request 001 Question 1-24.			X
CR-3	T-Mobile Response to Cal Advocates Data Request 001 Question 1-24.		X	
CR-4	Sprint 3rd Quarter 2017 Earnings Call	X		
CR-5	T-Mobile Response to Cal Advocates Data Request 002, Question 2-2	X		
CR-6	T-Mobile BingeOn Statistics		X	
CR-7	Massive MIMO and Beamforming	X		
CR-8	Nokia White Paper on Beamforming and mMIMO	X		
CR-9	Nokia White Paper on 5G Deployment below 6 GHz	X		
CR-10	Nokia White Paper on 5G Radio Access	X		

Docket: A.18-07-011 and A.18-07-012

Witness: Cameron Reed

Date: January 7, 2019

Public Advocates Office

Exhibit CR-1

"International Technical Union – Radiocommunication Sector (ITU-R) Recommendation M.2083"

International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Recommendation ITU-R M.2083-0
(09/2015)

IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond

M Series

Mobile, radiodetermination, amateur and related satellite services

International Telecommunication Union

Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

Policy on Intellectual Property Right (IPR)

ITU-R policy on IPR is described in the Common Patent Policy for ITU-T/ITU-R/ISO/IEC referenced in Annex 1 of Resolution ITU-R 1. Forms to be used for the submission of patent statements and licensing declarations by patent holders are available from http://www.itu.int/ITU-R/go/patents/en where the Guidelines for Implementation of the Common Patent Policy for ITU-T/ITU-R/ISO/IEC and the ITU-R patent information database can also be found.

Series of ITU-R Recommendations

(Also available online at http://www.itu.int/publ/R-REC/en)

Series	Title
BO	Satellite delivery
BR	Recording for production, archival and play-out; film for television
BS	Broadcasting service (sound)
BT	Broadcasting service (television)
F	Fixed service
M	**Mobile, radiodetermination, amateur and related satellite services**
P	Radiowave propagation
RA	Radio astronomy
RS	Remote sensing systems
S	Fixed-satellite service
SA	Space applications and meteorology
SF	Frequency sharing and coordination between fixed-satellite and fixed service systems
SM	Spectrum management
SNG	Satellite news gathering
TF	Time signals and frequency standards emissions
V	Vocabulary and related subjects

Note*: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

Electronic Publication
Geneva, 2015

RECOMMENDATION ITU-R M.2083-0

IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond

(2015)

Scope

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.

Keywords

IMT, IMT-2020

Abbreviations/Glossary

ICT	Information and Communication Technology
IMT	International Mobile Telecommunications
IoT	Internet of Things
M2M	Machine-to-Machine
MIMO	Multiple Input Multiple Output
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio access technology
RLAN	Radio Local Area Network

Related ITU Recommendations, Reports

Recommendation ITU-R M.1645 – Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000

Recommendation ITU-R M.2012 – Detailed specifications of the terrestrial radio interfaces of International Mobile Telecommunications Advanced (IMT-Advanced)

Report ITU-R M.2320 – Future technology trends of terrestrial IMT systems

Report ITU-R M.2370 – IMT Traffic estimates for the years 2020 to 2030

Report ITU-R M.2376 – Technical feasibility of IMT in bands above 6 GHz

Report ITU-R M.2134 – Requirements related to technical performance for IMT-Advanced radio interface(s)

The ITU Radiocommunication Assembly,

considering

a) that ITU has contributed to standardization and harmonized use of IMT, which has provided telecommunication services on a global scale;

b) that technological advancement and the corresponding user needs will promote innovation and accelerate the delivery of advanced communication applications to consumers;

c) that Question ITU-R 229/5 addresses further development of the terrestrial component of IMT and the relevant studies under this Question are in progress within ITU-R;

d) that Recommendation ITU-R M.1645 defines the framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000;

e) that for global operation and economies of scale, which are key requirements for the success of mobile telecommunication systems, it is desirable to establish a harmonized timeframe for future development of IMT considering technical, operational and spectrum related aspects;

f) that wireless communication applications are expected to expand into new market segments to facilitate the digital economy, e.g. smart grid, e-health, intelligent transport systems and traffic control, which would bring requirements beyond what can be addressed in today's IMT application areas;

g) that rapid uptake of smartphones, tablets and innovative mobile applications created by users has resulted in a tremendous increase in the volume of mobile data traffic;

h) that the number of devices accessing the network are expected to increase due to the emerging applications of Internet of Things (IoT);

i) that technologies such as beamforming, massive-Multiple Input Multiple Output (MIMO) are easier to implement in higher frequencies due to short wavelength;

j) that wide contiguous bandwidth would enhance data delivery efficiency and ease the complexity of hardware implementation;

k) that the cell size is being reduced (e.g. the order of some tens of metres) to provide larger area traffic capacity in dense areas;

l) that IMT interworks with other radio systems,

recognizing

a) that some administrations had deployed IMT-Advanced systems before global deployment due to the rapid increase of data traffic;

b) that development of new radio interfaces that support the new capabilities of IMT-2020 is expected along with the enhancement of IMT-2000 and IMT-Advanced systems,

noting

that pursuant to Article 44 of the ITU Constitution, Member States shall endeavour to apply the latest technical advances as soon as possible,

recommends

that the Annex should be used as the framework and the overall objectives for the future development of IMT for 2020 and beyond.

Annex

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1 Introduction

The socio-technical evolution in the last few decades has been significantly driven by the evolution of mobile communications and has contributed to the economic and social development of both developed and developing countries. Mobile communications has become closely integrated in the daily life of the whole society. It is expected that the socio-technical trends and the evolution of mobile communications systems will remain tightly coupled together and will form a foundation for society in 2020 and beyond.

In the future, however, it is foreseen that new demands, such as more traffic volume, many more devices with diverse service requirements, better quality of user experience (QoE) and better affordability by further reducing costs, will require an increasing number of innovative solutions.

The objective of this Recommendation is to establish the vision for IMT for 2020 and beyond, by describing potential user and application trends, growth in traffic, technological trends and spectrum implications, and by providing guidelines on the framework and the capabilities for IMT for 2020 and beyond.

2 Observation of trends

2.1 User and application trends

Mobile devices play various, continuously evolving roles in everyday life. Future IMT systems should support emerging new use cases, including applications requiring very high data rate communications, a large number of connected devices, and ultra-low latency and high reliability applications. More specific user and application trends are explained in §§ 2.1.1 to 2.1.8.

2.1.1 Supporting very low latency and high reliability human-centric communication

People expect the experience of instantaneous connectivity wherein applications need to exhibit "flash" behaviour without waiting times: a single click and the response is perceived as instantaneous. Flash behaviour will be a key factor for the success of cloud services and virtual reality and augmented reality applications. The low latency and high reliability communication that supports such behaviour thus becomes an enabler for the future development of new applications, e.g. in health, safety, office, entertainment, and other sectors.

2.1.2 Supporting very low latency and high reliability machine-centric communication

The reliability and latency in today's communication systems have been designed with the human user in mind. For future wireless systems, the design of new applications is envisaged based on machine-to-machine (M2M) communication with real-time constraints. Driverless cars, enhanced mobile cloud services, real-time traffic control optimization, emergency and disaster response, smart grid, e-health or efficient industrial communications are examples of where low latency and high reliability can improve quality of life.

2.1.3 Supporting high user density

Users will expect a satisfactory end-user experience in the presence of a large number of concurrent users, for example in a crowd with a high traffic density per unit area and a large number of handsets and machines/devices per unit area. Examples are audio-visual content to be provided concurrently across an entire cell or infotainment applications in shopping malls, stadiums, open air festivals, or other public events that attract a lot of people. This includes users who use their phone while in unexpected traffic jams, or when travelling in public transportation systems, as well as professionals working in organisations such as police, fire brigades, and ambulances to exploit the public communication networks in crowded environments and machine-centric devices.

2.1.4 Maintaining high quality at high mobility

A connected society in the years beyond 2020 will need to accommodate a similar user experience for end-users on the move and when they are static e.g. at home or in the office. To offer the "best experience" to highly mobile users and communicating machine devices, robust and reliable connectivity solutions are needed as well as the ability to efficiently maintain service quality with mobility.

Maintaining high quality at high mobility will enable successful deployment of applications on user equipment located within a moving platform such as cars or high-speed trains which are being deployed in several countries. Connectivity on mobile platforms may be provided via IMT, Radio Local Area Network (RLAN) or another network on that platform using suitable backhaul.

2.1.5 Enhanced multimedia services

It is likely that demand for mobile high-definition multimedia will increase in many areas beyond entertainment, such as medical treatment, safety, and security.

User devices will get enhanced media consumption capabilities, such as Ultra-High Definition display, multi-view High Definition display, mobile 3D projections, immersive video conferencing, and augmented reality and mixed reality display and interface. This will all lead to a demand for significantly higher data rates. Media delivery will be both to individuals and to groups of users.

2.1.6 Internet of Things

In the future, every object that can benefit from being connected will be connected through wired or wireless internet technologies. Therefore, the number of connected devices will grow rapidly and is expected to exceed the number of human user devices in the future.

These connected "things" can be smart phones, sensors, actuators, cameras, vehicles, etc., ranging from low-complexity devices to highly complex and advanced devices. A significant number of connected devices are expected to use IMT systems.

As a result, the connected entities are bound to have varying levels of energy consumption, transmission power, latency requirements, cost, and many other indices critical for stable connection.

In addition, as more and more things get connected, various services that utilize the connection capabilities of things will appear. Smart energy distribution grid system, agriculture, healthcare, vehicle-to-vehicle and vehicle-to-road infrastructure communication are generally viewed as potential fields for further growth of the Internet of Things (IoT).

2.1.7 Convergence of applications

New applications are increasingly being delivered over IMT, including e-Government, public protection and disaster relief communication, education, linear[1] and on-demand audio-visual content, and e-health. This convergence of applications must take account of the requirements associated with these applications.

2.1.8 Ultra-accurate positioning applications

As the accuracy of positioning gets better, location-based service applications that provide improved emergency rescue services, as well as precise ground based navigation service for unmanned vehicles or drones may expand extensively.

2.2 Growth in IMT traffic

There are many drivers influencing the growth of future IMT traffic demand, especially the adoption of devices with enhanced capabilities that require increased bit rates and bandwidth usage. Similar drivers increased traffic in the transition from IMT-2000 to IMT-Advanced.

The main drivers behind the anticipated traffic growth include increased video usage, device proliferation and application uptake. These are expected to evolve over time, and this evolution will differ between countries due to social and economic differences. These drivers and other trends which impact traffic growth are detailed in Report ITU-R M.2370. The Report contains global IMT traffic estimates beyond 2020 from several sources. These estimates anticipate that global IMT traffic will grow in the range of 10-100 times from 2020 to 2030.

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[1] A linear audio-visual service refers to the "traditional" way of offering radio or TV services. Listeners and viewers "tune in" to the content organised as a scheduled sequence that may consist of e.g. news, shows, drama or movies on TV or various types of audio content on radio. These sequences of programmes are set up by content providers and cannot be changed by a listener or a viewer. Linear services are not confined to a particular distribution technology. For example, a live stream on the Internet is to be considered as a linear service as well.

Traffic asymmetry aspects for this period are also presented in Report ITU-R M.2370. It is observed that the current average traffic asymmetry ratio of mobile broadband is in favour of the downlink, and this is expected to increase due to growing demand for audio-visual content.

2.3 Technology trends

Report ITU-R M.2320 provides a broad view of future technical aspects of terrestrial IMT systems considering the timeframe 2015-2020 and beyond. It includes information on technical and operational characteristics of IMT systems, including the evolution of IMT through advances in technology and spectrally-efficient techniques, and their deployment. Report ITU-R M.2320 provides more detailed information on the following technical aspects presented in §§ 2.3.1 to 2.3.8. In addition, technologies required to enable higher data rates are explained in § 2.3.9.

2.3.1 Technologies to enhance the radio interface

Advanced waveforms, modulation and coding, and multiple access schemes, e.g. filtered OFDM (FOFDM), filter bank multi-carrier modulation (FBMC), pattern division multiple access (PDMA), sparse code multiple access (SCMA), interleave division multiple access (IDMA) and low density spreading (LDS) may improve the spectral efficiency of the future IMT systems.

Advanced antenna technologies such as 3D-beamforming (3D-BF), active antenna system (AAS), massive MIMO and network MIMO will achieve better spectrum efficiency.

In addition, TDD-FDD joint operation, dual connectivity and dynamic TDD can enhance the spectrum flexibility.

Simultaneous transmission and reception on the same frequency with self-interference cancellation could increase spectrum efficiency.

Other techniques such as flexible backhaul and dynamic radio access configurations can also enable enhancements to the radio interface.

In small cells, higher-order modulation and modifications to the reference-signal structure with reduced overhead may provide performance enhancements due to lower mobility in small cell deployments and potentially higher signal-to interference ratios compared to the wide-area case.

Flexible spectrum usage, joint management of multiple radio access technologies (RATs) and flexible uplink/downlink resource allocation, can provide technical solutions to address the growing traffic demand in the future and may allow more efficient use of radio resources.

2.3.2 Network technologies

Future IMT will require more flexible network nodes which are configurable based on the Software-Defined Networking (SDN) architecture and network function virtualization (NFV) for optimal processing the node functions and improving the operational efficiency of network.

Featuring centralized and collaborative system operation, the cloud RAN (C-RAN) encompasses the baseband and higher layer processing resources to form a pool so that these resources can be managed and allocated dynamically on demand, while the radio units and antenna are deployed in a distributed manner.

The radio access network (RAN) architecture should support a wide range of options for inter-cell coordination schemes. The advanced self-organizing network (SON) technology is one example solution to enable operators to improve the OPEX efficiency of the multi-RAT and multi-layer network, while satisfying the increasing throughput requirement of subscriber.

2.3.3 Technologies to enhance mobile broadband scenarios

A relay based multi-hop network can greatly enhance the Quality of Service (QoS) of cell edge users. Small-cell deployment can improve the QoS of users by decreasing the number of users in a cell and user quality of experience can be enhanced.

Dynamic adaptive streaming over HTTP (DASH) enhancement is expected to improve user experience and accommodate more video streaming content in existing infrastructure.

Bandwidth saving and transmission efficiency improvement is an evolving trend for Evolved Multimedia Broadcast and Multicast Service (eMBMS). Dynamic switching between unicast and multicast transmission can be beneficial.

IMT systems currently provide support for RLAN interworking, at the core network level, including seamless as well as non-seamless mobility, and can offload traffic from cellular networks into license-exempt spectrum bands.

Context aware applications may provide more personalized services that ensure high QoE for the end user and proactive adaptation to the changing context.

Proximity-based techniques can provide applications with information whether two devices are in close proximity of each other, as well as enable direct device-to-device (D2D) communication. Group communication, including push-to-talk type of communication, is highly desirable for public safety.

2.3.4 Technologies to enhance massive machine type communications

Future IMT systems are expected to connect a large number of M2M devices with a range of performance and operational requirements, with further improvement of low-cost and low-complexity device types as well as extension of coverage.

2.3.5 Technologies to enhance ultra-reliable and low latency communications

To achieve ultra-low latency, the data and control planes may both require significant enhancements and new technical solutions addressing both the radio interface and network architecture aspects.

It is envisioned that future wireless systems will, to a larger extent, also be used in the context of machine-to-machine communications, for instance in the field of traffic safety, traffic efficiency, smart grid, e-health, wireless industry automation, augmented reality, remote tactile control and tele-protection, requiring high reliability techniques.

2.3.6 Technologies to improve network energy efficiency

In order to enhance energy efficiency, energy consumption should be considered in the protocol design.

The energy efficiency of a network can be improved by both reducing RF transmit power and saving circuit power. To enhance energy efficiency, the traffic variation characteristic of different users should be well exploited for adaptive resource management. Examples include discontinuous transmission (DTX), base station and antenna muting, and traffic balancing among multiple RATs.

2.3.7 Terminal technologies

The mobile terminal will become a more human friendly companion as a multi-purpose Information and Communication Technology (ICT) device for personal office and entertainment, and will also evolve from being predominantly a hand-held smart phone to also include wearable smart devices.

Technologies for chip, battery, and display should therefore be further improved.

2.3.8 Technologies to enhance privacy and security

Future IMT systems need to provide robust and secure solutions to counter the threats to security and privacy brought by new radio technologies, new services and new deployment cases.

2.3.9 Technologies enabling higher data rates

In order to achieve higher data rates and improvements in capacity, the following key techniques are needed:

Spectrum:

- Utilization of large blocks of spectrum in higher frequency bands
- Carrier aggregation

Physical Layer:

- Enhanced spectral efficiency by means of e.g. advanced physical layer techniques (modulation, coding) and advances in spatial processing (network MIMO and Massive MIMO), plus exploitation of other novel/alternative ideas.

Network:

- Network densification

2.4 Studies on technical feasibility of IMT between 6 and 100 GHz

The development of IMT for 2020 and beyond is expected to enable new use cases and applications, and addresses rapid traffic growth, for which contiguous and broader channel bandwidths than currently available for IMT systems would be desirable. This suggests the need to consider spectrum resources in higher frequency ranges.

Report ITU-R M.2376 provides information on the technical feasibility of IMT in the frequencies between 6 and 100 GHz. It includes information on potential new IMT radio technologies and system approaches, which could be appropriate for operation in this frequency range.

The Report presents measurement data on propagation in this frequency range in several different environments. Both line-of-sight and non-line-of-sight measurement results for stationary and mobile cases as well as outdoor-to-indoor results have been presented in the report. It also includes performance simulations results for several different deployment scenarios.

The Report describes solutions based on MIMO and beamforming with a large number of antenna elements, which compensate for the increasing propagation loss with frequency; these have become increasingly feasible due to the ability to exploit chip-scale antenna solutions and modular adaptive antenna arrays that do not require an ADC/DAC for each antenna element. The practicality of manufacturing commercial transmitters and receivers at these frequencies is investigated, as evidenced by availability of commercial 60 GHz multi-gigabit wireless systems (MGWS) products and prototyping activities that are already underway at frequencies such as 11, 15, 28, 44, 70 and 80 GHz.

The potential advantages of using the same spectrum for both access and fronthaul/backhaul, as compared with using two different frequencies for access and fronthaul/backhaul, are described in the Report.

The theoretical assessment, simulations, measurements, technology development and prototyping described in the Report indicate that utilizing the bands between 6 and 100 GHz is feasible for studied IMT deployment scenarios, and could be considered for the development of IMT for 2020 and beyond.

2.5 Spectrum implications

Report ITU-R M.2290 provides the results of studies on estimated global spectrum requirements for terrestrial IMT in the year 2020. The estimated total requirements include spectrum already identified for IMT plus additional spectrum requirements.

It is noted that no single frequency range satisfies all the criteria required to deploy IMT systems, particularly in countries with diverse geographic and population density; therefore, to meet the capacity and coverage requirements of IMT systems multiple frequency ranges would be needed. It should be noted that there are differences in the markets and deployments and timings of the mobile data growth in different countries.

For future IMT systems in the year 2020 and beyond, contiguous and broader channel bandwidths than available to current IMT systems would be desirable to support continued growth. Therefore, availability of spectrum resources that could support broader, contiguous channel bandwidths in this time frame should be explored. Research efforts must be continued to increase spectrum efficiency and to explore the availability of contiguous broad channels.

Furthermore, if additional spectrum is made available for IMT, the potential implications to the existing uses and users of that spectrum need to be addressed.

2.5.1 Spectrum harmonization

As the amount of spectrum required for mobile services increases, it becomes increasingly desirable for existing and newly allocated and identified spectrum to be harmonized. The benefits of spectrum harmonization include: facilitating economies of scale, enabling global roaming, reducing equipment design complexity, preserving battery life, improving spectrum efficiency and potentially reducing cross border interference. Typically, a mobile device contains multiple antennas and associated radio frequency front-ends to enable operation in multiple bands to facilitate roaming. While mobile devices can benefit from common chipsets, variances in frequency arrangements necessitate different components to accommodate these differences, which leads to higher equipment design complexity.

Therefore, harmonization of spectrum for IMT will lead to commonality of equipment and is desirable for achieving economies of scale and affordability of equipment.

2.5.2 Importance of contiguous and wider spectrum bandwidth

The proliferation of smart devices (e.g. smartphones, tablets, televisions, etc.) and a wide range of applications requiring a large amount of data traffic have accelerated demand for wireless data traffic. Future IMT systems are expected to provide significant improvement to accommodate this rapidly increasing traffic demand. In addition, future IMT systems are expected to provide gigabit-per-second user data rate services. The currently available frequency bands and their bandwidth differ across countries and regions and this leads to many problems associated with device complexity and possible interference issues. Contiguous, broader and harmonized frequency bands, aligned with future technology development, would address these problems and would facilitate achievement of the objectives of future IMT systems.

In particular, bandwidths to support the different usage scenarios in § 4 (e.g. enhanced mobile broadband, ultra-reliable and low-latency communications, and massive machine type communications) would vary. For those scenarios requiring several hundred MHz up to at least 1 GHz, there would be a need to consider wideband contiguous spectrum above 6 GHz.

3 Evolution of IMT

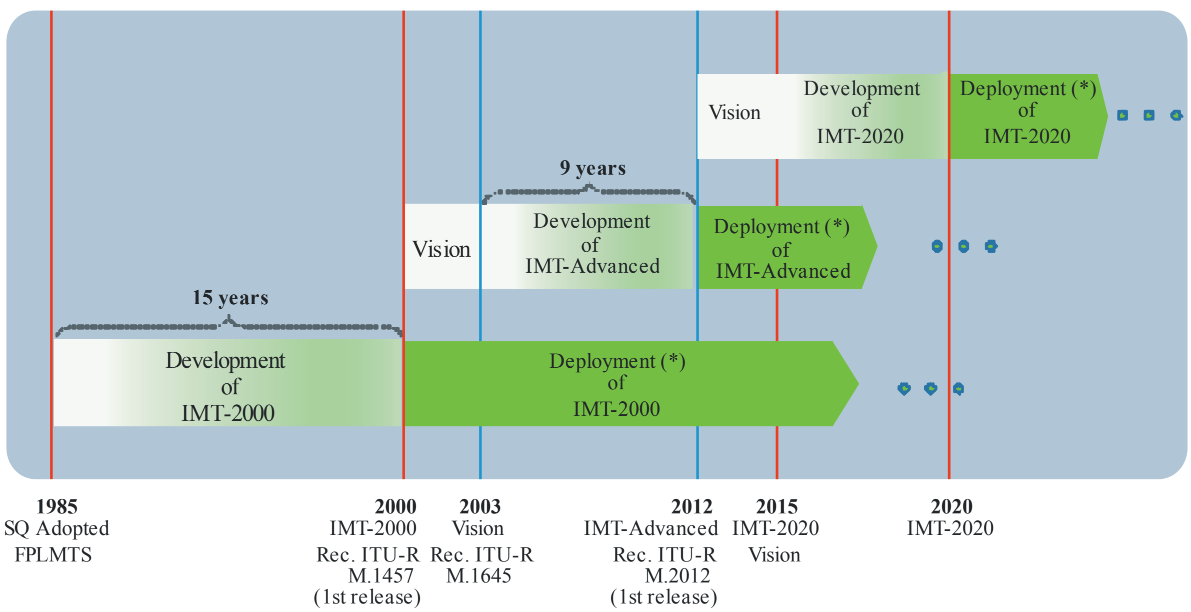
3.1 How IMT has developed

Following the adoption by International Radio Consultative Committee (CCIR) of the Study Question on the Future Public Land Mobile Telecommunication Systems (FPLMTS) in 1985, it took a total of 15 years for the identification of the radio spectrum in 1992 and development of IMT-2000 specifications (Recommendation ITU-R M.1457). After this development, deployment of IMT-2000 systems started.

The ITU then immediately started to develop the vision Recommendation (Recommendation ITU-R M.1645, June 2003) on Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000. Based on this Recommendation, the ITU has released the Recommendation ITU-R M.2012 in the terrestrial radio interface of IMT-Advanced in 2012. It took nine years for the ITU to develop the second phase of IMT after the completion of the vision recommendation. After this development, deployment of the IMT-Advanced systems started.

FIGURE 1

Overview of timeline for IMT development and deployment



(*) Deployment timing may vary across countries.

M.2083-01

3.2 Role of IMT for 2020 and beyond

IMT systems serve as a communication tool for people and a facilitator which assists the development of other industry sectors, such as medical science, transportation, and education. Considering the key trends described in § 2, IMT should continue to contribute to the following:

– **Wireless infrastructure to connect the world**: Broadband connectivity will acquire the same level of importance as access to electricity. IMT will continue to play an important role in this context as it will act as one of the key pillars to enable mobile service delivery and information exchanges. In the future, private and professional users will be provided with a wide variety of applications and services, ranging from infotainment services to new industrial and professional applications.

– **New ICT market**: The development of future IMT systems is expected to promote the emergence of an integrated ICT industry which will constitute a driver for economies around the globe. Some possible areas include: the accumulation, aggregation and analysis of big data; delivering customized networking services for enterprise and social network groups on wireless networks

– **Bridging the Digital Divide**: IMT will continue to help closing the gaps caused by an increasing Digital Divide. Affordable, sustainable and easy-to-deploy mobile and wireless communication systems can support this objective while effectively saving energy and maximizing efficiency.

– **New ways of communication**: IMT will enable sharing of any type of contents anytime, anywhere through any device. Users will generate more content and share this content without being limited by time and location.

– **New forms of education**: IMT can change the method of education by providing easy access to digital textbooks or cloud-based storage of knowledge on the internet, boosting applications such as e-learning, e-health, and e-commerce.

– **Promote Energy Efficiency**: IMT enables energy efficiency across a range of sectors of the economy by supporting machine to machine communication and solutions such as smart grid, teleconferencing, smart logistics and transportation.

– **Social changes**: Broadband networks make it easier to quickly form and share public opinions for a political or social issue through social network service. Opinion formation of a huge number of connected people due to their ability to exchange information anytime anywhere will become a key driver of social changes.

– **New art and culture**: IMT will support people to create works of art or participate in group performances or activities, such as a virtual chorus, flash mob, co-authoring or song writing. Also, people connected to a virtual world are able to form new types of communities and establish their own cultures.

4 Usage scenarios for IMT for 2020 and beyond

IMT for 2020 and beyond is envisaged to expand and support diverse usage scenarios and applications that will continue beyond the current IMT. Furthermore, a broad variety of capabilities would be tightly coupled with these intended different usage scenarios and applications for IMT for 2020 and beyond. The usage scenarios for IMT for 2020 and beyond include:

– **Enhanced Mobile Broadband**: Mobile Broadband addresses the human-centric use cases for access to multi-media content, services and data. The demand for mobile broadband will continue to increase, leading to enhanced Mobile Broadband. The enhanced Mobile Broadband usage scenario will come with new application areas and requirements in addition to existing Mobile Broadband applications for improved performance and an increasingly seamless user experience. This usage scenario covers a range of cases, including wide-area coverage and hotspot, which have different requirements. For the hotspot case, i.e. for an area with high user density, very high traffic capacity is needed, while the requirement for mobility is low and user data rate is higher than that of wide area coverage. For the wide area coverage case, seamless coverage and medium to high mobility are desired, with much improved user data rate compared to existing data rates. However the data rate requirement may be relaxed compared to hotspot.

– **Ultra-reliable and low latency communications**: This use case has stringent requirements for capabilities such as throughput, latency and availability. Some examples include wireless control of industrial manufacturing or production processes, remote medical surgery, distribution automation in a smart grid, transportation safety, etc.

– **Massive machine type communications**: This use case is characterized by a very large number of connected devices typically transmitting a relatively low volume of non-delay-sensitive data. Devices are required to be low cost, and have a very long battery life.

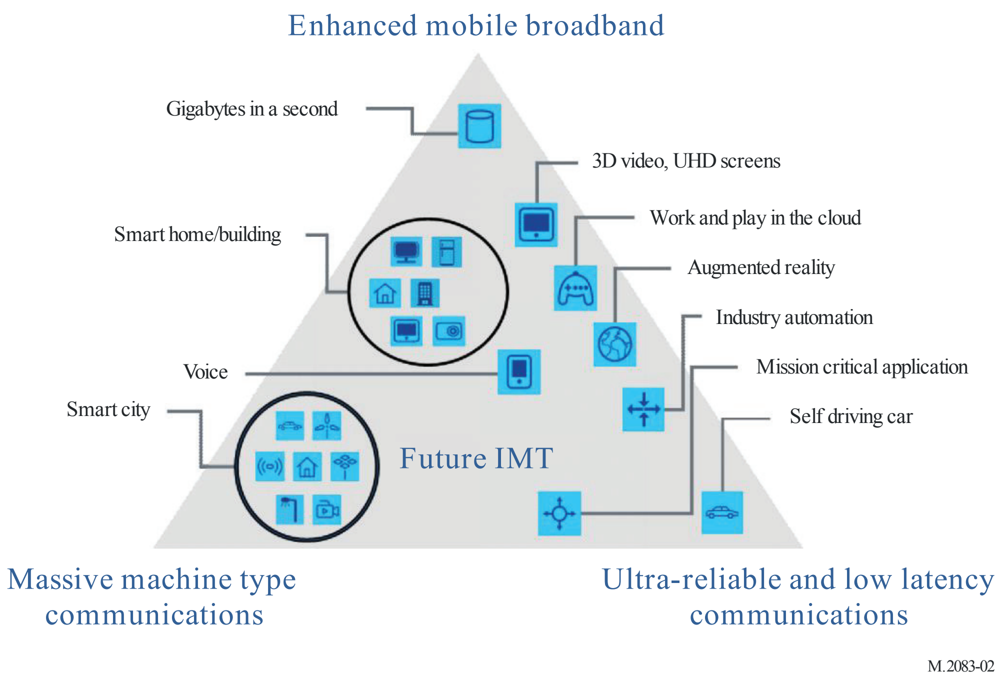
Additional use cases are expected to emerge, which are currently not foreseen. For future IMT, flexibility will be necessary to adapt to new use cases that come with a wide range of requirements.

Future IMT systems will encompass a large number of different features. Depending on the circumstances and the different needs in different countries, future IMT systems should be designed in a highly modular manner so that not all features have to be implemented in all networks.

Figure 2 illustrates some examples of envisioned usage scenarios for IMT for 2020 and beyond.

FIGURE 2

Usage scenarios of IMT for 2020 and beyond



5 Capabilities of IMT-2020

IMT for 2020 and beyond is expected to provide far more enhanced capabilities than those described in Recommendation ITU-R M.1645, and these enhanced capabilities could be regarded as new capabilities of future IMT. As ITU-R will give a new term IMT-2020 to those systems, system components, and related aspects that support these new capabilities, the term IMT-2020 is used in the following sections.

A broad variety of capabilities, tightly coupled with intended usage scenarios and applications for IMT-2020 is envisioned. Different usage scenarios along with the current and future trends will result in a great diversity/variety of requirements. The key design principles are flexibility and diversity to serve many different use cases and scenarios, for which the capabilities of IMT-2020, described in the following paragraphs, will have different relevance and applicability. In addition, the constraints on network energy consumption and the spectrum resource will need to be considered.

The following eight parameters are considered to be key capabilities of IMT-2020:

Peak data rate

Maximum achievable data rate under ideal conditions per user/device (in Gbit/s).

User experienced data rate

Achievable data rate that is available ubiquitously[2] across the coverage area to a mobile user/device (in Mbit/s or Gbit/s).

Latency

The contribution by the radio network to the time from when the source sends a packet to when the destination receives it (in ms).

Mobility

Maximum speed at which a defined QoS and seamless transfer between radio nodes which may belong to different layers and/or radio access technologies (multi-layer/-RAT) can be achieved (in km/h).

Connection density

Total number of connected and/or accessible devices per unit area (per km^2).

Energy efficiency

Energy efficiency has two aspects:

– on the network side, energy efficiency refers to the quantity of information bits transmitted to/ received from users, per unit of energy consumption of the radio access network (RAN) (in bit/Joule);

– on the device side, energy efficiency refers to quantity of information bits per unit of energy consumption of the communication module (in bit/Joule).

Spectrum efficiency

Average data throughput per unit of spectrum resource and per cell[3] (bit/s/Hz).

Area traffic capacity

Total traffic throughput served per geographic area (in Mbit/s/m^2).

IMT-2020 is expected to provide a user experience matching, as far as possible, fixed networks. The enhancement will be realized by increased peak and user experienced data rate, enhanced spectrum efficiency, reduced latency and enhanced mobility support.

In addition to the conventional human-to-human or human-to-machine communication, IMT-2020 will realize the Internet of Things by connecting a vast range of smart appliances, machines and other objects without human intervention.

IMT-2020 should be able to provide these capabilities without undue burden on energy consumption, network equipment cost and deployment cost to make future IMT sustainable and affordable.

The key capabilities of IMT-2020 are shown in Fig. 3, compared with those of IMT-Advanced.

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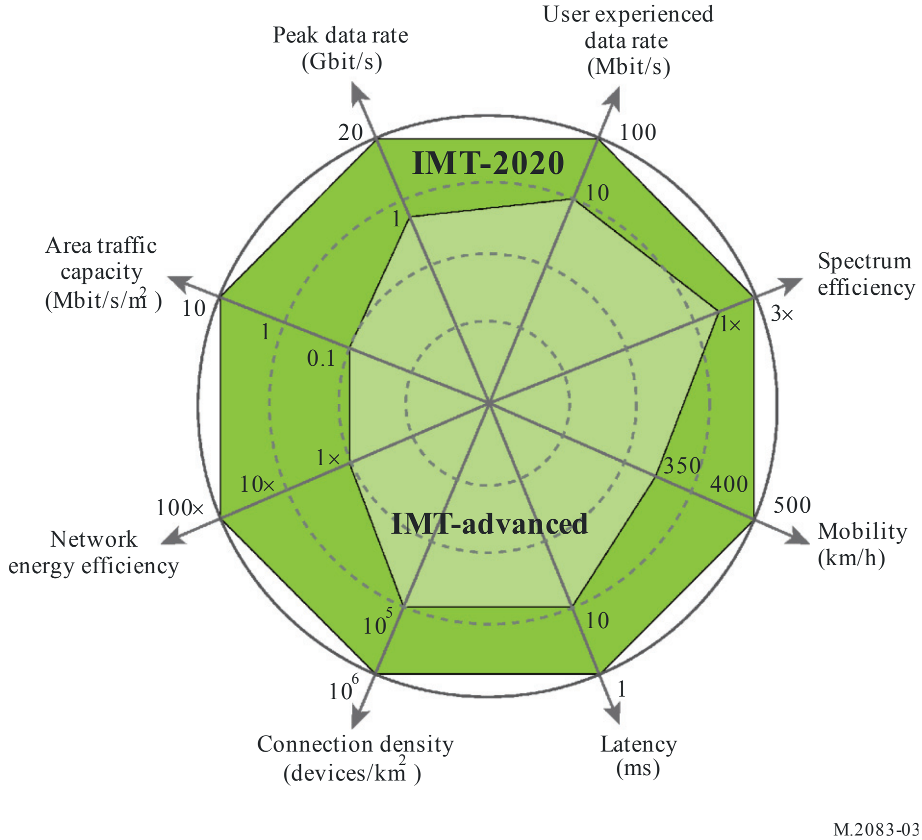
[2] The term "ubiquitous" is related to the considered target coverage area and is not intended to relate to an entire region or country.

[3] The radio coverage area over which a mobile terminal can maintain a connection with one or more units of radio equipment located within that area. For an individual base station, this is the radio coverage area of the base station or of a subsystem (e.g. sector antenna).

FIGURE 3

Enhancement of key capabilities from IMT-Advanced to IMT-2020



The values in the Figure above are targets for research and investigation for IMT-2020 and may be further developed in other ITU-R Recommendations, and may be revised in the light of future studies. The targets are further described below.

The peak data rate of IMT-2020 for enhanced Mobile Broadband is expected to reach 10 Gbit/s. However under certain conditions and scenarios IMT-2020 would support up to 20 Gbit/s peak data rate, as shown in Fig. 3. IMT-2020 would support different user experienced data rates covering a variety of environments for enhanced Mobile Broadband. For wide area coverage cases, e.g. in urban and sub-urban areas, a user experienced data rate of 100 Mbit/s is expected to be enabled. In hotspot cases, the user experienced data rate is expected to reach higher values (e.g. 1 Gbit/s indoor).

The spectrum efficiency is expected to be three times higher compared to IMT-Advanced for enhanced Mobile Broadband. The achievable increase in efficiency from IMT-Advanced will vary between scenarios and could be higher in some scenarios (for example five times subject to further research). IMT-2020 is expected to support 10 Mbit/s/m^2 area traffic capacity, for example in hot spots.

The energy consumption for the radio access network of IMT-2020 should not be greater than IMT networks deployed today, while delivering the enhanced capabilities. The network energy efficiency should therefore be improved by a factor at least as great as the envisaged traffic capacity increase of IMT-2020 relative to IMT-Advanced for enhanced Mobile Broadband.

IMT-2020 would be able to provide 1 ms over-the-air latency, capable of supporting services with very low latency requirements. IMT-2020 is also expected to enable high mobility up to 500 km/h with acceptable QoS. This is envisioned in particular for high speed trains.

Finally, IMT-2020 is expected to support a connection density of up to 10^6/km^2, for example in massive machine type communication scenarios.

The reference values for IMT-Advanced shown in Fig. 3 for the peak data rate, mobility, spectrum efficiency and latency are extracted from Report ITU-R M.2134. The Report this was published in 2008 and was used for the evaluation of IMT-Advanced candidate radio interfaces described in Recommendation ITU-R M.2012.

As anticipated above, whilst all key capabilities may to some extent be important for most use cases, the relevance of certain key capabilities may be significantly different, depending on the use cases/scenario. The importance of each key capability for the usage scenarios *enhanced Mobile Broadband*, *ultra-reliable and low latency communication* and *massive machine-type communication* is illustrated in Fig. 4. This is done using an indicative scaling in three steps as "high", "medium" and "low".

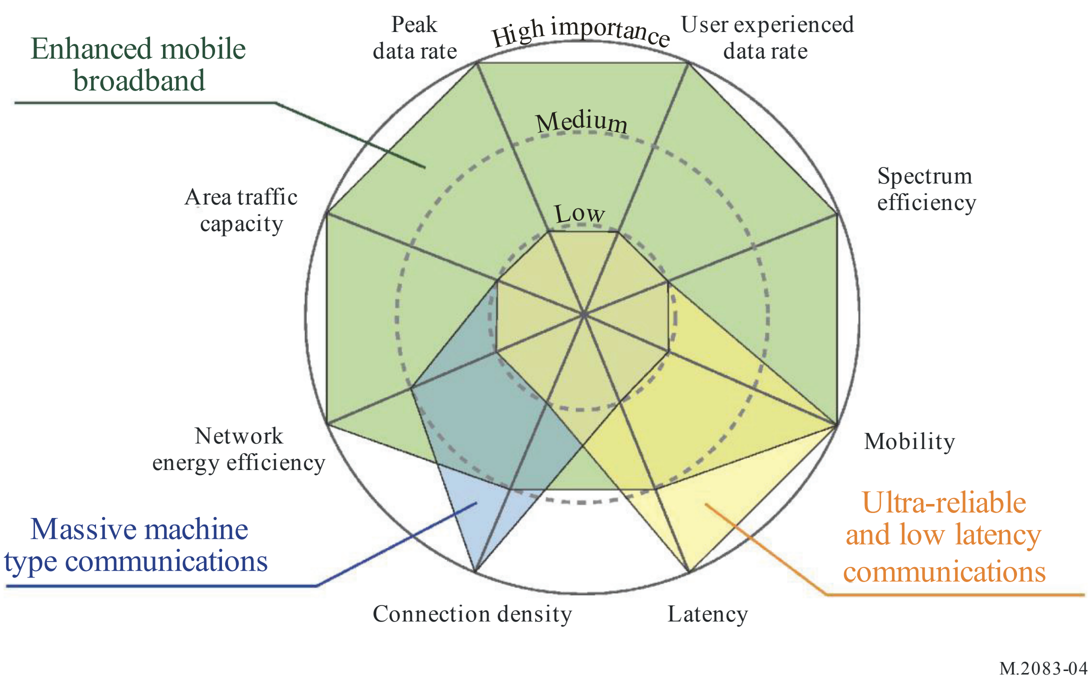
In the enhanced Mobile Broadband scenario, user experienced data rate, area traffic capacity, peak data rate, mobility, energy efficiency and spectrum efficiency all have high importance, but mobility and the user experienced data rate would not have equal importance simultaneously in all use cases. For example, in hotspots, a higher user experienced data rate, but a lower mobility, would be required than in wide area coverage case.

In some ultra-reliable and low latency communications scenarios, low latency is of highest importance, e.g. in order to enable the safety critical applications. Such capability would be required in some high mobility cases as well, e.g. in transportation safety, while, e.g. high data rates could be less important.

In the massive machine type communication scenario, high connection density is needed to support tremendous number of devices in the network that e.g. may transmit only occasionally, at low bit rate and with zero/very low mobility. A low cost device with long operational lifetime is vital for this usage scenario.

FIGURE 4

The importance of key capabilities in different usage scenarios



Other capabilities may be also required for IMT-2020, which would make future IMT more flexible, reliable, and secure when providing diverse services in the intended usage scenarios:

Spectrum and bandwidth flexibility

Spectrum and bandwidth flexibility refers to the flexibility of the system design to handle different scenarios, and in particular to the capability to operate at different frequency ranges, including higher frequencies and wider channel bandwidths than today.

Reliability

Reliability relates to the capability to provide a given service with a very high level of availability.

Resilience

Resilience is the ability of the network to continue operating correctly during and after a natural or man-made disturbance, such as the loss of mains power.

Security and privacy

Security and privacy refers to several areas such as encryption and integrity protection of user data and signalling, as well as end user privacy preventing unauthorized user tracking, and protection of network against hacking, fraud, denial of service, man in the middle attacks, etc.

Operational lifetime

Operational life time refers to operation time per stored energy capacity. This is particularly important for machine-type devices requiring a very long battery life (e.g. more than 10 years) whose regular maintenance is difficult due to physical or economic reasons.

6 Framework and objectives

The objective of the development of IMT-2020 is to address the anticipated needs of users of mobile services in the years 2020 and beyond. The goals for the capabilities of IMT-2020 system described in § 5 are only targets for research and investigation and may be further developed in other ITU Recommendations, and may be revised in the light of future studies. This section provides relationships between IMT-2020 and existing IMT/other access systems, timelines and focus areas for further study as framework and objectives for the development of IMT-2020.

6.1 Relationships

6.1.1 Relationship between existing IMT and IMT-2020

In order to support emerging new scenarios and applications for 2020 and beyond, it is foreseen that development of IMT-2020 will be required to offer enhanced capabilities as those described in § 5. The values of these capabilities go beyond those described in Recommendation ITU-R M.1645. The minimum technical requirements (and corresponding evaluation criteria) to be defined by ITU-R based on these capabilities for IMT-2020 could potentially be met by adding enhancements to existing IMT, incorporating new technology components and functionalities, and/or the development of new radio interface technologies.

Furthermore, IMT-2020 will interwork with and complement existing IMT and its enhancements.

6.1.2 Relationship between IMT-2020 and other access systems

Users should be able to access services anywhere, anytime. To achieve this goal, interworking will be necessary among various access technologies, which might include a combination of different fixed, terrestrial and satellite networks. Each component should fulfil its own role, but also should be integrated or interoperable with other components to provide ubiquitous seamless coverage.

IMT-2020 will interwork with other radio systems, such as RLANs, broadband wireless access, broadcast networks, and their possible future enhancements. IMT systems will also closely interwork with other radio systems for users to be optimally and cost-effectively connected.

6.2 Timelines

In planning for the development of IMT-2020 as well as future enhancement of the existing IMT, it is important to consider the timelines associated with their realization, which depend on a number of factors:

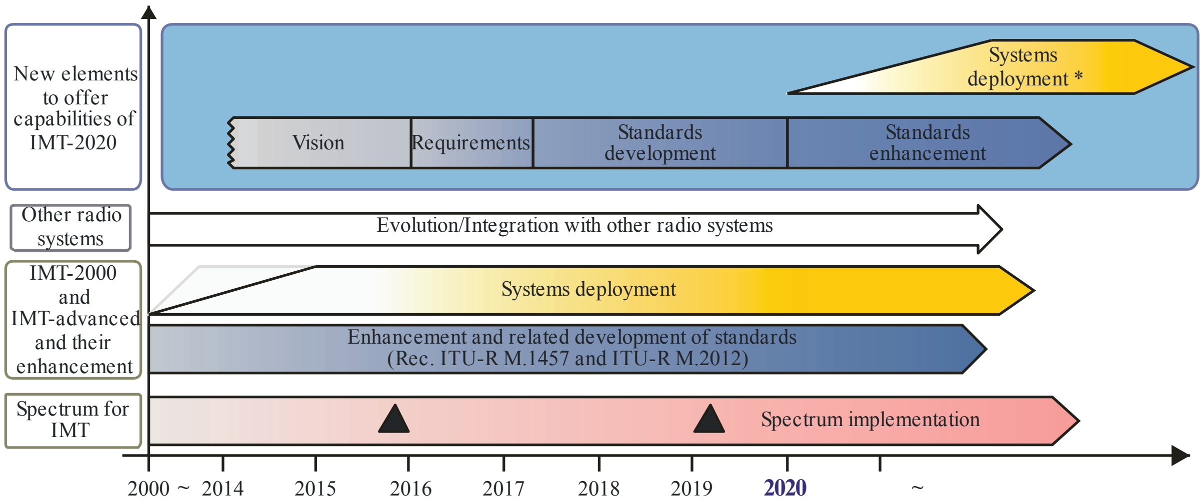
- user trends, requirements and user demand;
- technical capabilities and technology development;
- standards development and their enhancement;
- spectrum matters;
- regulatory considerations;
- system deployment.

All of these factors are interrelated. The first five have been and will continue to be addressed within ITU. System development and deployment relates to the practical aspects of deploying new networks, taking into account the need to minimize additional infrastructure investment and to allow time for customer adoption of the services of a new system. ITU will complete its work for standardization of IMT-2020 no later than the year 2020 to support IMT-2020 deployment by ITU members expected from the year 2020 onwards.

The timelines associated with these different factors are depicted in Fig. 5. When discussing the phases and timelines for IMT-2020, it is important to specify the time at which the standards are completed, when spectrum would be available, and when deployment may start.

FIGURE 5

Phase and expected timelines for IMT-2020



The sloped dotted lines in systems deployment indicate that the exact starting point cannot yet be fixed.

▲ : Possible spectrum identification at WRC-15 and WRC-19

* : Systems to satisfy the technical performance requirements of IMT-2020 could be developed before year 2020 in some countries.
: Possible deployment around the year 2020 in some countries (including trial systems)

M.2083-05

6.2.1 Medium term

In the medium-term (up to about the year 2020) it is envisaged that the future development of IMT-2000 and IMT-Advanced will progress with the ongoing enhancement of the capabilities of the initial deployments, as demanded by the marketplace in addressing user needs and allowed by the status of technical developments. This phase will be dominated by the growth in traffic within the existing IMT spectrum, and the development of IMT-2000 and IMT-Advanced during this time will be distinguished by incremental or evolutionary changes to the existing IMT-2000 and IMT-Advanced radio interface specifications (i.e. Recommendations ITU-R M.1457 for IMT-2000 and ITU-R M.2012 for IMT-Advanced, respectively).

It is envisaged that the bands identified by WRCs will be made available for IMT within this timeframe subject to user demand and other consideration.

6.2.2 Long term

The long term (beginning around the year 2020) is associated with the potential introduction of IMT-2020 which could be deployed around the year 2020 in some countries. It is envisaged that IMT-2020 will add enhanced capabilities described in § 5, and they may need additional frequency bands in which to operate.

6.3 Focus areas for further study

The research forums and other external organizations wishing to contribute to the future development of IMT-2020 are encouraged to focus especially in the following key areas:

a) radio interface(s) and their interoperability;

b) access network related issues;

c) spectrum related issues;

d) traffic characteristics.

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Docket: A.18-07-011 and A.18-07-012

Witness: Cameron Reed

Date: January 7, 2019

Public Advocates Office

Exhibit CR-2

"Sprint Response to Cal Advocates Data Request 001 Question 1-24"

Contains CONFIDENTIAL SPRINT Information

Docket:	A.18-07-011 and A.18-07-012
Witness:	Cameron Reed
Date:	January 7, 2019

Public Advocates Office

Exhibit CR-3

"T-Mobile Response to Cal Advocates Data Request 001 Question 1-24"

Contains CONFIDENTIAL T-Mobile Information

Docket: A.18-07-011 and A.18-07-012

Witness: Cameron Reed

Date: January 7, 2019

Public Advocates Office

Exhibit CR-4

"Sprint 3rd Quarter 2017 Earnings Call"

02-Feb-2018

Sprint Corp. (S)

Q3 2017 Earnings Call

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MANAGEMENT DISCUSSION SECTION

Operator: Good morning, and thank you for standing by. Welcome to the Sprint Fiscal Third Quarter 2017 Conference Call. During today's conference call, all participants will be in a listen-only mode. Following the opening remarks, the conference will be opened for questions. I would now like to turn the call over to Mr. Jud Henry, Vice-President of Investor Relations. Please go ahead, sir.

Jud Henry

Vice President & Head of Investor Relations, Sprint Corp.

Thank you, Cindy. Good morning, and welcome to Sprint's quarterly results conference call. Joining me on the call today are Sprint's CEO, Marcelo Claure; our new President and CFO, Michel Combes, and our CTO, Dr. John Saw. Before we get underway, let me remind you that our release, quarterly investor update, and presentation slides that accompany this call are all available on the Sprint Investor Relations website at www.Sprint.com/investors.

Slide 2 is our cautionary statement. I want to point out that in our remarks this morning we will be discussing forward-looking information which involves a number of risks and uncertainties that may cause actual results to differ materially from our forward-looking statements. We provide a comprehensive list of risk factors in our SEC filings which I encourage you to review. Throughout our call, we will refer to several non-GAAP metrics as shown on slide 3. Reconciliations of our non-GAAP measures to the appropriate GAAP measures for the quarter can be found on our Investor Relations website. I will now turn the call over to Marcelo to provide you an update on our transformation.

Raul Marcelo Claure

Chief Executive Officer & Director, Sprint Corp.

Thank you, Jud, and good morning, everyone. It's good to be here today not only to update you on another successful quarter in our turnaround journey, but also to share with you our strategy for the next phase of Sprint's turnaround. First, let me share with you our results for the quarter that reflect our continued momentum in our turnaround. I'm happy to report that we had the highest retail net additions in nearly three years. At the same time, we achieved the highest adjusted EBITDA for fiscal third quarter in 11 years and the 8th consecutive quarter of operating income. This adjusted EBITDA milestone was propelled by the transformation in our cost structure, and we have already taken out more than $1 billion of expenses this year, which marks the fourth year in a row of at least $1 billion of net reductions to cost of services and SG&A.

This improvement in profitability has helped us achieve positive adjusted free cash flow in eight of the last nine quarters. In addition, our network continue to improve as demonstrated by Ookla Speedtest data which shows Sprint's network was the most improved of any national carrier in 2017 with average download speeds up 60% year-over-year and we have now passed AT&T in average download speed during this past quarter.

Turning to slide 5. This has been another remarkable quarter as it marks the fourth consecutive quarter that we're handset net add positive in all three of our segments of consumer postpaid business and prepaid.

Our postpaid net additions were 256,000 in the third quarter, and our phone net additions of 184,000 mark the tenth consecutive quarter of growth. We estimate our share of industry postpaid phone gross add was around 20% again this quarter which continues to be nearly double our market share of 12%.

Postpaid churn was 1.71%. We recognized that our churn is higher than our peers, but let me share with you what some of the impact is by design and why we're very confident that our churn should improve in the future.

First, we can now target specific locations within our network for improvement thanks to a new tool that we have implemented called quality of experience or QOE. It is sophisticated, a statistical scoring model of each customer's network KPI based on their individual experience with us.

We find in markets in which we have deployed our tri-band LTE with three carrier aggregation have a high QOE and those customers have lower churn. In some cases, around 1%, which is very close to our competitors. This allow us to build where we can have the greatest impact on the customer experience.

This also gives us the confidence that we can deliver churn levels closer to peers with a great network, and we will share with you later on how we plan to get there.

We have also made the decision to manage the business at a higher churn rate. We're selectively managing higher ARPU subs in our base as they do not have access to our more aggressive acquisition offers and some are above our competitive rate for unlimited plans. We're comfortable using this strategy as it creates more enterprise value to have a higher churn than to write-down our base. We also see some churn pressure from leasing, but we believe that the total economics of leasing more than compensate for a higher churn level.

In addition, our business segment continues to have an amazing momentum with phone gross adds up 36% year-over-year and the lowest churn in over five years. Our small and medium business has delivered positive phone net adds for six consecutive quarters, and our enterprise group has had positive handset net adds for two consecutive quarters. This is a big achievement as this group had been losing customers for years.

Now let's discuss prepaid, where we also maintain our positive momentum in the fiscal third quarter with 63,000 net adds. This was the fourth consecutive quarter of net additions in prepaid and marks an improvement of over 500,000 year-over-year. Prepaid churn also improved year-over-year for the sixth consecutive quarter and prepaid gross adds grew year-over-year for the second consecutive quarter.

We have made tremendous improvement in the last three years as you can see reflected on slide 6. In the first phase of our transformation, we have increased our postpaid phone gross adds per year by nearly 800,000, we've gone from losing 1.3 million postpaid phone customers per year to gaining nearly 1 million last year.

We have reduced our operating expenses across cost of service and SG&A by $6 billion, and we have nearly doubled our adjusted EBITDA. In addition, we have swung from an operating loss of more than $1.5 billion to operating income of more than $2.5 billion. We have gone from burning adjusted free cash flow of more than $5 billion to generating more than $0.5 billion. As you can see, we have made tremendous improvement in the first phase of our turnaround and I could not be more excited for the next chapter of our success story based on the principles you see here on slide 7.

I am very confident in Sprint's future based on the competitive advantage that we will have with the deployment of 5G on our 2.5 GHz spectrum. We're working with Qualcomm and network and device manufacturers in order to launch the first truly mobile network in the United States by the first half of 2019. This latest development will put Sprint at the forefront of technology and innovation on par with other leading carriers around the world. This is where the power of 2.5 GHz comes to life to provide a unified 5G platform to enable innovative products and services and to partner with our sister companies under the SoftBank Group.

The Sprint is a strategic asset for SoftBank, along with leading technology companies like ARM, OneWeb, Alibaba, along with rights sharing robotic and artificial intelligence companies. Our strategy is predicated on creating an amazing customer experience, offering customers the best products and services while delivering superior financial results. First, we recognize that to be a truly a great company, we have to have a great product which for us is our network. While our network is much improved, we believe our Next-Gen Network will truly differentiate Sprint over the next couple of years due to our strong spectrum assets that enable Sprint to be the leader in the true mobile 5G.

This is the biggest network capital program in many years, and I will share more details about our network strategy in a few moments. I cannot wait to once and for all be able to sell the product that is best in the industry with competitive coverage, the fastest speed, and the highest capacity.

Second, we will continue to deliver the most compelling value proposition to our customers across all of our segments. We will continue to play from a position of strength by leveraging our spectrum holdings and continue to lead with the best unlimited offering in the market. Data usage trends are projected to grow exponentially, especially with 5G. By having the most spectrum, combined with new technology that massively increases our capacity, we're certain that we'll be best positioned for to support unlimited data in the future.

Third, we will continue to drive a smart distribution strategy with over 1,000 new stores open year-to-date across our Sprint and Boost brands and several hundred more planned throughout next year. We have designed a dynamic distribution model that allow us to continuously optimize the right balance of physical and digital distribution. The radical simplicity of our offer, OneRate plan for unlimited enable us to grow our digital transactions.

Our commercial growth strategy is fueled by continued cost transformation that is focused on maximizing operational efficiency. Our cost transformation program has led to operational improvements and we will simplify our business even further in the next phase of our turnaround. You may have seen that I have streamlined my senior leadership team in the last few months and we expect to look for ways to carry that through the rest of the organization to deliver a leaner and more agile workforce across our noncustomer facing functions. This includes reducing the total number of executives at the top and throughout the organization to get better alignment of responsibilities and better operational effectiveness.

Turning to slide 8, we will improve even more with our Next-Gen Network strategy that will deliver blazing-fast network with gigabit speeds and position Sprint to have competitive coverage and be the network leader in speed and capacity over the next couple of years.

First, we plan to increase our total number of macro sites by nearly 20% to expand our LTE footprint. And we have already issued search rings to leading tower and infrastructure companies.

Second, we're putting our spectrum resources to work as we tri-band nearly all of our existing sites with all three of our spectrum bands, 800 MHz, 1.9 GHz and 2.5 GHz, to provide great coverage and capacity across our footprint. Roughly half of our macro sites have 2.5 GHz today, and we have already started on thousands of site upgrades and expect to complete the majority of site upgrades in 2018. We have already signed agreements with two major tower companies to facilitate a swift rollout of these site upgrades.

Next, we plan to deploy more than 40,000 outdoor small cell solutions. In addition, our strategic agreements with Altice and Cox will also enable us to quickly and cost effectively deploy our various small cell solutions, including at least 15,000 strand mounted small cells and improved backhaul economics for our macro sites. We are already working to light up Long Island, and look forward to expanding the rest of Altice and Cox footprints to accelerate our network deployment.

Also, we continue deployment of Sprint Magic Boxes and plan to deploy more than one million Sprint Magic Boxes. I'm excited to say that we have already deployed more than 80,000 Sprint Magic Boxes to businesses and consumers in approximately 200 cities across the country, making this one of the largest small cell deployments in the U.S. Customers with a Magic Box are enjoying significant improvement in indoor and outdoor coverage, as well as an increasing download of speeds of more than 200%.

Furthermore, our Next-Gen Network utilizes technology such as multiple carrier aggregation, which deliver bigger pipes for faster speeds, Frame Config 2 for a greater allocation of our 2.5 GHz spectrum for downlink, and this is a TDD spectrum advantage only Sprint has for more efficient use of our spectrum capacity and beamforming for better coverage and cell edge performance.

Now let me tell you about another element of our Next-Gen Network plan that we are beyond excited about, and that is the rollout of Massive MIMO. It leverages our 2.5 GHz and creates a strategic advantage for Sprint.

Massive MIMO involves deploying a new integrated unit that will have 128 antenna elements with 64 transmitters and 64 receivers and which deliver a capacity increase of up to 10 times on LTE relative to current LTE systems, while also increasing our coverage and cell edge performance.

More importantly, because only Sprint uses TDD spectrum versus our competitors which use FDD spectrum, nearly all of our customers will be able to instantly take advantage of this significant performance enhancement on their existing devices whereas Massive MIMO on our competitors' FDD spectrum will require new devices.

Massive MIMO will also serve as Sprint's bridge to 5G, which is another strategic advantage of our 2.5 GHz spectrum as shown on slide 9. Massive MIMO radios are software upgradeable to 5G NR, allowing us to fully utilize our spectrum for both LTE and 5G simultaneously, while we enhance capacity even further with 5G and begin to support new 5G use cases.

There are a lot of claims being made about 5G by our competitors. We believe that Sprint is best positioned to be the first carrier with a nationwide mobile 5G platform.

Verizon and AT&T talk about a path to 5G, but they're relying on millimeter wave spectrum that, sure, it will give you super wide channels of capacity, but the propagation is limited to a very short distance, in most cases requiring line of sight. It is really just a hot zone and not a true mobile experience unless they spend a fortune to massively densify their network to connect the dots which will take a long time under current regulatory restrictions for permits.

Sprint is the only carrier that doesn't have to compromise what 5G can deliver because we can deliver the super-wide channels of more than 100 MHz while still delivering mid-band coverage characteristics. With more than 160 MHz of 2.5 GHz spectrum available in the top 100 U.S. markets, this gives Sprint the largest nationwide bloc of sub-6 GHz 5G spectrum available in the U.S. Sprint's priority is mobile 5G, and we expect to provide commercial services and devices by the first half of 2019.

Moving to slide 10, with this great network we're going to continue to offer the best value proposition for unlimited data in the industry. We have been the industry leader in unlimited since the beginning, and we will continue to play to our strength with more spectrum per customer of any carrier.

Sprint offers the best fully featured unlimited data plan in the industry including HD video, mobile hotspot, free data roaming in more countries than any other carrier and many other features that benefit customers, all for the best price in the industry.

To add even more value for our customers, we recently included access to Hulu in all of our unlimited plans to take mobile entertainment to a new high by combining our industry-leading unlimited service with all the hit television shows, award winning original series and popular movies Hulu has to offer.

Furthermore, on slide 11, we're optimizing and expanding our smart distribution to lower the average cost per transaction, increase our brand presence and better serve our customers. We have opened over 500 new Sprint branded stores year-to-date. In addition, we have opened over 500 new Boost stores this year as well as dramatically updating some older stores to the latest format on furnishing, which have proven to deliver greater productivity on a same-store basis.

We plan to add hundreds of more Sprint and Boost stores throughout next year, while also updating more existing stores to be more productive and appealing. And we continue to enhance our digital capabilities and I'm proud to say that My Sprint app is now rated 4.5 stars providing our customers a convenient way to check their account, upgrade their device, pay their bill, or perform many other functions instantly and easy.

Next, I'm excited to share with you some proof points that show that our strategy is working on slide 12. As I discussed a few moments ago, we're implementing our commercial strategy to deploy our Next-Gen Network, expand our retail and digital distribution and leverage target local marketing. We have accelerated this blueprint across a few markets, such as Chicago, Cincinnati and Orlando and we're seeing some very encouraging early success.

We haven't even put the full capabilities of our Next-Gen Network in place yet and our distribution is still ramping up, and yet we're already seeing improved share of postpaid gross adds in excess of 30% in this market according to estimates from KPMG and churn in the low 1% range in some of these markets. I'm optimistic that as we expand our full playbook across all the major markets, we will see further acceleration of our subscriber performance.

In a moment, I will turn the call over to Michel to take you through our financial results, but first I want to say a few things about our CFO transition. First of all, everyone at Sprint thanks Tarek for his many contributions for Sprint's turnaround success over the last couple of years. The Sprint is much stronger today thanks to Tarek, and we wish him all the best in the future. I look forward to working with Michel as we execute the next phase of our turnaround as he brings a lot of experience as a transformational specialist who believes in the importance of investing in the network and customer experience.

I'll now let Michel walk you through our financial results.

Michel Combes

President, Chief Financial Officer & Director, Sprint Corp.

Thank you, Marcelo. I am very excited to join Sprint and to be a part of this remarkable turnaround story. I am energized by the strategy that Marcelo has laid out for you, and I believe that Sprint has the best spectrum assets of any carrier I have seen in my career. I would also like to thank Tarek for his gracious support as we transitioned over the last month. Tarek has clearly helped provide Sprint with a better cost structure, a stronger balance sheet and diversified capital sources

Moving to revenue, on slide 13. Consolidated net operating revenues were $8.2 billion for the quarter. Wireless service revenue of over $5.6 billion declined 2% year-over-year when normalizing for the change in our device insurance program, which is the lowest year-over-year decline in the last 15 quarters. The sustained improvement in consumer trends has translated into better financial results as prepaid wireless service revenue grew year-over-year for the first time in nearly three years. Postpaid phone average billings per user was $68.54 were flat year-over-year on a normalized basis while postpaid average billings per account or ABPA was $170.39 for the quarter.

At the end of the quarter, 79% of our postpaid phone base was on unsubsidized rate plans. This leaves only about 10% of our postpaid phone base to be transitioned to unsubsidized rate plans assuming that penetration will level off around 90% due to business and other legacy plans. Meanwhile, our prepaid ARPU grew year-over-year to $37.46 in the fiscal third quarter.

Regarding our operating expenses on slide 14, we continued to execute on our cost transformation in the fiscal third quarter. We have realized over $1 billion in net reductions in combined operating expenses year-to-date across cost of services and SG&A expenses when you adjust for the hurricane and other nonrecurring impacts this year.

For the fiscal third quarter, our combined cost of services and SG&A improved by roughly $260 million from a year ago when excluding the hurricane and other nonrecurring items. Cost of services for the quarter of $1.7 billion was down 10% year-over-year driven by changes to our device insurance program as the program revenue and cost accounted for and reported on a net basis, as well as lower network expenses. SG&A were $2.1 billion in the quarter and were relatively flat compared to a year ago as the year-over-year increases in prepaid marketing and sales expenses were mostly offset by lower bad debt expenses.

Cost of product of $1.7 billion for the quarter decreased by 16% from a year ago, mostly driven by higher mix of postpaid activations and leasing. We remain focused on our cost transformation to deliver net cost reductions year-over-year in fiscal 2017 after investments into growth platforms for the business including retail distribution, network densification, digitalizations of sales and care and prepaid growth initiatives.

Furthermore, we are already developing initiatives for additional expense reductions in 2018 and beyond as continued cost transformation will provide the foundation to fund our growth strategy and further improve margins in the future as Marcelo outlined at the beginning of the call.

The company has taken roughly $6 billion of costs out of the business, but I will tell you that I still see more room to improve operational efficiency and extract significantly more costs out of the business by focusing on reducing complexity and improving our agility to be laser focused on our core priorities that Marcelo outlined. My goal will be to help optimize Sprint's cost structure in order to invest in our network, our value proposition and our smart distribution.

Now turning to slide 15, our adjusted EBITDA of $2.7 billion for the quarter was the highest fiscal third quarter in 11 years and improved by 11% compared to a year ago. Operating income of $727 million in fiscal third quarter, more than doubled from the year ago quarter. While this quarter included $66 million of hurricane impacts and roughly $300 million related to favorable legal settlements and other items; our operating income is up roughly $190 million year-over-year after adjusting for these special items driven by our cost transformation.

Moving to slide 16, Sprint reported net income this quarter of $7.2 billion or $1.79 per share compared to a net loss of $479 million or $0.12 per share in the year-ago period. This quarter included $7.1 billion of noncash benefit from tax reform, which is resulting from a reduction of deferred tax liabilities due to the lower corporate tax rate and an overall increase in our net deferred tax assets due to changes in the rules applicable to net operating loss carry forwards. Adjusting for these impacts of tax reform, favorable legal [ph] statements and the hurricanes (26:41), our underlying net loss has improved by roughly $300 million year-over-year driven by our cost transformation.

Turning to slide 17, total cash capital expenditures were $1.4 billion in fiscal third quarter, compared to $1.2 billion a year ago. Excluding capitalized device leases, cash capital expenditures were $696 million in the quarter, up more than 45% compared to the year-ago period with a year-over-year increase driven by the ramp-up of our network improvement initiative and our densification program.

Net cash provided by operating activities of $1.2 billion for the quarter was up nearly 80% compared to $650 million a year ago. Year-to-date, our net cash flow provided by operating activities is over $4.4 billion, which is up more than 50% year-over-year. This metric is a key focus of management as cash is king and it is the optimum source of funding for our growth initiatives and network investments.

Adjusted free cash flow was $397 million of fiscal third quarter and $1.1 billion on a year-to-date basis. We have now reported positive adjusted free cash flow in eight of the last nine quarters. While we do expect adjusted free cash flow to be negative in fiscal fourth quarter due to increased network CapEx, we are clearly making strong progress in consistent adjusted free cash flow generation.

We also continue to strengthen our balance sheet as we retired $2 billion of debt during the quarter. This included the final payments on the second tranche of MLS, $1.3 billion payments under our Network LeaseCo facility, and the early retirement of the Clearwire exchangeable notes that were callable on December 1.

Subsequent to the end of the quarter, we made the final payment under our Network LeaseCo facility in January and have now terminated that facility. These facilities or notes all add interest rates in the mid- to high-single digits, so these payments allow us to further reduce our future interest expenses.

Moving forward, we would expect to raise additional capital in the coming months to prefund our capital deployment plans. This activity would include issuing the second tranche of spectrum-backed notes under the existing $7 billion program. However, given the strength of global capital markets, we may look at other markets opportunistically as well.

As we move into the last quarter of fiscal 2017, let's turn the page to our full fiscal year 2017 guidance on slide 18. We expect to be near the midpoint of our adjusted EBITDA guidance of $10.8 billion to $11.2 billion in fiscal 2017. We are raising our operating income guidance from $2.1 billion to $2.5 billion, and now expect $2.5 billion to $2.7 billion in fiscal year 2017 to reflect the favorable legal settlements this past quarter. This guidance includes expected depreciation for lease device of $3.6 billion to $3.8 billion for fiscal 2017.

Regarding our guidance for cash capital expenditures, excluding lease devices, we continue to expect spending to increase significantly year-over-year but now expect CapEx to be near the low end of our guidance of $3.5 billion to $4 billion. We continue to expect CapEx to increase to $5 billion to $6 billion in fiscal 2018.

Lastly, we are raising our guidance for adjusted free cash flow to $500 million to $700 million versus our previous expectations to be around breakeven, reflecting our strong performance year-to-date.

Thank you. I now turn the call back to Jud to begin the Q&A.

Jud Henry

Vice President & Head of Investor Relations, Sprint Corp.

Thanks, Michel. In just a moment, we will begin the Q&A. Cindy, please inform our participants on how to queue up for the question-and-answer session.

QUESTION AND ANSWER SECTION

Operator: [Operator Instructions] Your first question comes from Philip Cusick from JPMorgan Securities.

Philip A. Cusick
Analyst, JPMorgan Securities LLC

Q

Thanks, guys. Two, if I can. First, Marcelo can you talk about Sprint's role in the SoftBank ecosystem? What synergies do you see with the ARM, OneWeb, Brightstar, Uber and others? And is there anything that's lost in having a public Sprint stub? And then one for Michel, welcome aboard, you pointed out that prepaid revenue is growing now, can you give us an update on how you see total service revenue trending? Can this stabilize in the next few quarters? Thanks.

Raul Marcelo Claure
Chief Executive Officer & Director, Sprint Corp.

A

Thanks for your question. So when we sit down and we start finding areas that make Sprint different than the rest – or big differentiators, we point out to two, right? One is our sub-6 GHz spectrum that we spoke in the call, and the ability for us to be the only company that can deploy a mobile 5G in early 2019.

And that is quite important because once you have this advanced 5G ecosystem, then you start thinking differently on how do you fit within the SoftBank ecosystem. As you know, SoftBank is the largest shareholder in many right-sharing companies and the future of right-sharing obviously is linked to connected cars, autonomous cars which require 5G type of networks. When you look at the future of IoT, ARM plays a key role in terms of defining the future of what is IoT going to be like, and it's definitely very helpful for Sprint to have a close relationship as they're both majority owned or in the case of ARM, completely owned. When you look at our longer-term project such as OneWeb and the potential launch in excess of 900 satellites in the low orbit satellite in the next couple of years; that could be an amazing supplement to a rural strategy that we have.

So when you look at ARM, OneWeb and other right-sharing companies, we're now starting to work all together to figure out how we can leverage each other's position for strength. But I will say more importantly is for Sprint to build a network that is going to satisfy their needs. The same applies to other robotic companies that SoftBank has acquired, and if you look at all those companies, all of them need the type of connectivity that we plan to bring, which is blazing gigabit speeds with most importantly low latency which is basically the future of 5G and the future of connecting the Internet of Things.

Michel Combes
President, Chief Financial Officer & Director, Sprint Corp.

A

On the second question. First, thanks, Phil. As I pointed out, wireless services revenue of $5.6 billion was down less than 1% sequentially and down 2% year-over-year, which shows that we have had our lowest year-over-year decline in the last 15 quarters when normalizing for the change in devices insurance program. So I guess that it's fair to expect that we should reach growth in service revenue by the end of fiscal year 2018. It's always a little bit difficult to predict quarter-on-quarter, but what we have seen during this quarter, the sequential decline of only $30 million, the fact that we have reignited growth in prepay, I guess that we have the report to come to this outcome by the end of 2018.

Philip A. Cusick
Analyst, JPMorgan Securities LLC

Q

Thanks, Michel. Marcelo if I can follow up, do you see anything lost in having a public stub at Sprint? As you said, SoftBank is an investor in a lot of companies where it's not a full owner. Is there any difference with Sprint?

Raul Marcelo Claure
Chief Executive Officer & Director, Sprint Corp.

A

So the going-private question is one that we get asked a lot of times, and I'll refer you that the ultimate question that is for SoftBank. [ph] First (35:30) SoftBank had been buying shares in the open market as a result of their strong belief in the Sprint future value, and becoming a wholly-owned subsidiary of SoftBank could be a possibility, but that obviously would depend 100% on Masa and I will let Masa answer that question. I guess he has an earnings call very soon.

Philip A. Cusick
Analyst, JPMorgan Securities LLC

Q

Thanks very much.

Operator: Your next question comes from Amir Rozwadowski from Barclays Capital.

Amir Rozwadowski
Analyst, Barclays Capital, Inc.

Q

Thank you very much, and good morning, folks. Thanks for taking the questions. Marcelo, maybe the first in terms of your commentary around how you approach churn going forward, you mentioned that you're happy to run it a higher level, but do you believe that given some of the initiatives that you have in place as you mentioned that you should see churn reduce on a year-over-year basis going forward?

Raul Marcelo Claure
Chief Executive Officer & Director, Sprint Corp.

A

So let's talk about churn, and that's always a hot topic of our calls. First let me – let's admit that there are further improvements to our network that needs to be made and those are going to reduce our churn. And let me walk you through something that we call QOE or quality of experience. What we have done is we've put close to 45 million retail customers, we have [ph] assigned an score (36:56), and that's based on the network experience that they're getting, based on the applications that they're using. And it took us a long time to basically – and this is a statistical dynamic model.

But what that allows us to do is in places where we're offering the quality of experience greater than three or four, this is one to five score, basically our churn falls in the range of 1% to 1.3%, which is exactly where we want to run our business. So what we need to do is we basically have to build – continue to build our network. But it's – we've done enough studies that basically show, if we provide the right quality of experience, a Sprint customer will stay with us and in many cases the churn is the same as our competitors. So that's one.

Now, there's also certain things that we do to have a higher churn, and we run the business from a value creation model. For example, when you're running a business model that allows customers to be out of a contract after 18 months because you're running an 18-month lease, that you have more customers out of contract meaning you're going to have a higher churn. However, the positive value of leasing is significantly higher than the cost of – than based on the churn – than the cost that you're creating by having a higher churn.

The same applies with certain customers who we don't voluntarily reach out to them, that they're on higher priced plans. If they proactively come to us, we will take them to a lower plan, but we're not proactively telling customers that they're at a higher rate plan. Those customers are at a higher churn but the additional revenue that would generate from those customers is significantly higher than the cost of churn. Now, as we predict churn, as we look at our churn models, obviously we're going to look at churn coming down in the next few years as we do our investment in our network and as we roll out our 5G network. So we know exactly what churn is going to be. We can predict it and we feel that next year churn will be better than this year's churn.

Amir Rozwadowski
Analyst, Barclays Capital, Inc.

Q

That's very helpful. And then a follow up in terms of your network strategy. You folks are targeting 5G network based on 2.5 GHz in the first half of 2019. How do we think about sort of the approach to the rollout here? I mean, are you seeing standard base equipment in terms of timing? And then, obviously, you've made a number of announcements with cable providers to get you the necessary densification and backhaul infrastructure that you need. Just trying to assess do you believe that you have the pieces in place at this juncture to really push forward with that first half 2019 target?

Raul Marcelo Claure
Chief Executive Officer & Director, Sprint Corp.

A

Yes. So obviously our priority is to launch mobile 5G, a true nationwide mobile 5G network in 2019. So in order for that to happen, we basically have to have agreements with three different type of vendors. The first one is with our network vendors and through the strategy that we have of deploying Massive MIMO first and then converting that to 5G and Dr. Saw can speak a little more to that. That had been confirmed.

The second one was basically speaking to Qualcomm and whether they're able to build a chipset that will allow the different phone manufacturers to be ready on time, and we have come to an agreement with Qualcomm that they are going to be able to release this towards the later end of 2018, the new chipset, so this is going to be positive for us.

And we have had a conversation with a manufacturer, a leading Korean manufacturer to basically have devices ready by the first half of 2019. So we have the three parts that we need in order to make a commitment to launch by first half of 2019, and this is very different than the networks that our competitors are announcing, due to the fact that this is going to be in our 2.5 GHz band in which we have over 100 megahertz of capacity to dedicate to 5G. There are very few companies in the world that are going to be able to launch a mobile 5G network. Most of them are going to be doing small millimeter wave launches, which is going to be very different.

So we are more excited than ever in terms of putting Sprint back at the forefront of technology by having what I believe will be the first mobile – the first mobile 5G network.

Amir Rozwadowski
Analyst, Barclays Capital, Inc.

Q

Thank you very much for the incremental color.

Operator: Your next question is from Jennifer Fritzsche from Wells Fargo.

Jennifer M. Fritzsche
Analyst, Wells Fargo Securities LLC
Q

Thank you. Two, if I may. Can you talk a little bit about the insurance program? I believe you said in the write-up that half of the decline in wireless service revenue is due to this, although I know this could be accretive to EBITDA. When will this abate a little bit or will that go until we see the point of growth at the end of this year? And then a second maybe for Michel. When should we expect the next iteration of Spectrum LeaseCo? I guess the question would be do you expect any hurdles or restrictive covenants? And you mentioned other markets. Should we assume other financing to be in the high yield market? Thank you.

Raul Marcelo Claure
Chief Executive Officer & Director, Sprint Corp.
A

Hi Jen, this is Marcelo. Could you repeat your first question for me?

Jennifer M. Fritzsche
Analyst, Wells Fargo Securities LLC
Q

Sure. On the insurance program, I believe that accounted for half the decline in wireless service revenue. Should that abate soon, that insurance impact?

Raul Marcelo Claure
Chief Executive Officer & Director, Sprint Corp.
A

I think we're getting close to a year of actually having rolled out the new Asurion programs, so I think going forward, if the calculations year-over-year should be – you shouldn't take into – it shouldn't take into consideration the changes on insurance.

Jud Henry
Vice President & Head of Investor Relations, Sprint Corp.
A

Yeah, Jennifer. This is Jud. That program went into effect on January 1, so this fiscal third quarter was the last quarter we will see a material impact there and you should have a pretty clean view as we go into our fourth fiscal quarter here.

Jennifer M. Fritzsche
Analyst, Wells Fargo Securities LLC
Q

Great. Thank you. And if I could on the Spectrum LeaseCo and high yield.

Michel Combes
President, Chief Financial Officer & Director, Sprint Corp.
A

Yes. So I guess that, in terms of funding our business, our strategy, as you know, is to diversify our sources of funding in order to allow our cost of capital and spectrum interest expenses. So as I have alluded to, the intent is obviously to go for the second tranche of our spectrum financing in the next coming weeks. So that's something that we contemplate and that we intend to do. And what I have just mentioned is that as the market is quite good, we might also contemplate to tap other compartments of the financial market to [ph] tread higher yields (43:51).

Jennifer M. Fritzsche
Analyst, Wells Fargo Securities LLC
Q

Great. Thank you very much.

Operator: Your next question comes from Brett Feldman from Goldman Sachs.

Brett Feldman
Analyst, Goldman Sachs & Co. LLC

Q

Thanks for the question. If we can talk about your cable partnerships a little bit. Obviously, the relationships you've created with Altice and Cox are going to give you access to dense broadband infrastructure, particularly fiber infrastructure, in the markets where those companies operate, but that's still a subset of the country. So I was hoping you could maybe expand upon how you're going to ensure that Sprint has access to the fiber that you need to densify the sites for a mobile 5G network and I'm particularly interested in whether you think there is opportunity to work with the other major cable companies. Thanks.

Raul Marcelo Claure
Chief Executive Officer & Director, Sprint Corp.

A

Okay. So let's recap the two partnerships that we have. The first one is with Altice, and Altice is a combination of an MVNO partnership combined with them giving us access to their cable infrastructure. We are, I think, the first proof point is going to be on Long Island, as we're massively densifying Long Island utilizing our technology and utilizing their infrastructure.

Secondly, as part of the legal settlement with Cox, we have come to a similar agreement. It is not an MVNO agreement. It is basically – it gives us access at highly preferred rates to their infrastructure and it allows us to have a second proof point. We've always been very bold that we believe in fixed wireless convergence in the future and this is just another proof point that we want to make sure that we can prove to ourselves and prove to the market that a combination of our wireless spectrum combined with cable infrastructure is a winning combination in the U.S. like it's a winning combination in the rest of the world.

As it relates to how we plan to build our network in the future and whether we see other potential partnerships with cable companies, I think that's wide open and I think they have – I believe that they have expressed the same – the same potential partnerships for the future. But I think what we want to do this time is we want to prove the model. We want to prove that you can build an incredibly dense network by leveraging each other's assets. And we're doing that in two maybe smaller markets that could potentially serve as a proof point for any future potential partnership with cable company.

Brett Feldman
Analyst, Goldman Sachs & Co. LLC

Q

Thanks for that color. And just as a quick follow up. When you think broadly about the fiber options available to you, how do you feel about other third-party options and is there a component of that $5 billion to $6 billion that you're targeting for next fiscal year that actually involves fiber densification?

John C. B. Saw
Chief Technology Officer, Sprint Corp.

A

Brad, John Saw here. The answer is yes. We are working aggressively with a lot of other fiber providers, companies like Zayo where we are bringing a lot of dark fiber to our sites. And this is especially important now as we roll out more and more sites requiring Massive MIMO to support 5G as well, that we do this even more aggressively. So a chunk of our CapEx spend is actually upgrading our backhaul networks using dark fiber, getting better lit fiber pricing [indiscernible] (47:01) gigabit per second, as well as continuing to use microwave backhaul where it makes sense.

Brett Feldman
Analyst, Goldman Sachs & Co. LLC

Q

Great. Thanks for the color.

John C. B. Saw
Chief Technology Officer, Sprint Corp.

A

Yeah.

Operator: Your next question comes from John Hodulik from UBS Securities.

John C. Hodulik
Analyst, UBS Securities LLC

Q

Great. Thanks. Two, if I may. Maybe first for Michel. You talked about some potential new areas for cost savings. Sprint has wireless margins now of about 35%. I realize you're sort of looking at it with a new set of eyes here, but do you see, given your experience, that there's some potential for meaningful margin accretion from here? Even with the new costs that should come on with the network build-out? And then maybe for Marcelo, maybe just some general comments on what you're seeing in terms of the competitive environment. In past quarters you've talked about the ability or the need to raise prices. Is that still where Sprint is? And if you could talk about that as it relates to ongoing ARPU trends of the company, that'd be great.

Michel Combes
President, Chief Financial Officer & Director, Sprint Corp.

A

Thanks, John. So on your first question, I guess first is, we should recognize that great work has been done up to now as we are on track to deliver the fourth year in a row of at least $1 billion of net reductions to our cost of services and SG&A. So which is quite a significant achievement. We are currently working with the team on new initiatives for 2018 and the years beyond in order to let's say continue to decrease our cost structure in the next coming years. I am very confident that there are lots of areas where we can still dig in while let's say of course preserving our investments in the three priorities which have been outlined by Marcelo.

So from my experience in other places, I see a lot of, let's say, potential there. And I will provide more specifics on next quarter call in conjunction with our annual guidance. You can expect that that there is still room of maneuver to decrease and to invest in the future of our business.

John C. Hodulik
Analyst, UBS Securities LLC

Q

Great.

Raul Marcelo Claure
Chief Executive Officer & Director, Sprint Corp.

A

So as it relates to the competitiveness in the market, it is competitive. Everybody has moved to buy one phone, get one free, and throw in a lot more into their unlimited. We feel we're in a very good position. If you look at our gross adds growth, year-over-year has been – we've been having it now four years, in which we continue to grow our gross adds pretty much on the last three years. So we have absolutely no problem in getting our share of the market when you look at our share of gross adds, close to the 20% range. And anytime you have a 20% share of gross adds with a market share of 12%, that is absolutely good.

What I can tell you is as a company, we could not be more excited that 5G is coming, right, and we see 5G as a very important milestone in the history of Sprint because we have the spectrum to basically lead on 5G and lead in a different way.

So we look at from other carriers, it is going to be very difficult for competitors to increase the price of unlimited, but we're going to have a lot of room to increase our price of unlimited to get to similar prices as Verizon and AT&T in the future. And you get that by having an amazing network. And you get that by being the first one to launch 5G. So we're looking at 5G as an amazing opportunity for the company not only to again to lead from a value proposition, lead with a great product, but potentially be able to charge for the blazing fast speeds.

Also something that allows you to do that is when you look at 5G, you have a significant reduction on your cost per gig, and that is also another – that's also another advantage that will allow us to potentially get in the place where we'd like to be, and that is be able to charge for our services while at the same time be able to reduce cost or having the lowest cost per bit.

As we relate from now till the time we launch our 5G network, which we're looking at a year, we have already increased our price. We used to be basically the first two lines for $90, now the second two lines are for $100 and then we're going to continue to look at the market and be able to see if there's extra room in order for us to be able to capture that share of gross adds that we feel comfortable plus minus 20%, while at the same time being able to charge the most amount that we can for our services.

John C. Hodulik
Analyst, UBS Securities LLC

Q

Got you. Thanks, guys.

Operator: Your next question comes from Michael Rollins from Citigroup Investment Research. Michael Rollins from Citigroup.

Jud Henry
Vice President & Head of Investor Relations, Sprint Corp.

A

Mike, you there? All right. Cindy, let's go to the next question.

Operator: Your next question comes from Matthew Niknam from Deutsche Bank.

Matthew Niknam
Analyst, Deutsche Bank Securities, Inc.

Q

Hey guys. Thank you for taking the question. Just one on leasing and then just one housekeeping item. On leasing, I think Marcelo you referred to it as a driver of some of the pressure this quarter on churn. In the past, I think you've actually referred to it as a churn killer about a year or a year-and-a-half ago when it was first introduced. So can you maybe talk to what's changed there? And then secondly, on CapEx, if you could just shed more light on what's driving some of the lower CapEx expectation this year, and then whether this is more of a deferral into fiscal 2018? Thanks.

Raul Marcelo Claure
Chief Executive Officer & Director, Sprint Corp.

A

Yes, our leasing program is working. It's actually working great, and it's giving us the profitability that we had expected when you have – when you're the only carrier with a leasing program. A couple of things that are important for us as it relates to leasing.

Before, we used to have a 24-month lease. We've moved to an 18-month lease with the ability of customers to upgrade after one year with an iPhone Forever or a Galaxy Forever. So in that case, you are going to have a little more churn because you have a larger amount of customers off contract, and this basically hasn't changed in our industry. Once a customer [ph] hit (53:42), they're off contract, they basically shop around, and in many cases, they will decide to go somewhere else if the offer is better.

Now, the customers that are within our – the customers that are upgrading within our 12-month program, we're seeing incredible low churn rates, and our goal is going to be over the course of the next few years to perfect the model where a customer is upgrading prior to their 18-month when their contract expires. So obviously there's different ways to get ahold of our customers. Leasing is new, but those customers absolutely, I mean, they are – they have a great churn profile.

Where things – where churn gets a little higher, it's basically when the customer is out of the contract after 18 months, and we're working on moving the least amount of customers there. So as I said before, we're very happy with leasing. The profit that we get from leasing, it's positive. The ability to pick up millions of used iPhones or used Galaxys and be able to remanufacture them and put them into our both our prepaid and postpaid businesses and be able to either subsidize less or use less cash in bringing those phones and bringing those customers is positive. So we've got to let the cycle of leasing basically to continue.

Michel Combes
President, Chief Financial Officer & Director, Sprint Corp.

A

On network CapEx, so as I have mentioned, we have $200 million year-over-year increase, so – which has been driven by the ramp-up of our network improvement initiatives and densification program. We will see an acceleration in next quarter. While it says in the guidance that I gave you implies a minimum of $1 billion spent in fiscal Q4 2017, and we should see an acceleration in 2018. This is driven by the fact that we're moving to more expensive upgrades, new sites built which are, let's say, are going to kick in, and a Massive MIMO, which will also start to roll out in the next coming quarters.

So that's what will pave the way for the next iteration of our CapEx spend in the next coming quarters, and that's why we are comfortable with the indications that I gave you for next year.

Raul Marcelo Claure
Chief Executive Officer & Director, Sprint Corp.

A

Let me give you a follow-up answer as it relates to leasing churn build-out and all those. So we're going through a cycle right now where we have the highest amount – where we've had over the last quarters the highest amount of customers off a contract, and that has created a higher churn than what we had before.

At the same time, as our competitors have launched unlimited, we are going to invest a lot of money into our network to basically deploy our 5G network. So when we look at our churn curve over the course of the next few years, what we've seen is this has been a year with a higher churn than last year. We expect this to peak in fiscal 2018, and then after that, basically for our churn to come down to similar levels that we've had in the past.

So we have very aggressive churn reductions over the course of the next few years. And I'll tell you, what I've learned and what has been an eye opening for us and hope would have realized it before, is the ability of launching our quality of experience and be able to pretty much forecast that Sprint has the ability to get down to churn levels that are similar to our competitors once we're offering a great quality of experience. So we're going to work hard in terms of lowering churn over the course of the next few quarters and years.

Matthew Niknam
Analyst, Deutsche Bank Securities, Inc.

Q

Marcelo, if I could just follow up, I just want to clarify. So you're saying that for the fiscal 2018, churn will peak before trending lower in fiscal 2019?

Raul Marcelo Claure
Chief Executive Officer & Director, Sprint Corp.

A

That is correct.

Matthew Niknam
Analyst, Deutsche Bank Securities, Inc.

Q

Thank you.

Jud Henry
Vice President & Head of Investor Relations, Sprint Corp.

All right. Cindy, that's all the time we have for questions today, but before we close, I'd like to turn the call back to Marcelo for some closing comments. If you have any additional questions following the call, please contact the Sprint Investor Relations team.

Marcelo?

Raul Marcelo Claure
Chief Executive Officer & Director, Sprint Corp.

Great. I want to thank everyone for joining us today and for your support of Sprint. Our fiscal third quarter results demonstrate continued progress in our five-year turnaround plan. We have improved profitability, delivering our highest fiscal third quarter adjusted EBITDA in 11 years, our eighth consecutive quarter of operating income, and positive adjusted free cash flow in eight of the last nine quarters. We delivered positive postpaid phone net additions for the tenth consecutive quarter and continue to grow our prepaid business for the fourth consecutive quarter.

I cannot emphasize enough how excited I am about the future of Sprint as we deploy our Next-Gen Network, we expand our physical distribution, and enhance our value proposition and continue to transform our cost structure. I'm excited for Sprint to take the leadership position as the first nationwide mobile 5G network and devices in the U.S. I look forward to sharing more info of our transformation success on our future calls. Thanks everybody for joining us today, and have a great day.

Operator: This concludes today's conference. You may now disconnect.

Docket: A.18-07-011 and A.18-07-012

Witness: Cameron Reed

Date: January 7, 2019

Public Advocates Office

Exhibit CR-5

"T-Mobile Response to Cal Advocates Data Request 002, Question 2-2"

Data Request 2-2.

Please provide the following information related to Your claim the merger will increase T-Mobile's ability to offer in-home broadband plans.

a) What broadband speeds does T-Mobile expect to be able to offer for in-home wireless broadband?

b) Will the customer need any special equipment such as a Femtocell or a receiving antenna to take advantage of 5G in-home broadband?

c) What counties/cities would T-Mobile deploy its in-home broadband offerings by 2021? By 2024?

d) How many rural California Points of Presence (POPs) does T-Mobile estimate will be covered by the 5G in-home broadband service by 2021? By 2024?

e) How much area can a single 5G tower or small cell cover in KM/Miles?

f) Will subscribers to the in-home 5G service have to share the bandwidth of their nearby tower?

g) Would subscribers to the in-home 5G service be subject to a data cap? If yes, what would this data cap be?

Response to Data Request 2-2.

T-Mobile objects to this Data Request on the grounds it is vague and ambiguous with respect to temporal scope and the phrases "5G tower," "small cell," "share the bandwidth," and "data cap." T-Mobile further objects to this Data Request on the grounds it seeks information that is dependent on decisions which will not and cannot be finalized until the transaction can be consummated. T-Mobile also objects to this Data Request on the grounds it seeks information that is neither germane to the pending Wireline or Wireless Applications nor is reasonably calculated to lead to the discovery of relevant information as broadband is an exclusively interstate service that is subject to the FCC's—not the Commission's—jurisdiction. T-Mobile further objects to this Data Request on the ground it seeks information that is readily available to the Cal PA as T-Mobile's plans to provide broadband services is discussed in numerous public filings including the PIS and the Wireless Application. T-Mobile also objects to this Data Request to the extent that it is duplicative of Cal PA DRs 1-6 and 1-122.

Subject to and without waiving its objections, T-Mobile responds as follows:

(a) New T-Mobile will provide *bona fide* alternatives to wired in-home broadband in two different ways: (1) use of the mobile 5G wireless service as a substitute; and (2) a new in-home service offering. First, New T-Mobile will provide 100 Mbps broadband service to **[BHC-AEO]** [redacted] **[EHC-AEO]** percent of Californians by 2024. Some areas will see much higher speeds, as New T-Mobile is expected to cover **[BHC-AEO]** [redacted] **[EHC-AEO]** Americans with speeds greater than 500 Mbps by 2024. See also Initial and Supplemental Responses to Cal PA DRs 1-6 and 1-122. This service will allow customers to use the New T-Mobile mobile wireless service as a substitute for in-home fixed service; thereby eliminating separate monthly charges. Second, New T-Mobile also will provide a separate in-home broadband service offering as a replacement for wired broadband by providing customers self-install wireless equipment to deliver services to a variety of devices within their home. The speeds of the in-home service will be 100

Mbps or higher. These speeds are fast enough to enable New T-Mobile to compete successfully with landline broadband services in these areas. The New T-Mobile in-home service will be priced below wired broadband services of the incumbent cable and wireline companies.

(b) New T-Mobile customers using the mobile 5G service as a wireless substitute for in-home fixed broadband do not require any additional equipment beyond their mobile devices. New T-Mobile customers subscribing to the in-home broadband service offering that is a replacement for wired broadband service will use customer premises equipment ("CPE"), much like a wireless router, to convert New T-Mobile's wireless network signal into a Wi-Fi signal. Unlike other in-home broadband offerings, the wireless nature of the offering will empower customers to avoid installation appointments and related charges as they will be able to self-provision the necessary in-home equipment. New T-Mobile will extend the Un-carrier customer care model to its in-home broadband offering, providing consumers with high-quality 24-7 customer support.

(c) For its mobile wireless broadband service that serves as a substitute for in-home fixed broadband, T-Mobile refers to the maps provided in its Second Supplemental Response to Cal PA DR 1-6. See also Wireless Application, Confidential Exhibit I. New T-Mobile's in-home replacement service will be offered where capacity is available. Nationally, T-Mobile estimates that the in-home service will be made offered in 52 percent of the zip codes.

(d) Based on the FCC's definition of "rural," T-Mobile forecasts that **[BHC-AEO]** [redacted] **[EHC-AEO]** percent of California's rural PoPs will be covered by its mobile broadband 5G service by 2024. See also Initial and Supplemental Responses to Cal PA DRs 1-6 and 1-122. T-Mobile estimates that the New T-Mobile in-home replacement service will be offered in 20 to 25 percent of the country's rural areas.

(e) New T-Mobile plans to use a combination of macro cells and small cells to provide 5G service. The reach of a small cell or macro cell site will depend on a variety of factors that affect propagation, and on an individual basis, the operating radius of a cell site may be impacted by its physical environment. Macro cell sites are used to cover greater areas, while small cells, which have smaller operating radii, are better suited to urban areas. Both can be used to provide 5G services. In general terms, the reach of a cell site depends on the frequency of spectrum on which the signals are transmitted and the technical rules dictated by the FCC for that spectrum. New T-Mobile's network will use low-band, mid-band, and high-band spectrum for 5G services.

Low-band spectrum (below 1 GHz) allows for broader coverage, both in-building and in rural areas. Spectrum below 1 GHz can support a macro cell site with an operating radius of up to 18 miles, allowing for broad coverage without the need for as much capital expenditure, especially in rural markets.

Mid-band spectrum (from 1 to 6 GHz) provides high capacity with some reduction in coverage capabilities as compared to sub-1 GHz spectrum bands. Because there is more spectrum in the mid-band, there is more capacity that can be delivered from a single cell site, and it is well-suited for urban and suburban markets where consumer demand for more capacity is highest. Because the propagation in the mid-band is more limited (operating radii of approximately up to 4 miles around cell sites) the band is not optimal for rural area coverage, as it requires more capital expenditures to cover those geographies.

High-band spectrum (above 20 GHz) is best utilized in dense urban markets where there are extreme capacity demands, need for low latency, and surging use of high-speed data applications. High-band spectrum cell operating radii are significantly less than one-half of one mile, making use of this spectrum only economical in very densely populated areas. The positive attributes of high-band spectrum are that it has large bandwidths available, enables the use of very small antennas, and can be readily reused within a market area. These features enable high-band spectrum to deliver much higher data rates and lower latency than mid-band or low-band spectrum.

New T-Mobile will leverage the variety of spectrum at its disposal to deploy greater quantities (more spectrum per cell site) more densely (to more cell sites throughout the network). New T-Mobile will be able to deploy a capacity layer of 2.5 GHz spectrum to provide much higher 5G data rates to consumers. Moreover, the combined company will be able to deploy more spectrum in more cell sites, providing a much more consistent signal strength throughout the coverage area. Signal strength is one of the best approximations of the actual user experience—the stronger and more consistent the signal strength, the more likely the consumer will have a steady and robust data and voice connection. For this reason, signal strength is directly related to the actual data rates delivered to a customer.

(f) Typically, mobile broadband infrastructure is shared by users connected to a cell site, and in-home broadband users will also share access to a cell site. However, capacity in the new nationwide 5G network will be ample to support these users as such capacity will rival and often surpass that of wired broadband.

(g) The Company expects that New T-Mobile will provide its in-home wireless broadband offering consistent with T-Mobile's Un-carrier approach, which eliminated service contracts and strict monthly data caps for mobile wireless service. Final parameters for the in-home product, however, have not been finalized.

Docket:	A.18-07-011 and A.18-07-012
Witness:	Cameron Reed
Date:	January 7, 2019

Public Advocates Office

Exhibit CR-6

"T-Mobile BingeOn Statistics"

Contains CONFIDENTIAL T-Mobile Information

Docket: A.18-07-011 and A.18-07-012

Witness: Cameron Reed

Date: January 7, 2019

Public Advocates Office

Exhibit CR-7

"Massive MIMO and Beamforming"

ANALOG DEVICES
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Massive MIMO and Beamforming: The Signal Processing Behind the 5G Buzzwords

By **Claire Masterson**

Introduction

Our thirst for high speed mobile data is insatiable. As we saturate the available RF spectrum in dense urban environments, it's becoming apparent that there's a need to increase the efficiency of how we transmit and receive data from wireless base stations.

Base stations consisting of large numbers of antennas that simultaneously communicate with multiple spatially separated user terminals over the same frequency resource and exploit multipath propagation are one option to achieve this efficiency saving. This technology is often referred to as massive MIMO (multiple-input, multiple-output). You may have heard massive MIMO described as beamforming with a large number of antennas. But this raises the question … what is *beamforming*?

Beamforming vs. Massive MIMO

Beamforming is a word that means different things to different people. Beamforming is the ability to adapt the radiation pattern of the antenna array to a particular scenario. In the cellular communications space, many people think of beamforming as steering a lobe of power in a particular direction toward a user, as shown in Figure 1. Relative amplitude and phase shifts are applied to each antenna element to allow for the output signals from the antenna array to coherently add together for a particular transmit/receive angle and destructively cancel each other out for other signals. The spatial environment that the array and user are in is not generally considered. This is indeed beamforming, but is just one specific implementation of it.

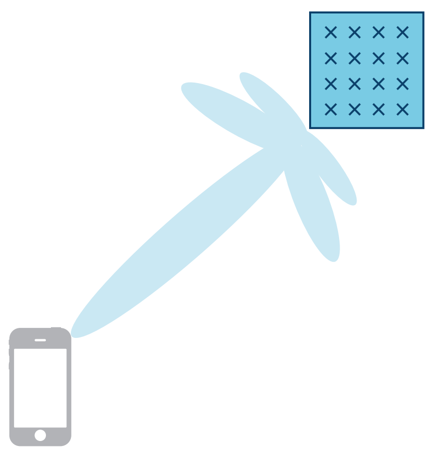


Figure 1. Traditional beamforming.

Massive MIMO can be considered as a form of beamforming in the more general sense of the term, but is quite removed from the traditional form. *Massive* simply refers to the large number of antennas in the base station antenna array. *MIMO* refers to the fact that multiple spatially separated users are catered for by the antenna array in the same time and frequency resource. *Massive MIMO* also acknowledges that in real-world systems, data transmitted between an antenna and a user terminal—and vice versa—undergoes filtering from the surrounding environment. The signal may be reflected off buildings and other obstacles, and these reflections will have an associated delay, attenuation, and direction of arrival, as shown in Figure 2. There may not even be a direct line of sight between the antenna and the user terminal. It turns out that these nondirect transmission paths can be harnessed as a power for good.

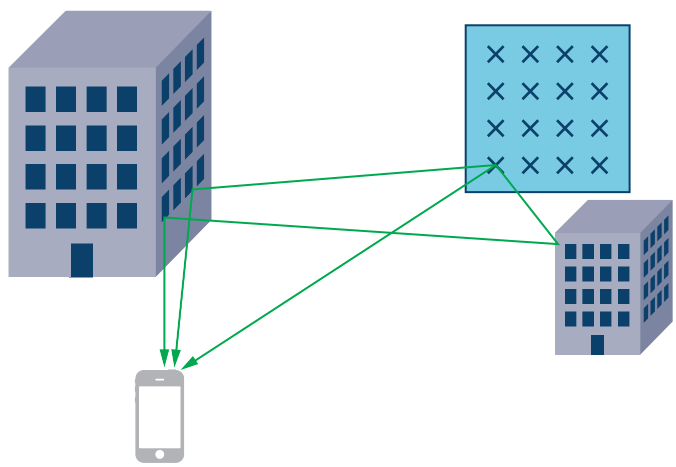


Figure 2. Multipath environment between antenna array and user.

In order to take advantage of the multiple paths, the spatial channel between antenna elements and user terminals needs to be characterized. In literature, this response is generally referred to as channel state information (CSI). This CSI is effectively a collection of the spatial transfer functions between each antenna and each user terminal. This spatial information is gathered in a matrix (H), as shown in Figure 3. The next section looks at the concept of CSI and how it is collected in more detail. The CSI is used to digitally encode and decode the data transmitted from and received by the antenna array.

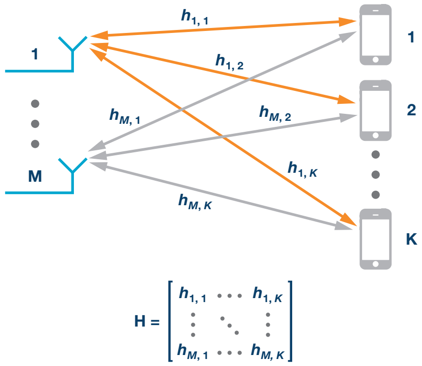


Figure 3. Channel state information needed to characterize a massive MIMO system.

Characterizing the Spatial Channel Between Base Station and User

An interesting analogy is to consider a balloon being popped at one location and the sound of this pop, or impulse, being recorded at another, as shown in Figure 4. The sound recorded at the microphone position is a spatial impulse response that contains information unique to the particular position of both the balloon and the microphone in the surrounding environment. The sound that is reflected off obstacles is attenuated and delayed compared to the direct path.

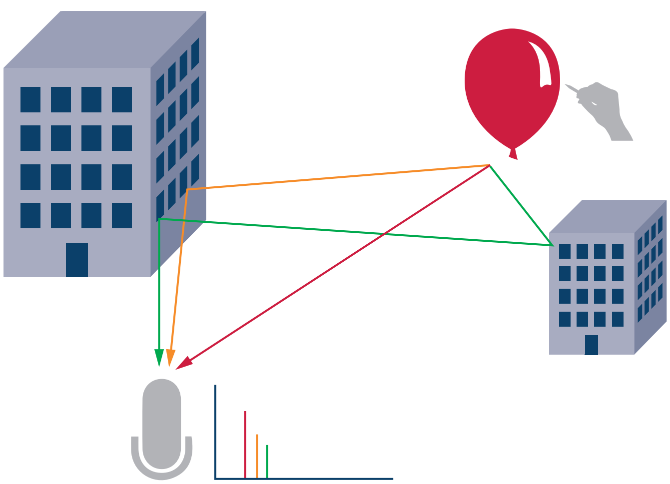


Figure 4. Audio analogy to demonstrate spatial characterization of a channel.

If we expand the analogy to compare to the antenna array/user terminal case, we need more balloons, as seen in Figure 5. Note that in order to characterize the channel between each balloon and the microphone, we need to burst each balloon at a separate time so the microphone doesn't record the reflections for different balloons overlapping. The other direction also needs to be characterized, as shown in Figure 6. In this instance, all the recordings can be done simultaneously when the balloon is popped at the user terminal position. This is clearly a lot less time consuming!

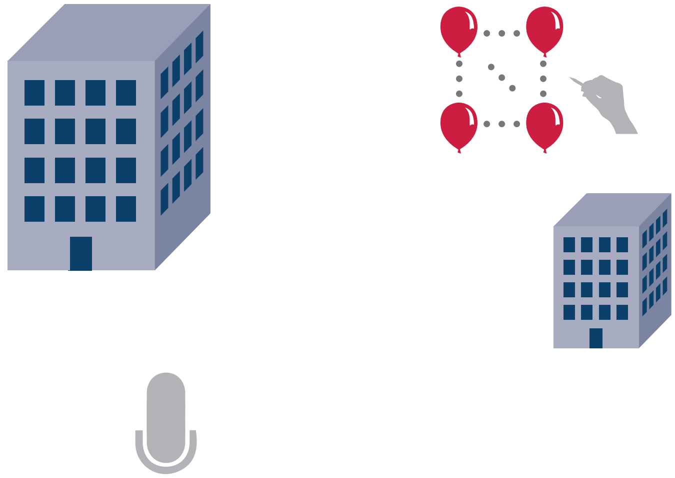


Figure 5. Audio analogy to downlink channel characterization.

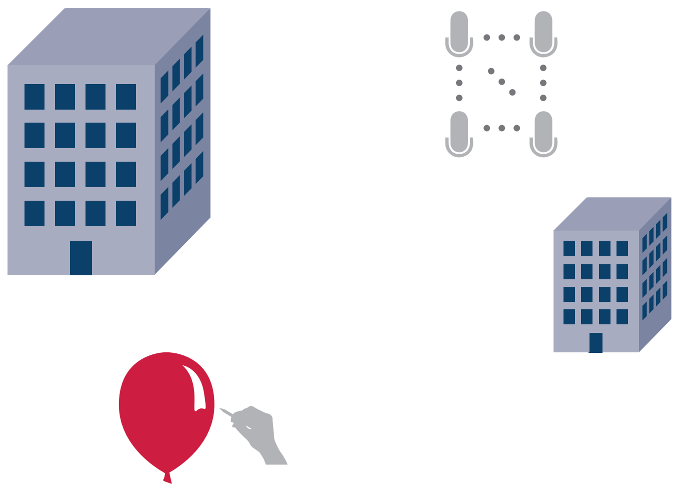


Figure 6. Audio analogy to uplink channel characterization.

In the RF space, pilot signals are used for characterizing the spatial channels. The over-the-air transmission channels between antennas and user terminals are reciprocal, meaning the channel is the same in both directions. This is contingent on the system operating in time division duplex (TDD) mode as opposed to frequency division duplex (FDD) mode. In TDD mode, uplink and downlink transmissions use the same frequency resource. The reciprocity assumption means the channel only needs to be characterized in one direction. The uplink channel is the obvious choice, as just one pilot signal needs to be sent from the user terminal and is received by all antenna elements. The complexity of the channel estimation is proportional to the number of user terminals, not the number of antennas in the array. This is of critical importance given the user terminals may be moving, and hence the channel estimation will need to be performed frequently. Another significant advantage of uplink-based characterization means that all the heavy duty channel estimation and signal processing is done at the base station, and not at the user end.

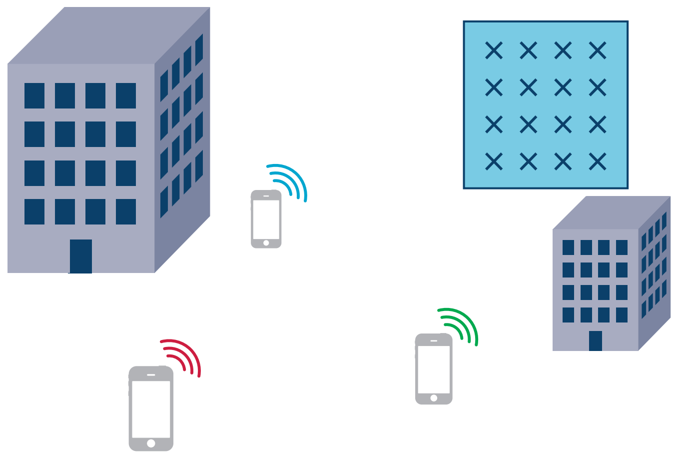


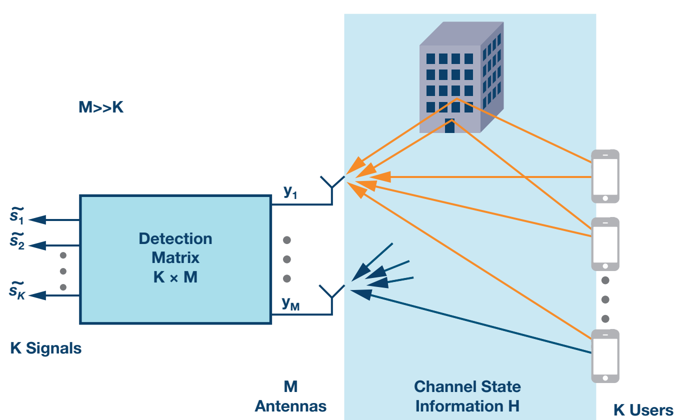
Figure 7. Each user terminal transmits orthogonal pilot symbol.

So now that the concept of collecting CSI has been established, how is this information applied to data signals to allow for spatial multiplexing? Filtering is designed based on the CSI to precode the data transmitted from the antenna array so that multipath signals will coherently add at the user terminals position. Such filtering can also be used to linearly combine the data received by the antenna array RF paths so that the data streams from different users can be detected. The following section addresses this in more detail.

The Signal Processing that Enables Massive MIMO

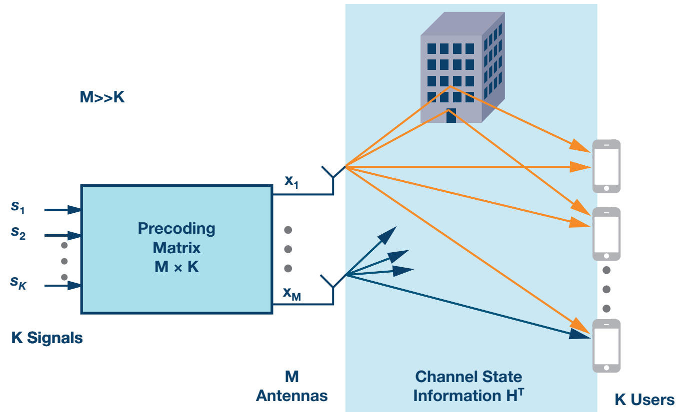
In the previous section we've described how the CSI (denoted by the matrix H) is estimated. Detection and precoding matrices are calculated based on H. There are a number of methods for calculating these matrices. This article focuses on linear schemes. Examples of linear precoding/detection methods are maximum ratio (MR), zero forcing (ZF), and minimum mean-square error (MMSE). Full derivations of the precoding/detection filters from the CSI are not provided in this article, but the criteria they optimize for, as well as the advantages and disadvantages of each method are discussed. A more detailed treatment of these topics can be found in the references at the end of this article.[1, 2, 3]

Figure 8 and Figure 9 give a description of how the signal processing works in the uplink and downlink respectively for the three linear methods previously mentioned. For precoding there may also be some scaling matrix to normalize the power across the array that has been omitted for simplicity.



Detection Type	
Maximum Ratio (MR)	$\tilde{s} = H^H \mathbf{y}$
Zero Forcing (ZF)	$\tilde{s} = (H^H H)^{-1} H^H \mathbf{y}$
NMSE or RZF	$\tilde{s} = (H^H H + \beta I)^{-1} H^H \mathbf{y}$

Figure 8. Uplink signal processing. ^{H} denotes the conjugate transpose.



Precoding Type	
Maximum Ratio (MR)	$\mathbf{x} = H^* \mathbf{s}$
Zero Forcing (ZF)	$\mathbf{x} = H^* (H^T H^*)^{-1} \mathbf{s}$
NMSE or RZF	$\mathbf{x} = H^* (H^T H^* + \beta I)^{-1} \mathbf{s}$

*Figure 9. Downlink signal processing. ^{T} denotes the transpose. * denotes the conjugate.*

Maximum ratio filtering, as the name suggests, aims to maximize the signal-to-noise ratio (SNR). It is the simplest approach from a signal processing viewpoint, as the detection/precoding matrix is just the conjugate transpose or conjugate of the CSI matrix, H. The big downside of this method is that inter user interference is ignored.

Zero forcing precoding attempts to address the inter user interference problem by designing the optimization criteria to minimize for it. The detection/precoding matrix is the pseudoinverse of the CSI matrix. Calculating the pseudoinverse is more computationally expensive than the complex conjugate as in the MR case. However, by focusing so intently on minimizing the interference, the received power at the user suffers.

MMSE tries to strike a balance between getting the most signal amplification and reducing the interference. This holistic view comes with signal processing complexity as a price tag. The MMSE approach introduces a regularization term to the optimization—denoted as β in Figures 8 and 9—that allows for a balance to be found between the noise covariance and the transmit power. It is sometimes also referred to in literature as regularized zero forcing (RZF).

This is not an exhaustive list of precoding/detection techniques, but gives an overview of the main linear approaches. There are also nonlinear signal processing techniques such as dirty paper coding and successive interference cancellation that can be applied to this problem. These offer optimal capacity but are very complex to implement. The linear approaches described above are generally sufficient for massive MIMO, where the number of antennas gets large. The choice of a precoding/detection technique will depend on the computational resources, the number of antennas, the number of users, and the diversity of the particular environment the system is in. For large antenna arrays where the number of antennas is significantly greater than the number of users, the maximum ratio approach may well be sufficient.

The Practical Obstacles Real-World Systems Present to Massive MIMO

When massive MIMO is implemented in a real-world scenario, there are further practical considerations to be taken into account. Consider an antenna array with 32 transmit (Tx) and 32 receive (Rx) channels operating in the 3.5 GHz band as an example. There are 64 RF signal chains to be put in place and the spacing between the antennas is approximately 4.2 cm given the operating frequency. That's a lot of hardware to pack into a small space. It also means there is a lot of power being dissipated, which brings inevitable temperature concerns. Analog Devices' integrated transceivers offer a highly effective solution to many of these issues. The AD9371 will be discussed in more detail in the next section.

Previously in this article, the application of reciprocity to the system to drastically cut the channel estimation and signal processing overheads were discussed. Figure 10 shows the downlink channel in a real-world system. It is split into three components; the over-the-air channel (H), the hardware response of the base station transmit RF paths (T_{BS}), and the hardware response of the user receive RF paths (R_{UE}). The uplink is the opposite of this with R_{BS} characterizing the base station receive hardware RF paths and T_{UE} characterizing the users transmit hardware RF paths. While the reciprocity assumption holds for the over the air interface, it does not for the hardware paths. The RF signal chains introduce inaccuracies into the system due to mismatched traces, poor synchronization between the RF paths, and temperature-related phase drift.

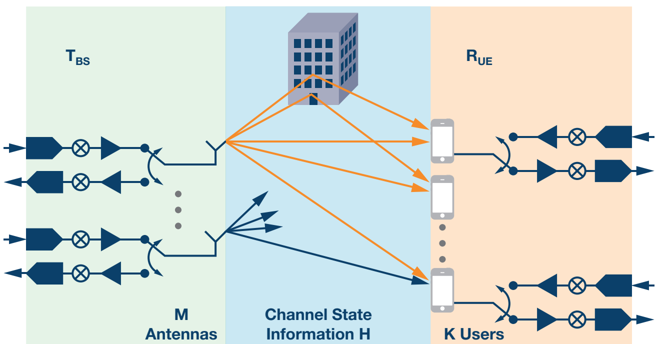


Figure 10. Real-world downlink channel.

Using a common synchronized reference clock for all LO (local oscillator) PLLs in the RF paths and synchronized SYSREFs for the baseband digital JESD204B signals will help address latency concerns between the RF paths. However, there will still be some arbitrary phase mismatch between the RF paths at system startup. Temperature-related phase drift contributes further to this issue and it is clear that calibration is required in the field when the system is initialized and periodically thereafter. Calibration allows for the advantages of reciprocity such as maintaining the signal processing complexity at the base station and uplink only channel characterization to be kept. It can generally be simplified so that only the base station RF paths (T_{BS} and R_{BS}) need to be considered.

There are a number of approaches to calibrating these systems. One is to use a reference antenna positioned carefully in front of the antenna array to calibrate both the receive and transmit RF channels. It's questionable whether having an antenna placed in front of the array in this way is suited to practical base station calibration in the field. Another is to use mutual coupling between the existing antennas in the array as the calibration mechanism. This may well be feasible. The most straight forward approach is probably to add passive coupling paths just before the antennas in the base station. This adds more complexity in the hardware domain, but should provide a robust calibration mechanism. To fully calibrate the system a signal is sent from one designated calibration transmit channel, which is received by all RF receive paths through the passive coupled connection. Each transmit RF path then sends a signal in sequence that is picked up at the passive coupling point before each antenna, relayed back to a combiner, and then to a designated calibration receive path. Temperature related effects are generally slow to change, so this calibration does not have to be performed very frequently, unlike the channel characterization.

Analog Devices' Transceivers and Massive MIMO

Analog Devices' range of integrated transceiver products are particularly suited to applications where there is a high density of RF signal chains required. AD9371 features 2 transmit paths, 2 receive paths, and an observation receiver, as well as three fractional-N PLLs for RF LO generation in a 12 mm × 12 mm package. This unrivaled level of integration enables manufacturers to create complex systems in a timely and cost-effective manner.

A possible system implementation featuring multiple AD9371 transceivers is shown in Figure 11. This is a 32 transmit, 32 receive system with 16 AD9371 transceivers. Three AD9528 clock generators provide the PLL reference clocks and JESD204B SYSREFs to the system. The AD9528 is a 2-stage PLL with 14 LVDS/HSTL outputs and an integrated JESD204B SYSREF generator for multiple device synchronization. The AD9528s are arranged in a fanout buffer configuration with one acting as a master device with some of its outputs used to drive the clock inputs and the SYSREF inputs of the slave devices. A possible passive calibration mechanism is included—shown in green and orange—where a dedicated transmit and receive channel are used to calibrate all the receive and transmit signal paths through a splitter/combiner, as discussed in the previous section.

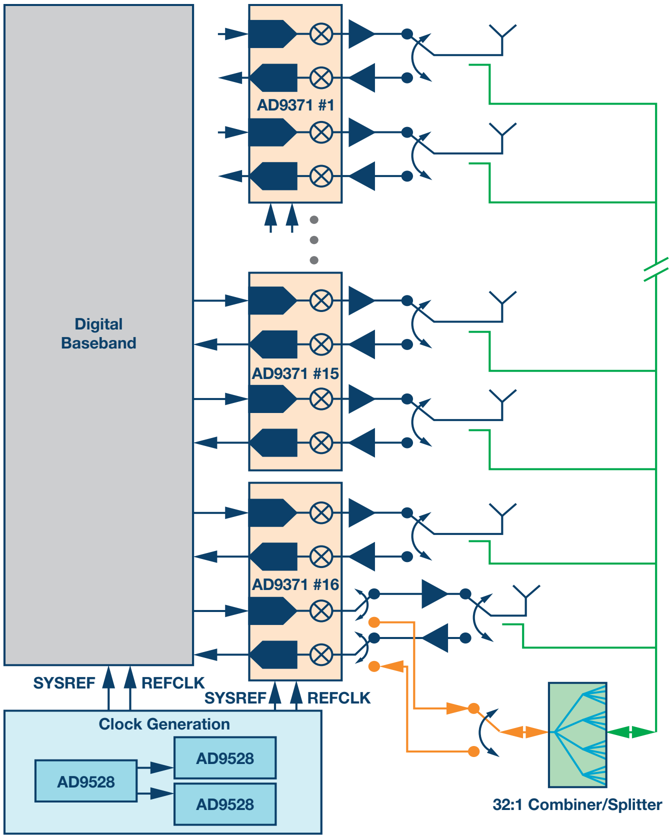


Figure 11. Block diagram of 32 Tx, 32 Rx massive MIMO radio head featuring Analog Devices' AD9371 transceivers.

Conclusion

Massive MIMO spatial multiplexing has the potential to become a game changing technology in the cellular communications space, allowing for increased cellular capacity and efficiency in high traffic urban areas. The diversity that multipath propagation introduces is exploited to allow for data transfer between a base station and multiple users in the same time and frequency resource. Due to reciprocity of the channel between the base station antennas and the users, all the signal processing complexity can be kept at the base station, and the channel characterization can be done in the uplink. Analog Devices' RadioVerse™ family of integrated transceiver products allow for a high density of RF paths in a small space, so they are well suited to massive MIMO applications.

References

1. Xiang Gao. *Massive MIMO in Real Propagation Environments*. Lund University, 2016.

2. Michael Joham, Josef A. Nossek, and Wolfgang Utschick. "Linear Transmit Processing in MIMO Communications Systems." *IEEE Transactions on Signal Processing*, Vol. 53, Issue 8, Aug, 2005.

3. Hien Quoc Ngo. *Massive MIMO: Fundamentals and System Design*. Linköping University, 2015.

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Claire Masterson

Docket: A.18-07-011 and A.18-07-012

Witness: Cameron Reed

Date: January 7, 2019

Public Advocates Office

Exhibit CR-8

"Nokia White Paper on Beamforming and mMIMO"

Beamforming for 4.9G/5G Networks

Exploiting Massive MIMO and Active Antenna Technologies

White Paper

NOKIA

Contents

NOKIA

1. Executive summary

Beamforming is an attractive solution to boost mobile network performance while reusing existing base station sites. It can use active antennas, simplifying installation and minimizing site impact. Nokia simulations and field measurements show that beamforming can provide an eight-fold increase in peak cell throughput and up to a five-fold improvement in the average cell capacity at 2.6 GHz bands with LTE. The gains will be even more substantial with 5G as control channels also support beamforming.

The higher frequency bands at millimeter waves enable beamforming with compact antennas, both at the base stations and also in the devices. Beamforming uses massive MIMO (Multiple Input Multiple Output) technology, which is supported by the latest 3GPP specifications for LTE and will be supported in 5G from the first deployments. Generally, massive MIMO provides both coverage and capacity gains at sub-6GHz frequency and coverage gains at mmWave frequencies for 5G.

Nokia is the leader in these technologies, testing active antennas in the field in 2009 and deploying commercial beamforming with TD-LTE in 2011. Nokia Bell Labs invented massive MIMO technology, while Nokia Airscale radio is designed to fully exploit the benefits of beamforming in LTE and in 5G networks.

2. Introduction

Network capacity can be increased by using more spectrum, more sites or by using more antennas to improve spectral efficiency. Since spectrum resources will soon be fully exploited, there is a growing need for antenna evolution. Beamforming using massive MIMO antennas is the main technology offering a significant improvement in spectral efficiency.

The underlying principle of beamforming is illustrated in Figure 1. The traditional solution transmits data over the whole cell area, while beamforming sends the data to users over a narrow beam transmission. With massive MIMO, the same resources can be reused for multiple users within a sector, interference can be minimized and cell capacity can be increased.

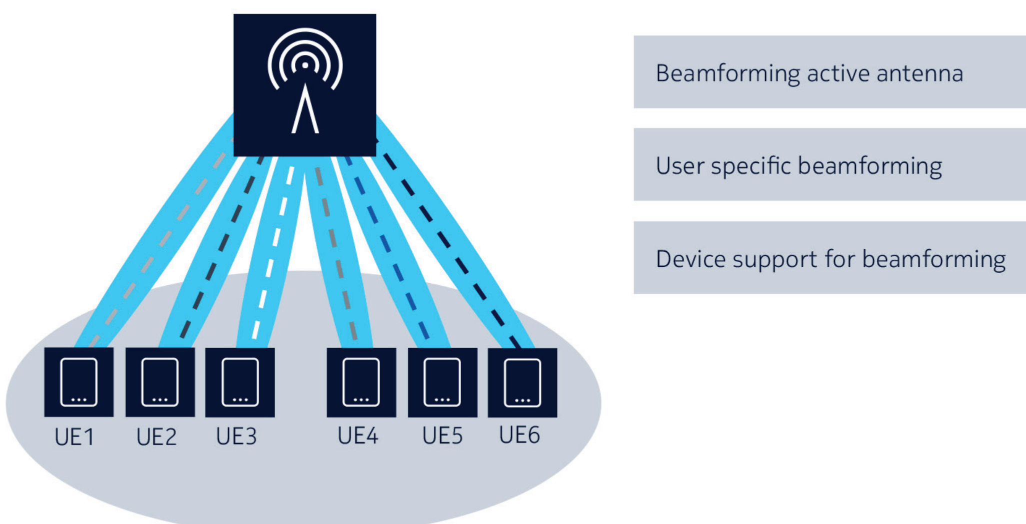

Figure 1. Beamforming enhances radio capacity and coverage.

Although beamforming has been widely studied in academic circles for years, it has not been widely used in real networks because there was no urgent capacity need, there were no supporting devices and active antenna implementation was not commercially feasible. All these factors are now changing and beamforming is advancing and being adopted in commercial networks, see Figure 2.

The first beamforming and its advanced implementation will take place in TD-LTE networks. It is expected that beamforming in LTE will be used mainly to improve capacity, while it will be the mainstream solution in 5G for increased coverage, particularly at high frequencies.

Capacity requirements	Technology capability	3GPP specs support
• Most macro networks will become congested • Spectrum <3 GHz and base station sites will run out of capacity by 2020	• Active antenna is becoming technically and commercially feasible • Massive MIMO requires active antennas	• 3GPP brings mMIMO support in Releases 13-14 for LTE and in Release 15 for 5G
All three components are happening now		

Figure 2. Beamforming massive MIMO is happening now.

A number of different terms are used in beamforming. The main ones include:

User specific beamforming: Each user has a dedicated beam created in the digital domain based on the feedback from the device and/or based on the uplink channel measurements.

Grid of beams: A number of fixed beams. The downlink transmission uses one beam, providing capacity and coverage gains with low overhead and low complexity.

Digital beamforming: Each antenna element has a transceiver unit with the adaptive Tx/Rx weights in the baseband, enabling frequency selective beamforming. Digital beamforming boosts capacity and flexibility and is most suited to bands below 6 GHz.

Analog Beamforming: There is one transceiver unit and one RF beam per polarization. Adaptive Tx/Rx weighting on the RF is used to form a beam. This is best suited for coverage at higher mmWave bands and offers low cost and complexity.

Hybrid beamforming: Combination of analog and digital beamforming. When some beamforming is in the analog domain, the number of transceivers is typically much lower than the number of physical antennas, which can simplify implementation, particularly at high frequency bands. This technique is suited to bands above 6 GHz.

MIMO: Multiple Input Multiple Output multi-antenna transmission and reception. Most LTE devices and networks use 2x2 MIMO, where two parallel data streams can be transmitted. Some of the latest devices and networks also support 4x4 MIMO which doubles the peak rate compared to 2x2 MIMO and increases the average rates by at least 50 percent. The current LTE MIMO is a single user version where the parallel data streams are sent to a single device.

Multiuser MIMO (MU-MIMO): Parallel MIMO data streams are transmitted to different users at the same time-frequency resources.

Massive MIMO: A large number of controllable antenna elements is considered as massive MIMO and where the number of controllable antenna elements is much greater than eight. The term massive MIMO originates from Thomas Marzetta of Nokia Bell Labs. Massive MIMO becomes more practical at high bands since antennas become physically smaller with higher frequency. The number of transmission ports can be higher than the number of MIMO streams, for example, 64 transmit ports and 16 MIMO streams.

3D beamforming / Full dimension MIMO: Three-dimensional beamforming refers to the use of massive MIMO for steering beams both in the horizontal and vertical dimensions. It is also known as full dimension MIMO.

Interference Rejection Combining (IRC): Uplink reception where both signal and interference levels are considered when combining samples from multiple antennas. The aim is to maximize signal-to-interference ratio. Essentially, IRC can create nulls towards the interfering user. The traditional simple solution considers only signal levels and cannot avoid interference.

Active antenna: Active antenna refers to the integration of small RF units inside the antenna. An active antenna is required in practice to implement massive MIMO efficiently.

3. Beamforming benefits below 6 GHz

Beamforming using massive MIMO can also provide substantial capacity benefits in frequencies below 6 GHz. The aim is to enhance radio network performance while reusing existing base station sites by adding new active beamforming antennas. We first show simulation results and then illustrate field performance. Beamforming with massive MIMO with 64TX simulation results are shown in Figure 3. This assumes TD-LTE2600 with 20 MHz bandwidth. The reference case is 8TX, which is the baseline in many TD-LTE networks. The average gains are three-fold, cell edge gains are doubled and in the very best case even improved by a factor of five. The gains depend on the number of antennas and the load of the network. If the reference case is 2TX configuration, the gains would be even higher.

Beamforming support applies both for Time Division Duplex (TDD) and Frequency Division Duplex (FDD). Beamforming in TDD can rely on the uplink channel measurements due to channel reciprocity, while FDD uses feedback from the device. 3GPP Release 9/10 supports 8TX, Release 13 supports 16TX and Release 14 supports 32TX in LTE. It is possible to use 64TX in TD-LTE from Release 9 due to channel reciprocity.

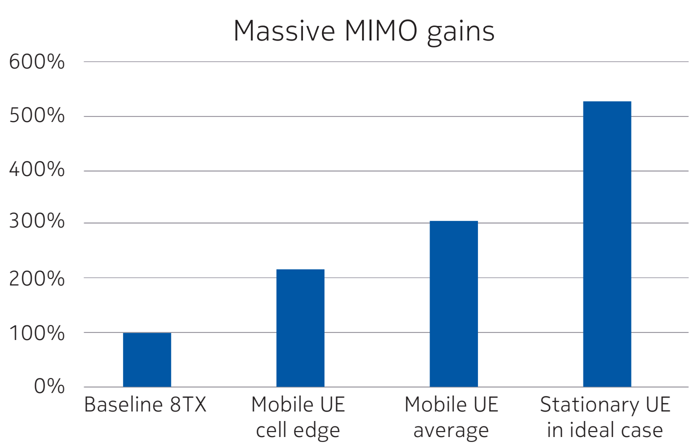

Figure 3. Massive MIMO gains with 64TX compared to 8TX for TD-LTE.

While massive MIMO can provide attractive gains in LTE, the performance benefits will be even higher with 5G. New 5G radios will exploit beamforming in the first release to provide the following potential benefits for massive MIMO:

- 5G supports more transmission branches. 5G will initially support at least 64TX, while LTE supports up to 32TX in Release 14
- 5G also supports beamforming for common channels and control channels, see Figure 4
- 5G has no legacy device limitations that would not support beamforming
- 5G devices are likely to have more receiver antennas, particularly at high frequency bands, which also enables beamforming in the device receiver.

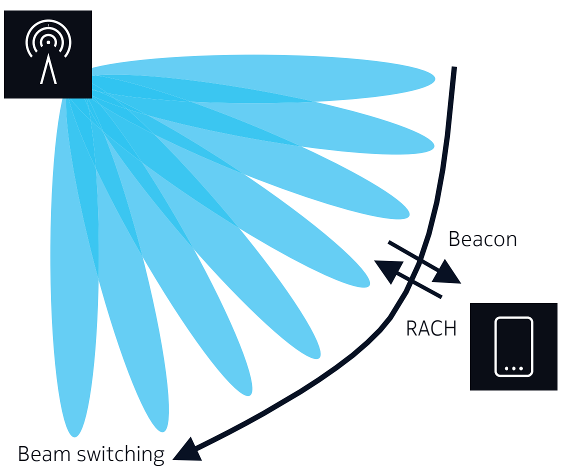

Figure 4. Common channel beamforming in 5G with beam switching.

Figure 5 illustrates the typical spectrum use for 5G. The most common spectrum globally will be 3.5 GHz covering up to 500 MHz from 3.3 to 3.8 GHz. Additionally, Japan will use 4.4-4.9 GHz. The spectrum around 3.5 GHz is attractive for 5G because it is available across the world and there is a high amount of spectrum available. The aim is to match the coverage of existing LTE1800/2100/2600 with 5G massive MIMO beamforming at 3.5 GHz. This allows the reuse of existing base station sites and provides virtually full urban, high data rate coverage for 5G. Therefore, beamforming is an essential technology in 5G networks.

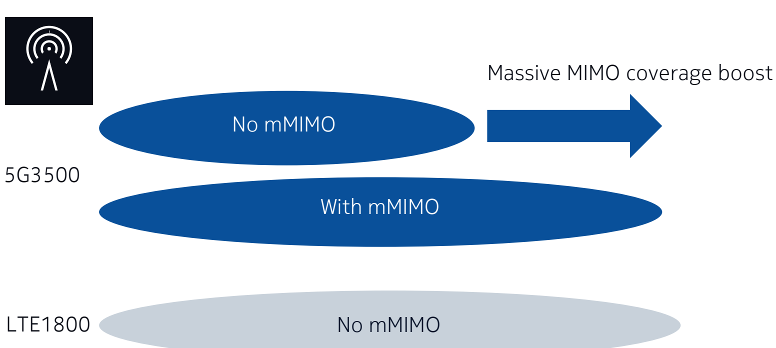

Figure 5. Beamforming can help 5G at 3.5 GHz to match LTE1800 coverage.

4. Field performance below 6 GHz

Field measurements can provide useful information about massive MIMO performance. The gain of a narrow beam transmission depends on the propagation environment and on the user locations. We show field measurements with 32TX using TD-LTE2600 and 20 MHz bandwidth in an urban environment in a macro cell network. The cell throughput was 88 Mbps with 8TX without massive MIMO, increasing to 360 Mbps with massive MIMO, with four times more throughput. The average user throughput in drive testing increased by three times from 17 Mbps to 52 Mbps. These results illustrate the great practical potential of massive MIMO technology.

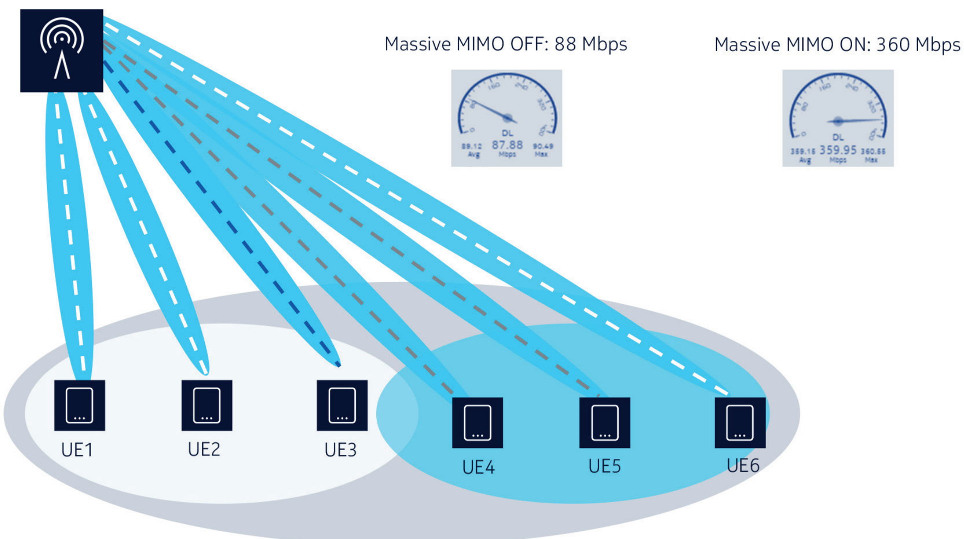

Figure 6. Massive MIMO performance in the field with TD-LTE2600 using 32TX.

Working with Sprint, USA, Nokia demonstrated 3D Beamforming using the Nokia AirScale Massive MIMO 64T64R active antenna. The downlink performance can be improved considerably but even more importantly, the demonstration shows up to an eight-fold improvement in uplink in TD-LTE 2600 using existing commercial devices. The uplink beamforming improvements were the result of 64 receive antennas with Nokia's innovative interference rejection algorithms. These promise benefits not only in the downlink, but also in the uplink.

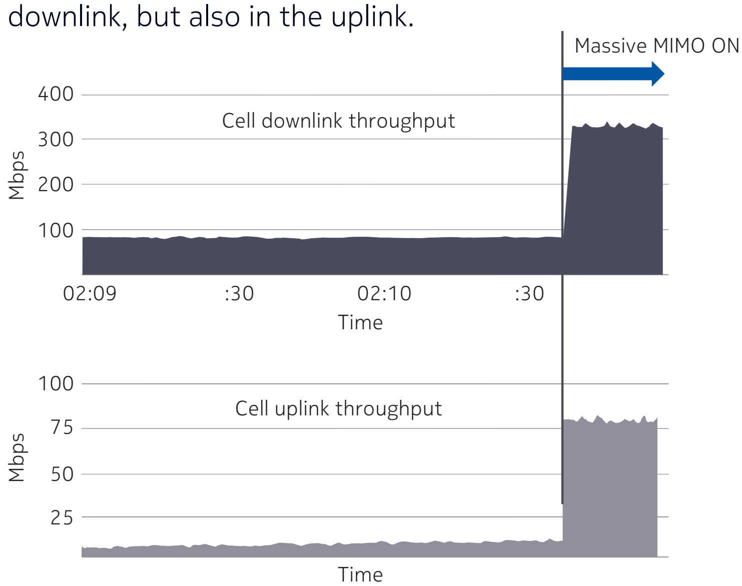

Figure 7. Massive MIMO shows major boost in uplink

5. Beamforming benefits above 20 GHz

5G radio is designed to support low bands starting from 400 MHz and high bands up to 90 GHz. The high frequencies above 30 GHz are commonly known as millimeter waves (mmW) as the wavelengths are in the order of millimeters long. Frequencies above 20 GHz are also sometimes counted as millimeter waves. The size of the antenna is dependent on the wavelength. When the wavelength gets shorter, the antenna also becomes smaller. Therefore, it is possible to design massive MIMO antennas in a compact format at mm waves.

Table 1 shows the differences between low bands and mm waves. The total aggregated bandwidth in low bands is typically limited to 100-200 MHz and cells are large. The main challenge is inter-cell interference control and a large number of simultaneous users.

The challenges are completely different for mm waves: high data rates and high capacity can be provided by using large bandwidth up to 2,000 MHz. There is no real need for multi-stream MIMO to increase user data rates. The challenge is that the propagation is limited and the cell size remains small. At high bands, beamforming is mainly needed to enhance the link performance and to increase cell size. The number of simultaneous users tends to be low. These characteristics explain why the massive MIMO solution at mm waves needs to be different compared to that used for low bands below 6 GHz.

	Below 6 GHz	**Above 20 GHz**
Bandwidth	Up to 100-200 MHz	Up to 1000-2000 MHz
Interference	Interference limited	Coverage (noise) limited
Cell size	Large >1 km	Small <0.2 km
BTS antenna ports	Few antenna ports	Many antenna ports
UE antenna ports	Low number of ports	Several ports feasible
Simultaneous UEs	High number of UEs	One or just a few
	Beamforming for interference control to enhance efficiency	Beamforming for link gain to enhance cell range

Table 1. Differences between low bands and mm waves.

An example antenna array configuration for mm waves is shown in Figure 8. The base station antenna uses cross-polarized antenna elements in a 16 x 16 array, giving a total of 512 transmit points. The device array is 2 x 4 with cross polarized elements and a total of 16 transmit points.

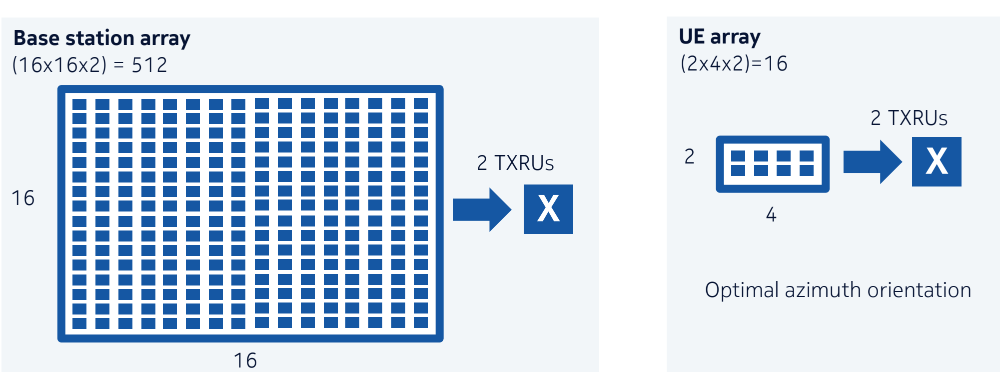

Figure 8. Example antenna configuration for mm wave use

6. Fixed Wireless Access above 20 GHz

5G presents an opportunity for CSPs to offer massive broadband access to homes in areas where conventional fiber-to-the-home (FTTH) is difficult or expensive to deploy. Figure 9 illustrates the expected user data rates for a fixed wireless access use case with beamforming antennas at 28 GHz and a 100-300 meter inter-site distance. Heavy foliage is assumed, which makes the results worst case. The average user data rate is 400-550 Mbps in all cases and at the cell edge is 130-240 Mbps with a 100-200 meter inter-site distance. This shows that 28 GHz spectrum with beamforming can provide attractive practical performance. If the distance increases to 300 meters, the cell edge data rate drops to 50 Mbps. Without interference from foliage, the cell edge data rate would be more than 200 Mbps in all cases.

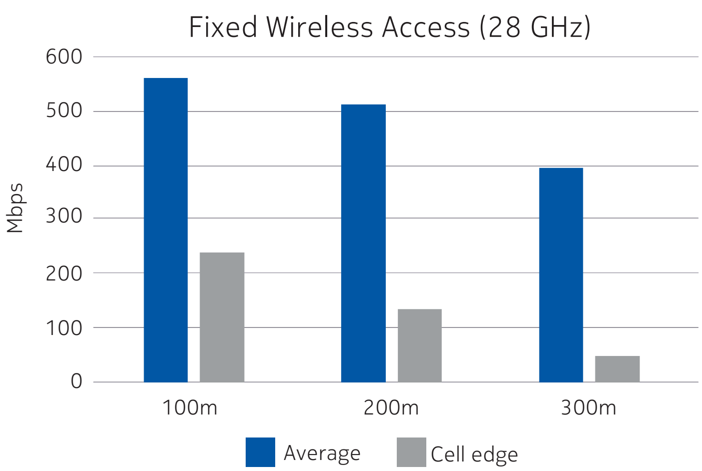

Figure 9. Data rates with 28 GHz fixed wireless access with beamforming.

7. Active antennas and site solution

Active antenna combines a large number of small RF units inside the antenna. The traditional solution has been a passive antenna and a separate RF unit. Active antenna technology enables the implementation of practical beamforming when phasing of the small power amplifiers can be controlled with digital processing. A typical number of RF units is 32, 64 or 128 inside the active antenna. If the total power is 200W, each power amplifier has just 1.6 – 6.4W. If the total power is 20W in 128TRX antenna, each power amplifier has just 0.16W, similar to the power of the device amplifier.

Active antennas also simplify installation, since there are no cables between the antenna and the radio units. The power efficiency can also be enhanced since there are no losses in RF cables and connectors. Essentially, active antennas bring the benefits of digitization to antennas, which have traditionally been simply passive elements.

Nokia active antenna with 64TRX is shown in Figure 10. Nokia AirScale massive MIMO Antenna for 2.6 GHz is less than half the height of a traditional 8Tx, reducing wind loading. It includes radio plus antenna and can deliver three carriers from single unit. The transmit power is 25 percent lower than 8Tx, yet it matches the coverage of the lower band.

Nokia active antenna minimizes OPEX through simple installation and reduced maintenance. If one or even a few power amplifiers out of 64 fail, there is just a marginal loss of RF power and a marginal increase in side lobe level. Digital algorithms can adjust the transmission weights to minimize the impact of failed units. There is no need to replace the antenna simply because of a few faulty units inside the antenna. Even if several units fail, there is still no urgent need for maintenance. In contrast, if the power amplifier fails in the traditional RF head, replacement work needs to be scheduled immediately.

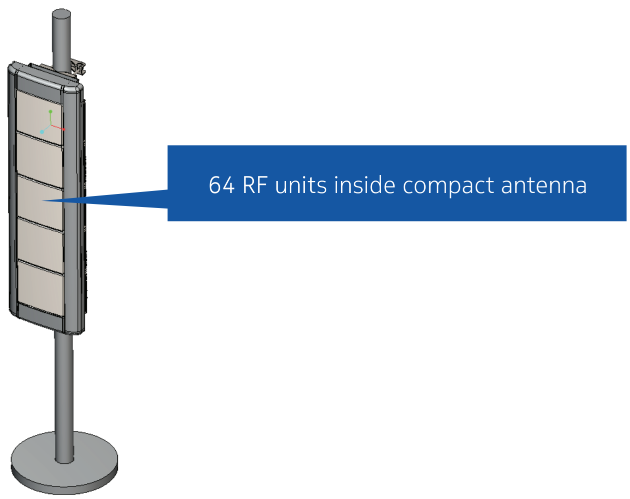

Figure 10. Nokia active antenna.

8. Massive MIMO in 3GPP

The latest 3GPP specifications enable beamforming. The first LTE specifications in 3GPP Release 8 supported single user MIMO with 2x2 and 4x4. Multi-antenna uplink was supported because it is transparent to the devices. The subsequent 3GPP releases have gradually improved the beamforming capability, see Figure 11.

8TX downlink for TDD was included in Release 9 with Transmission Mode 8 (TM8), 8TX downlink with feedback in Release 10 with Transmission Mode 9 (TM9) and multi-cell Coordinated Multipoint (CoMP) in Release 11. Massive MIMO for LTE is covered in Releases 13 and 14 for 16TX and 32TX. All LTE releases are backwards compatible, allowing the new MIMO features to be deployed on the same frequency as any legacy devices. Release 15 brings the 5G new radio with enhanced beamforming capabilities for all new devices.

Release 8	Release 9	Release 10	Release 11
• 4x4MIMO • 4x2MIMO • 8RX uplink • Uplink CRAN	• 8TX TM8	• 8TX TM9	• Downlink CoMP (TM10)
Release 12	**Release 13**	**Release 14**	**Release 15+**
• Downlink eCoMP • New 4TX codebook	• Massive MIMO 16TX	• Massive MIMO 32TX	• 5G massive MIMO 64TX+

Figure 11. Multi-antenna feature evolution in 3GPP releases.

9. Conclusions

Beamforming using Massive MIMO for 4.9G and 5G with high spectral efficiency offers significant improvements in network capacity, coverage, installation and operation with reduced OPEX. It is supported by 3GPP specifications and commercially viable, initially for TD-LTE and later for FDD LTE.

Beamforming for LTE is mainly used for capacity, while for 5G it is used also for coverage. Beamforming for 5G offers even more benefits than LTE, providing higher spectral efficiency.

10. Further reading

Nokia white paper: “5G Master Plan” https://pages.nokia.com/5g-master-plan.html

Nokia white paper: “5G for Mission Critical Communication” https://pages.nokia.com/GC200007.html

Nokia white paper: “Translating 5G use cases into viable business cases” https://resources.ext.nokia.com/asset/201152

Nokia white paper: “Dynamic end-to-end network slicing for 5G white paper” https://pages.nokia.com/GC200339.html

Nokia white paper: “5G System of Systems white paper” https://pages.nokia.com/GC200012.html

11. Abbreviations

CoMP	Coordinated Multipoint
CQI	Channel Quality Indicator
FDD	Frequency Division Duplex
IRC	Interference Rejection Combining
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
MU-MIMO	Multiuser MIMO
OPEX	Operating Expenses
RF	Radio Frequency
RX	Receiver
TDD	Time Division Duplex
TM	Transmission Mode
TX	Transmitter

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Docket: A.18-07-011 and A.18-07-012

Witness: Cameron Reed

Date: January 7, 2019

Public Advocates Office

Exhibit CR-9

"Nokia White Paper on 5G Deployment below 6 GHz"

5G deployment below 6 GHz

Ubiquitous coverage for critical communication and massive IoT

White Paper

There has been much attention on the ability of new 5G radio to make use of high frequency spectrum, such as mmWave bands, as an effective way to provide huge amounts of capacity to meet rocketing demand. Yet the early phases of commercial 5G are more likely to be deployed on lower frequency spectrum, especially sub-6 GHz.

This Nokia paper explains the reasons and the benefits of deploying 5G on these low bands below 6 GHz, as well as describing the technology and practical solutions.

Contents

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1. Executive Summary

5G is the first radio system designed to support any spectrum between 400 MHz and 90 GHz. This wide range of spectral options provides the best combination of high capacity, high data rates, ubiquitous coverage and ultra-reliability.

The low bands below 6 GHz meet the needs of wide area coverage and data rates of up to a few Gbps. Reliable coverage is important for providing connectivity for Internet of Things (IoT) devices and for critical communications like remote control or automotive applications.

The main spectrum options for 5G in its early phases are around 3.5 GHz and 4.5 GHz and millimeter waves at 24-28 GHz and 39 GHz with Time Division Duplex (TDD) technology. The initial phase aims to use existing base station sites for 3.5/4.5 GHz to simplify 5G introduction. 5G at 3.5 GHz with massive MIMO (Multiple Input Multiple Output) beamforming antennas can match the coverage of existing 4G networks using the 2 GHz band with traditional passive antennas. Peak data rates up to 2 Gbps can be achieved with 5G by using 100 MHz of bandwidth, providing a capacity up to 10 times greater than 4G. Millimeter wave spectrum offers up to 1 GHz per operator to enable peak rates of up to 20 Gbps and very high hotspot capacity.

5G can also use sub-1 GHz Frequency Division Duplex (FDD) bands to provide wide area coverage, including deep indoor penetration. The low band spectrum can take advantage of the new 700 MHz allocation in Europe or 600 MHz allocation in USA, as well as the refarming of 850/900 MHz released by minimizing the use of legacy 2G/3G spectrum. The aggregation of the different spectrum bands from sub-1 GHz to millimeter waves provides the best combination of coverage, capacity and user data rates.

5G can also be deployed on shared spectrum, like the 3.5 GHz in USA, and in unlicensed spectrum, like 5 GHz. This approach opens new opportunities for enterprises and industries to benefit from 5G technology without the need for licensed spectrum.

Evolving 4G to 4.9G provides an excellent path to 5G. New 5G technologies will deliver even greater performance in terms of latency, spectral efficiency, massive MIMO optimization, energy efficiency and reliability, encouraging the refarming of existing spectrum to 5G.

The first phase of 3GPP 5G specifications will include the RF requirements for the new spectrum allocations and for refarming most current frequencies.

2. Spectrum below 6 GHz

Spectrum is the key asset for a communications service provider (CSP). The available spectrum has a major impact on how a network’s maximum capacity and coverage are defined.

The mainstream spectrum will be 3.5 GHz with up to 400 MHz available from 3.4 to 3.8 GHz, including 3GPP bands 42 and 43. Additionally, China will use 3.3 to 3.4 GHz and Japan 4.4 to 4.9 GHz.

The spectrum around 3.5 GHz is attractive for 5G because it is available globally and offers a high amount of spectrum – potentially more than 100 MHz of contiguous spectrum per CSP. But with 3.5 GHz spectrum, the cell range is limited because radio propagation reduces as the frequency increases. Therefore, 3.5 GHz provides less coverage than the 2 GHz used by 4G networks. However, deploying massive MIMO beamforming antennas at 3.5 GHz can match the coverage of existing LTE1800/2100, effectively enabling full urban coverage with 5G.

5G can also use sub-1 GHz spectrum to provide deep indoor penetration, a reliable uplink and large coverage. Extensive coverage is important for new uses cases like IoT and critical communications. Low data rate IoT connectivity can be supported with wider coverage using various extension solutions.

The low band could make use of 700 MHz spectrum, which has been made available, or will soon become available, in various countries. Another option is 900 MHz, which is mainly occupied by 2G and 3G today. Most CSPs are likely to keep 2G and 3G running until 2020 but will minimize the allocation of spectrum for legacy radios in order to make room for 5G. Another option for the 5G low band in the USA is 600 MHz.

Typically, the early phases of 5G will use mmWaves to provide up to 20 Gbps, 3.5/4.5 GHz to offer up to 2 Gbps, and low bands for ubiquitous coverage running at more than 200 Mbps throughput.

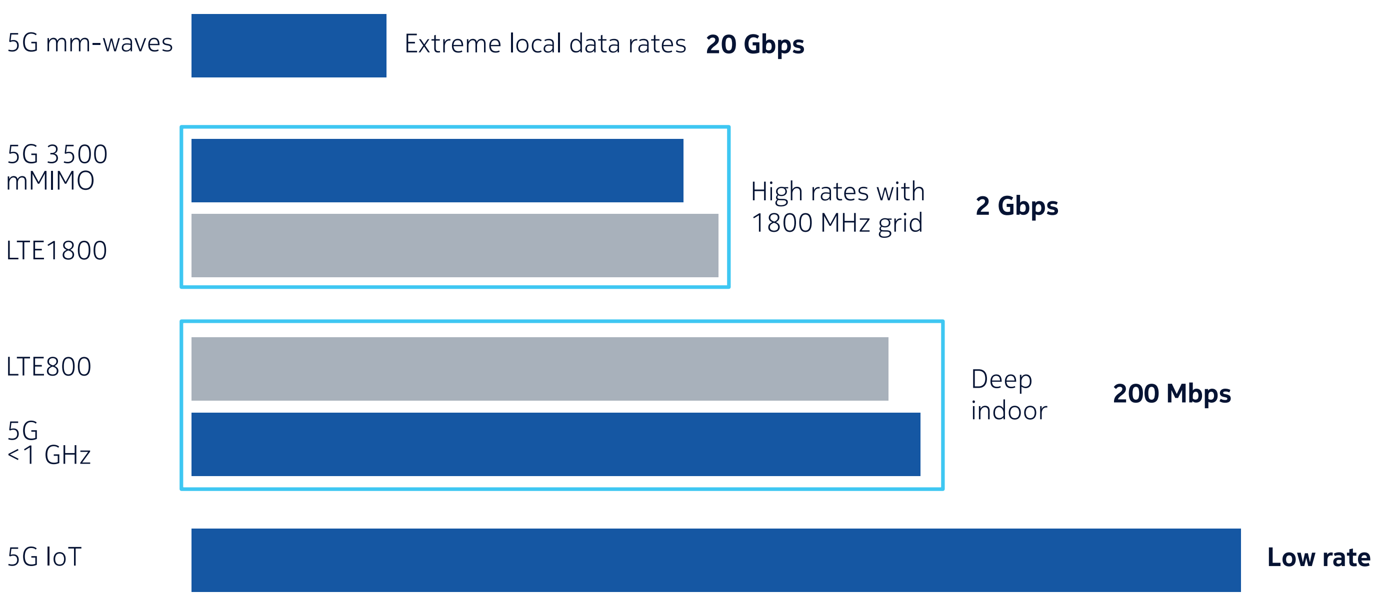

Figure 1. Typical 5G spectrum use in the early phases of 5G (mMIMO=massive MIMO).

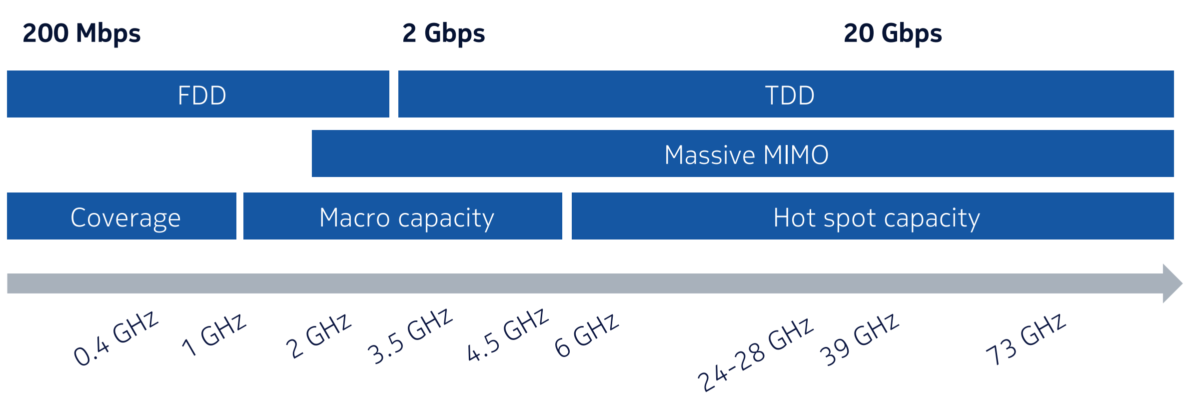

Figure 2. Overview of 5G spectrum options, the main technologies (FDD, TDD, antennas) and the main use area (coverage, capacity). The low bands are FDD-based and provide coverage, while the high bands are TDD-based and offer high capacity when used with massive MIMO.

2.1. Coverage and beamforming

Bands below 1 GHz provide excellent coverage with typical LTE antenna configurations known such as 2x2 MIMO. In addition, typical FDD designs in these low bands provide good coverage and long signal travel times, enabling tens of km of extended cell radii. The large wavelengths below 1 GHz, however, limit the option to use 5G features like massive MIMO. That's because handheld devices are typically not large enough to accommodate more than two sub-1 GHz antennas, while size, weight, wind load and visual impact considerations limit the number of deployable antenna elements at base stations. This does mean, though, that sub-1 GHz 5G coverage can be implemented relatively easily and with minimal technological risk.

Coverage in and around the 3.5 GHz band can be enhanced by using beamforming antennas and lower frequency bands for the uplink. Figure 3 illustrates the relative outdoor coverage for the different frequencies compared to a 2100 MHz uplink. The calculation assumes the Okumura-Hata propagation model, a downlink that is 8 dB better than the uplink, and a massive MIMO (mMIMO) gain of 6 dB compared to 2x2MIMO. This calculation shows that 5G at 3500 MHz downlink with massive MIMO can exceed LTE1800 MHz 2x2MIMO coverage.

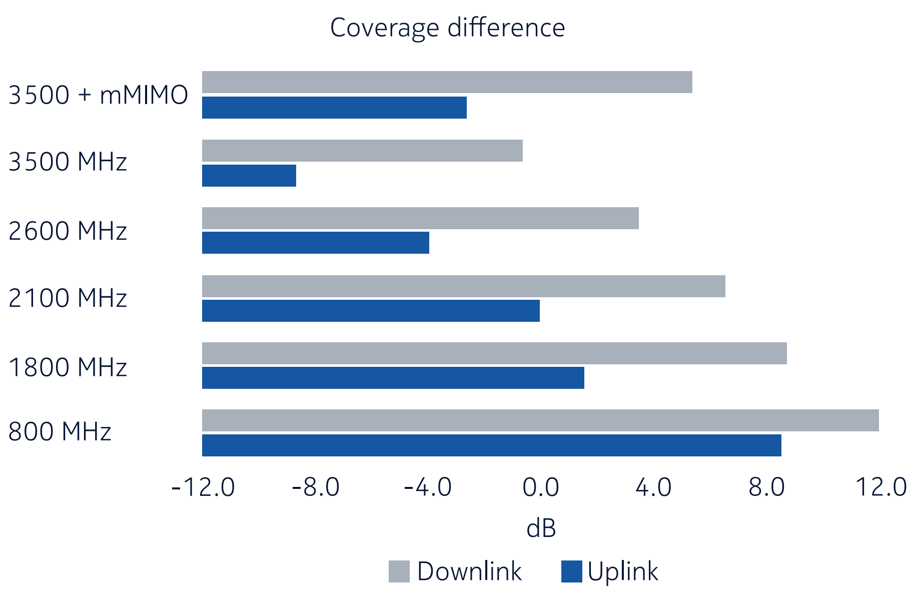

Figure 3. Outdoor coverage difference compared to 2100 MHz uplink.

Macro network coverage is uplink limited because the 0.2W maximum output power of devices is much lower than the base station power which can be in excess of 100W. Therefore, a 3500 MHz uplink falls short of LTE2100 or LTE1800 coverage.

One solution is to deploy 5G at low bands which are then aggregated with the 3.5 GHz band. Another option is to share the uplink frequency between 5G and LTE, for example, at 1800 MHz or 800 MHz. Figure 4 illustrates this latter configuration. Spectrum utilization on the uplink is generally lower than on the downlink because traffic is asymmetric with downlink traffic volume typically ten times higher than uplink traffic because of the use of video streaming. Therefore, it is feasible to also use part of the LTE uplink spectrum for 5G.

LTE and 5G sharing an uplink may restrict practical 5G deployment. The same antenna direction is required for LTE and 5G, while changes to the existing LTE equipment are likely to be needed. Using a dedicated low band for 5G would be a more flexible solution.

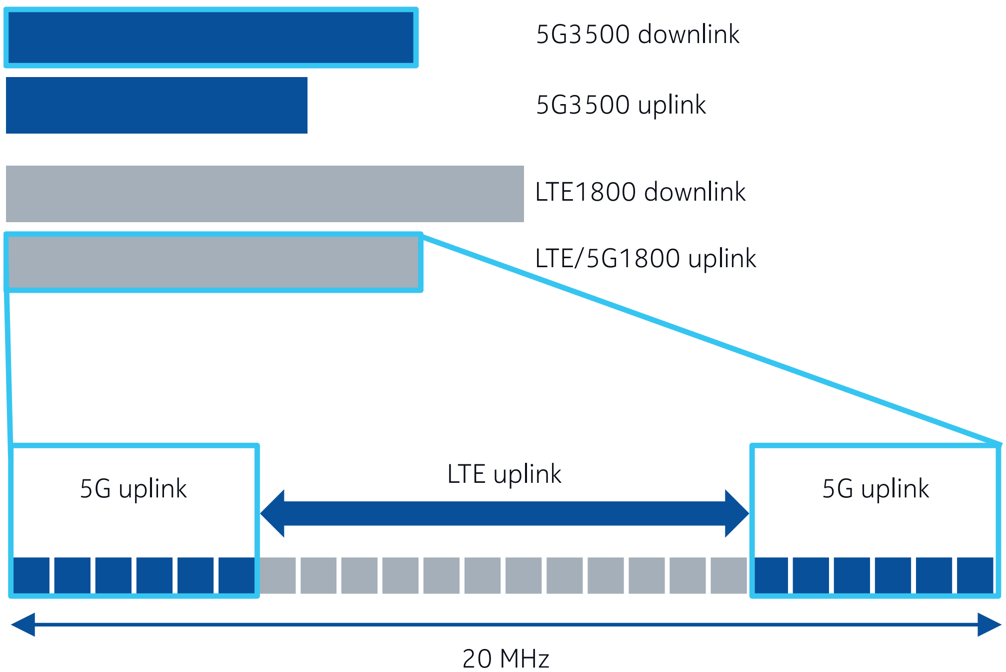

Figure 4. 5G uplink in lower band together with LTE.

2.2. Capacity below 6 GHz

Higher capacity can be provided by using more bandwidth and deploying more antennas. Combining these two measures boosts capacity substantially. Figure 5 illustrates a simplified view of cell capacity at 3.5 GHz compared to the existing 4G cell capacity. This assumes that the 3.5 GHz band has 100 MHz of bandwidth available while LTE1800 has 20 MHz. Massive MIMO can improve spectral efficiency by a factor of two to four. The new 3.5 GHz band is the most efficient way of increasing the capacity of existing cell sites, achieving an increase of 10-20x.

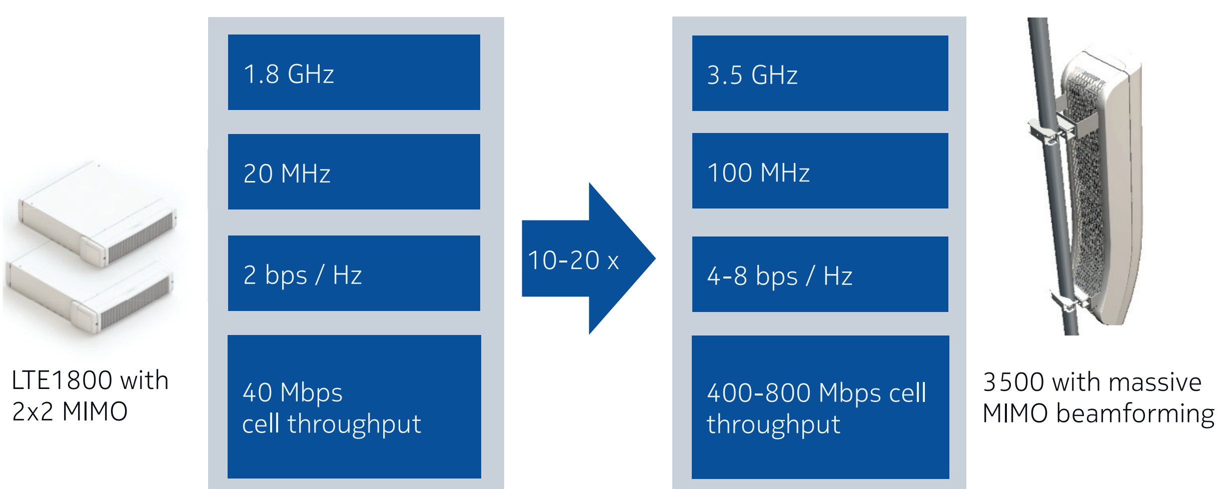

Figure 5. 5G versus 4G capacity per cell.

Sub-1 GHz capacity is limited by the comparatively narrow bandwidths available, typically 2x 10 MHz FDD, and the limited options for using advanced 5G antenna technology. However, this does not affect the performance of most of the new 5G services that require moderate data rates, but does enable them to benefit from the excellent coverage properties of these bands.

Future network deployments, especially high capacity sites, need to take into account Electromagnetic Field (EMF) limits in terms of maximum allowed Equivalent Isotropic Radiated Power (EIRP). These limits are country specific, which calls for flexibility in the way that solutions can be deployed. Nokia solutions achieve this flexibility by enabling dynamic power sharing in multiband RF units, minimizing average transmission power with lean carriers, and the seamless integration of small cells with the macro network.

Low bands become even more important where high power levels are not feasible to boost coverage.

3. The benefits of running 5G on low bands

5G will enable extreme mobile broadband, massive IoT connectivity and ultra-reliable critical communications. Ubiquitous coverage is the most important aspect of reliable connectivity, especially for massive IoT and critical communications, see Figure 6. Therefore, low bands are highly important for the success of 5G.

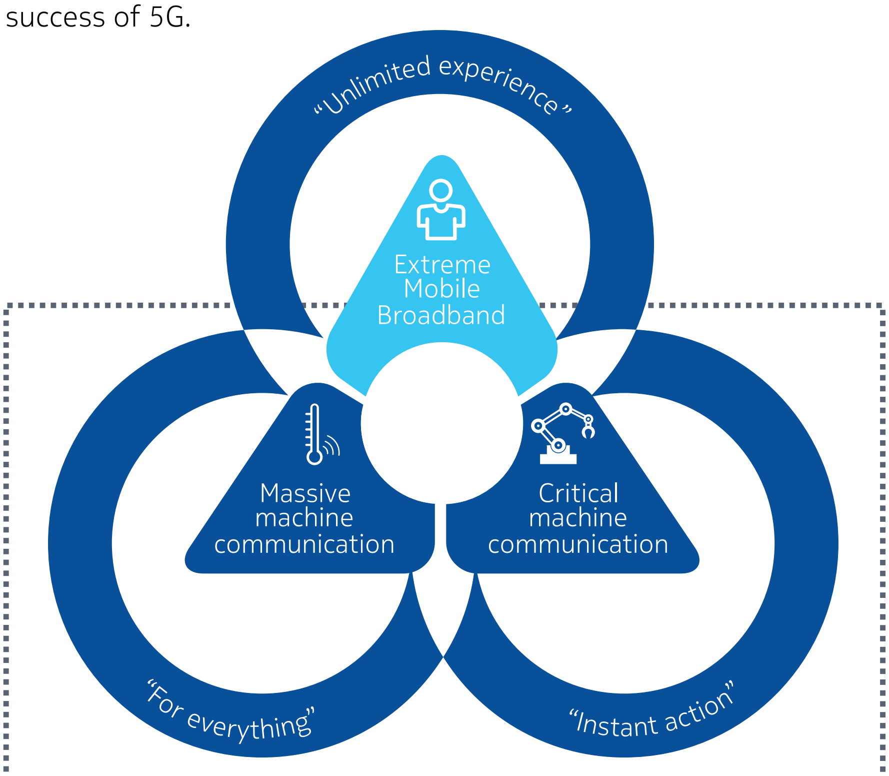

Figure 6. IoT and critical communication requires ubiquitous coverage.

5G radio can substantially improve network performance and efficiency, as summarized in Figure 7.

Yet some of these gains can also be obtained with 4.9G, which is an evolution of existing LTE networks. Nokia expects 5G to be able to provide lower latency, lower IoT power consumption, higher network energy efficiency and enhanced spectral efficiency. The values in Figure 7 are based on the following assumptions:

- The shortest transmission time in 5G is 0.125 ms, which enables a round trip time of 1 ms.
- IoT average power consumption of 7 mW with one transmission per minute
- Efficiency energy use is based on a 3-sector 100 MHz macro base station with a busy hour average throughput of 1 Gbps, 7 percent busy hour share, 200 W base station average power consumption, and 20 percent of base stations carrying 50 percent of traffic. These assumptions deliver an average base station utilization of less than 15 percent.

  The five-fold efficiency improvement over LTE is obtained through power saving techniques used at low loads and with a wideband carrier of up to 100 MHz at 3.5 GHz. 5G technology has built-in components to minimize energy consumption compared to a similar LTE configuration, although the absolute power consumption per base station in 5G may be higher than in LTE because of high power massive MIMO transmission.
- A spectral efficiency of 10 bps/Hz/cell assumes the use of massive MIMO beamforming and four antenna devices. By comparison a typical LTE downlink efficiency is 2 bps/Hz/cell in live networks and 30-50 percent more with 4x4MIMO.

10x lower latency	<1 ms	• New radio design • Distributed architecture
10x lower IoT power	<10 µWh per tx	• Protocol optimization • Non-orthogonal uplink
5x energy efficiency	<2 kWh/TB	• Lean carrier • Wideband carrier
3x spectral efficiency	>10 bps/cell/Hz	• Massive MIMO, lean design, interference cancellation

Figure 7. Summary of 5G technology capabilities compared to the existing LTE networks.

4. Example deployment in a large city

Let's now look at a potential deployment and spectrum utilization for early phase 5G implementation.

The scenario is located in a major European city as shown in Figure 8. The low band 700 MHz layer is used to provide wide area coverage and indoor penetration. The low band enables low latency communication for ultra-reliable use cases and for IoT connectivity.

Across the larger metropolitan area, new 5G applications, such as automated driving and smart grids, can benefit from 5G coverage.

The 700 MHz network can reuse existing 800/900 MHz base station sites. The dense urban coverage and high data rates are provided by the 3.4-3.8 GHz band which supports enhanced mobile broadband with much more capacity. Existing base station sites around 2 GHz can also be reused.

Extreme hotspot capacity and data rates are provided by 25 GHz mmWave bands. The millimeter wave coverage is focused on stadiums, airports and other areas with high usage density, as well as research and development centers to allow interested parties to develop, implement and test new 5G applications.

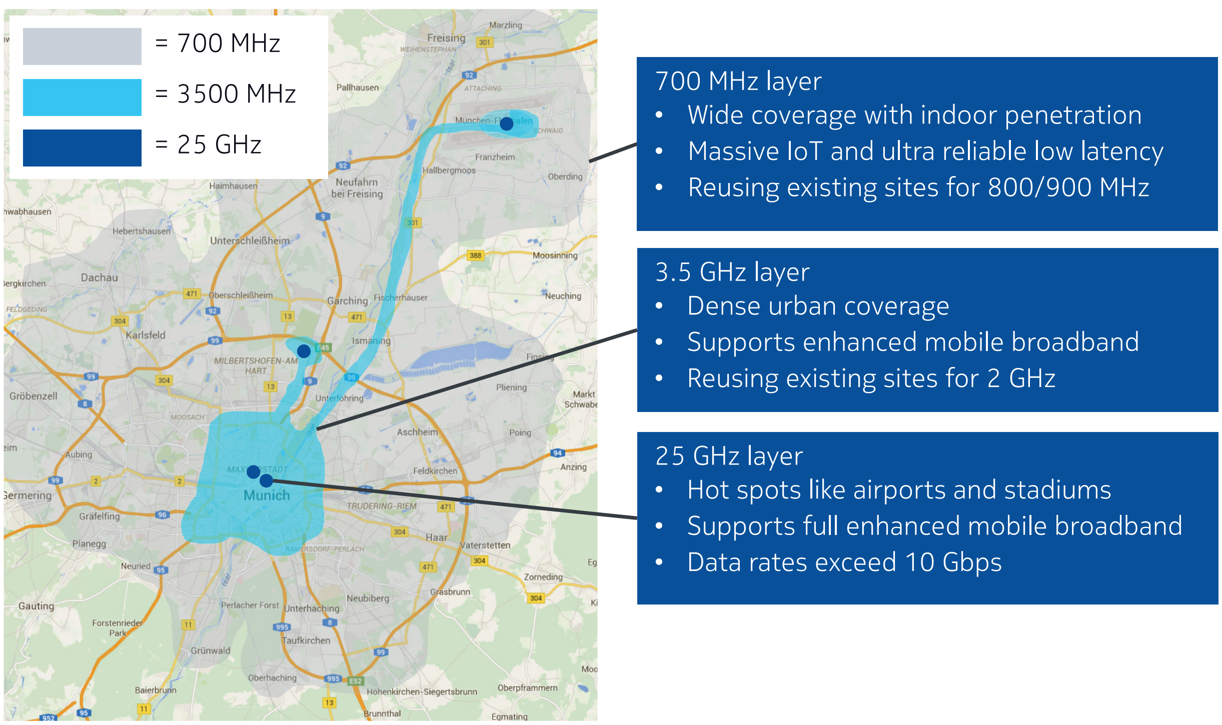

Figure 8. Example early phase 5G deployment in a European city.

5. Shared and unlicensed spectrum

3GPP technologies have traditionally been deployed only on licensed spectrum bands, but future deployments will be different. 5G is designed for licensed, unlicensed and shared spectrum. This opens up a wide range of possibilities for enterprises and industries to take advantage of reliable 5G connectivity without the need for a spectrum license.

The unlicensed band plans in 3GPP are shown in Figure 9. 5G can also be deployed on shared spectrum like 3.5 GHz in USA where 5G can access a large amount of spectrum without affecting incumbent services.

Large number of spectrum options considered	For example 5 GHz, 37 GHz and 60 GHz spectrum
Standalone unlicensed operation included	Standalone unlicensed and dual connectivity with licensed bands
Regulatory aspects and fairness considered	Listen-before-talk and other co-existence solutions

Figure 9. Unlicensed spectrum with 5G.

6. Conclusion

While the deployment of 5G on high frequency bands in the mmWave range will provide extreme capacity, the roll out of 5G in sub-6 GHz low bands will characterize early commercial phases, providing a capacity boost and wide coverage to support most applications.

A selection of technologies is available to help CSPs evolve smoothly to 5G and use existing and new spectrum to build capacity and ubiquitous coverage.

5G is most likely to be first deployed on newly available 3.5 GHz and 4.5 GHz spectrum, sub-1 GHz spectrum released by the digital switch-off, on spectrum made available by refarming 2G and 3G frequencies, and using new unlicensed spectrum. In addition, we will see 25-39 GHz mmWave spectrum being used to meet the needs of extreme hotspots like event stadiums.

This flexibility of 5G to be able to use a vast range of different spectral bands is an attractive benefit for CSPs and enterprises, one they have not enjoyed with any previous mobile radio standard.

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Further reading

Nokia white paper: “5G Master Plan” https://pages.nokia.com/5g-master-plan.html

Nokia white paper: “5G for Mission Critical Communication” https://pages.nokia.com/GC200007.html

Nokia white paper: “Translating 5G use cases into viable business cases” https://resources.ext.nokia.com/asset/201152

Nokia white paper: “Dynamic end-to-end network slicing for 5G white paper” https://pages.nokia.com/GC200339.html

Nokia white paper: “5G System of Systems white paper” https://pages.nokia.com/GC200012.html

Abbreviations

EIRP	Equivalent Isotropic Radiated Power
EMF	Electromagnetic Field
FDD	Frequency Division Duplex
IoT	Internet of Things
LTE	Long Term Evolution
mMIMO	Massive MIMO
TDD	Time Division Duplex

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Docket: A.18-07-011 and A.18-07-012

Witness: Cameron Reed

Date: January 7, 2019

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Exhibit CR-10

"Nokia White Paper on 5G Radio Access"

NOKIA

5G Radio Access System Design Aspects

Contents

Introduction

Wireless data traffic will grow 10,000 fold within the next 20 years due to ultra-high resolution video streaming, cloud-based work, entertainment and increased use of a variety of wireless devices. These will include smartphones, tablets and other new devices, including machine type communications for the programmable world.

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.

In addition to the more traditional cellular access bands below 6 GHz, 5G is expected to exploit the large amount of spectrum above 6 GHz. One or more new radio interface technologies will be needed to address this regime of frequency bands due to different channel characteristics. Extending the LTE air-interface to frequencies above 6 GHz may be considered, but a simpler and more efficient air interface can be designed to address specific challenges.

For the end user, 5G should be transparent and seen as one system guaranteeing a consistent experience. Furthermore, mobile network operators expect straightforward 5G deployment and operation. This calls for tight integration of 5G layers with existing systems such as LTE and their evolution via Single Radio Access Network (RAN) solutions. This approach will simplify network management from 2G to 5G, and will also enable a gradual introduction of 5G.

The network and deployment flexibility, as well as the air interface design, will help curb the growth of energy consumption. The consumed energy per delivered bit must fall drastically at both ends of the radio link, for example, the energy used by unconnected devices and in network nodes not operating at capacity.

A holistic, flexible design and tight integration of existing technologies are key Nokia priorities.

Improving network capacity

The 10,000 fold increase in network capacity, along with a ten-fold improvement in user experience (reaching 100 Mbit/s even in unfavorable network conditions) will be achieved through:

1. Massive densification of small cells
2. More spectrum
3. Increased spectral efficiency

Densification

The densification of network deployments is a trend already apparent in 3G and 4G. 5G will enable the design of a flexible system from a clean slate and allow optimization for cell sizes below a 200m inter-site distance. In contrast to LTE, where the small cell design is based on the rigid wide-area macro cell design, the clean-slate approach allows a higher degree of optimization and adaptation to small cell sizes. It is, however, important that while optimizing the design for ultra-dense network deployments with small cells, 5G also brings wide area macro cell deployments, further underlining the need for design flexibility.

Spectrum

The frequencies allocated or under discussion for additional bandwidth for cellular use have so far all been below 6 GHz, mostly due to the favorable wide area coverage properties of the lower frequencies. While more spectrum below 6 GHz is needed and there are promising techniques to increase the use of already allocated frequencies, there will also be an increasing need to unlock new spectrum bands. These bands will help to meet the high capacity and data rate requirements of the 5G era. Bands above 6 GHz can be broadly split in two parts, centimetric wave (3-30 GHz) and millimetric wave (30-300 GHz), based on different radio propagation characteristics and the carrier bandwidth possible in the different frequency ranges.

The centimetric waves behave similarly to traditional cellular bands (for example, reflections and path loss exponents), but some effects will be different, such as the overall path loss and diffraction, particularly at the higher end of the centimeter wave band. The contiguous bandwidth that is potentially available with the centimetric wave band, roughly 100-500 MHz, is wider than LTE-Advanced is designed for and the LTE air interface design, optimized at around 2 GHz, is not well suited for centimetric wave frequencies.

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At millimetric wavelengths, starting from 30 GHz, the radio propagation and RF engineering is different from the sub-6 GHz spectrum range in some respects, such as higher diffraction and higher foliage and structure penetration losses. However, recent measurements have shown that millimetric wave frequencies are also similar to those below 6 GHz in other respects, such as reflections and path loss exponents. Furthermore, Nokia has recently demonstrated very high data rates, for example, 15 Gbps, with a proof-of-concept system operating at 73 GHz with a 2 GHz bandwidth. Even though there is a well-defined buffer of 30 GHz between the centimetric wave and millimetric wave bands (1 cm wavelength), the radio propagation changes more smoothly and there is no sharp transition point in radio propagation characteristics.

In addition to the licensed spectrum, the existing unlicensed spectrum bands can also offer good potential as additional capacity for future 5G deployments.

The Radio Communication Sector of the International Telecommunication Union (ITU-R), working on the allocation and global management of radio spectrum, is working towards realizing the future "IMT-2020" vision (a.k.a. "5G") of mobile broadband communications.

Currently, WP 5D, an ITU-R sub group, is working on various reports to provide guidance on what may be expected in the future development of IMT for 2020 and beyond, including systems operating above 6 GHz.

The World Radio Conference WRC-15 decided on the agenda items for WRC-19. WRC-19 will decide on the bands between 24 – 86 GHz (as shown in Figure 1) for future 5G deployments and related sharing and compatibility studies are being carried out.

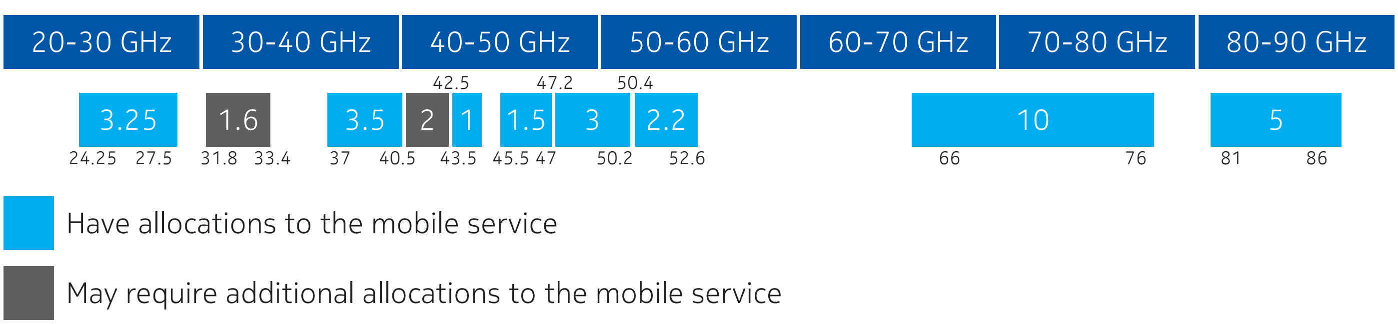

Fig. 1. Spectrum bands to be studied for 5G for ITU-R WRC-19

WRC-19 will not address the bands below 24 GHz. Using these bands would, however, be a logical step for cellular access as they are closer to currently used frequency ranges. While the global harmonization of the bands below 24 GHz is postponed, it may be possible to introduce those bands for 5G national use as a first step. It is, therefore important to continue future studies also on those bands to fully characterize radio propagation within them.

It is essential that the industry and regulators work together to secure sufficient spectrum for mobile communications beyond 2020. This will facilitate the development of the technology and will improve society and economic development.

Spectral efficiency

Spectral efficiency is a measure of how efficiently spectrum can be used during data transmission, in other words, how many bits per Hz per second the system is able to deliver over the air. A system is designed with various spectral efficiencies in mind, such as peak, average user and cell edge. By increasing these spectral efficiencies, the capacity of the network increases without the need to add more cell sites or to use more spectrum. Multiple components affect the spectral efficiency of the radio link, for example modulation, multi-antenna operation, signal waveform, and the entire system, including coordination between nodes, interference suppression, and collaborative radio resource management. LTE already has a high radio link spectral efficiency, but the spectral efficiency of the system (or area) still allows improvements that are less expensive but also use less energy and are simpler overall.

A key technical component for 5G in general and to improve spectral efficiency in particular is massive MIMO.

Integrating large scale antenna arrays into the air interface design of 5G systems in the centimetric wave or millimetric wave bands will show significant differences to the MIMO solutions currently deployed in 4G systems. Firstly, the more noise-limited nature of high-bandwidth systems at centimetric wave or millimetric wave bands will allow simple solutions that do not need to actively mitigate other-cell interference. Secondly, 4G systems at 3 GHz and below are bandwidth and interference limited, so the emphasis with MIMO technology in those systems has been to increase spectral efficiency to overcome these limitations.

The high bandwidth systems at millimetric wave bands may not be bandwidth or interference limited, but tend to be path-loss limited. As a result, the emphasis with MIMO technology will initially be on providing power gain through beam forming. Spatial multiplexing, critical to high performance in 4G systems, will not be the main emphasis with millimetric (mmWave) systems due to the need to overcome path loss limitations, although at a minimum, single-user rank-two spatial multiplexing based on polarization discrimination will be a key component at all frequency bands. The centimetric (cmWave) systems, however, will operate somewhere in between 4G systems and mmWave systems with regards to bandwidth and interference limitations. This means that cmWave systems will likely incorporate both the MIMO and beam forming technology elements found in 4G and mmWave systems.

Thirdly, with the small scale antenna arrays deployed in 4G systems at 3 GHz and below (for example, arrays with eight or fewer antenna ports) and two or four receive antennas at the user device, single user spatial multiplexing provides most of the gains available from spatial multiplexing on the downlink. With small scale arrays, multi-user spatial multiplexing provides little gain over single user multiplexing on the downlink. With large scale arrays below 3-6 GHz, multi-user MIMO will be required to provide significant gains over small scale arrays.

MU-MIMO is also important to boost spectral efficiency for carrier frequencies below 6 GHz by serving a large number of UEs on the same time-frequency resources, but spatially separated. Theoretically, the upper limit for the spectral efficiency is determined by the degrees of freedom provided by the massive MIMO array, the maximum number of concurrently scheduled UEs and the accuracy of the channel knowledge used to beam form multiple data streams. However, massive MIMO with MU-MIMO alone cannot tackle the interference-limitation typical for urban macro scenarios below 6 GHz. Nokia's view of the 5G system concept for below 6 GHz is based on the combination of cooperative network massive MIMO with a holistic interference mitigation framework for both intra-cell and inter-cell interference. With proper design of the system details, the possible gains are significant and therefore the novel channel estimation and reporting schemes are important enablers of higher spectral efficiency. The ITU target for IMT-2020 spectral efficiency is three times that of IMT-A and massive MIMO will be instrumental in achieving this – for some cases this can even be exceeded.

In contrast, for mmWave systems with large scale arrays, multi-user MIMO will not be a main emphasis due to the need to overcome power limitations. For cmWave systems, both single user and multi-user spatial multiplexing will likely be incorporated into the system design. Also, the higher the frequency band, the smaller the antenna size, and hence with cmWave systems and especially with mmWave systems, large scale antenna arrays will be relatively small compared to the smaller scale antenna arrays of current 4G systems.

Fourthly, with large scale arrays deployed at millimetric wave bands, obtaining channel estimates for each antenna will be difficult due to the inherent power and path-loss limitations. As a result, the MIMO/beam forming techniques at millimetric wave bands will initially operate with per-beam channel knowledge rather than per-antenna channel knowledge, which will necessitate significant changes in the PHY layer compared to current 4G systems. The difficulty with acquiring per-antenna information means user-specific beam formed demodulation reference signals (DMRS) will be used, rather than common reference signals (CRS). The lack of CRS improves energy efficiency, since pilots would be transmitted only when information is being transmitted. Also, the use of beam formed user-specific pilots adds flexibility for enhancing MU-MIMO performance.

Furthermore, the severe path loss limitations can be mitigated through the use of a beam-based air interface, where all signals are beam formed with high-gain, narrow beam width beams. In such a system, the common control channel can be transmitted in a broadcast manner by means of a beam sweeping process, where the control information is repeated on multiple narrow-beam width high-gain beams in a TDM or combination TDM/FDM fashion. The common control channel transmitted over a high gain beam would be completely self-contained and would include all the necessary synchronization signals for network entry and link maintenance and random access opportunities. The beam sweeping process for the common control would be repeated periodically and would also be used to update and track the best beam for a UE. Also, with large scale arrays deployed at the base station, there is the potential for deploying large numbers of antennas on a UE, especially at the centimetric and millimetric bands where the antenna sizes become rather small. UE beam forming can be combined with the beam forming at the base station to further improve coverage and capacity performance. A beam-based air interface can be also used to provide enhanced coverage, not just at the millimetric or centimetric bands, but also at the lower carrier frequencies, for example, below 6 GHz for deep in-building coverage.

Whereas massive MIMO is a good technique to improve both link spectral efficiency and coverage reliability, system spectral efficiency gains can be achieved by better utilization of radio resources. Interference rejection is one technique aimed at boosting system spectral efficiency. This works by replacing a well-known mechanism of coordinating inter-cell interference – for example, by trying to use the least interfered radio blocks in LTE or applying frequency reuse greater than one between neighboring cells - while accepting the interference and later suppressing it in the receiver. Interference rejection combining is already known and used in LTE and 5G is an opportunity to design a system optimized for using it. Another technique for optimizing spectrum utilization is dynamic TDD operation, which allocates the spectrum between the uplink and the downlink based on immediate traffic needs.

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Latency

Radio latency is the one-way transit time between a packet being available at the IP layer in either the device / RAN edge node and the availability of this packet at the IP layer in the RAN edge node / device. The relevance of latency is often overlooked by people focusing on achievable data rates, but with high latency, even the fastest connections cannot provide a good experience for interactive services. Furthermore, when the TCP protocol is used, high latency will also affect the achievable throughput.

One current example of a service that requires low latency is online gaming. However, in future, the pool of interactive applications will broaden very quickly as we see the rise of augmented reality, work and entertainment in the cloud, automated cars and remotely controlled robots. All of these applications require extremely low latencies for which a 5G system needs to be designed.

Reducing the radio latency is not only important for these interactive services but is also an enabler for high data rates and the overall responsiveness of the system. Achieving high data throughputs in networks with high latency means that transmitter buffers need to be large, increasing the device cost. Reducing the network latency means that buffers are emptied faster and hence can be smaller and cheaper. Also, the speed of all network procedures, such as system access or handover, relies on radio latency.

Reduced air interface latency and high data rates contribute to lowering the device's battery consumption. Fast transitions between sleep and active modes, micro-sleep within a frame when data is not transmitted or received, a short active time with high data rates and a low sleep mode power consumption all contribute to improving the energy efficiency of the device.

The latency of 4G/LTE is superior to that of 3G, but still inferior to what can be achieved with the wired Internet. One way to reduce radio interface latency is by using dynamic TDD with a short frame duration and an adaptive frame structure. Dynamic TDD involves different cells in the network employing different uplink-downlink TDD splits based on the traffic load for their cell. It is expected that the main mode of operation for 5G ultra-dense networks operating above 6 GHz frequency bands will be dynamic TDD. Dynamic TDD is attractive for use in 5G small cells as it assigns the full spectrum allocation to whichever link direction needs it the most. A TDD transceiver is also easier and cheaper to build than a FDD transceiver.

With some limitations in adapting the DL/UL allocation, dynamic TDD was already introduced in Long Term Evolution Advanced (LTE-A). However, the air interface latency of TDD LTE-A is limited by its physical frame structure. It is possible to include up to two uplink/downlink switching points inside one 10 ms radio frame, which sets the hard limit for the air interface latency. This is clearly not achieving the 5G radio layer latency target.

Evolutions of LTE-A will not be able to support major latency reductions due to the restrictions of incremental evolution. For example, changes in the numerology and frame structure design to enable reduced latency cannot be introduced for backwards compatibility reasons. The studies currently conducted in 3GPP on shorter TTIs (Transmission Time Interval) for LTE-A evolution are considering the possibilities to reduce TTI length up to one slot for LTE TDD and even shorter for LTE FDD, while maintaining backwards compatibility.

Consequently, a new 5G air interface is needed to enable the required physical layer latencies. A good frame structure candidate is one without any switching point restrictions so that any subframe can be either uplink or downlink, and in addition, the frame structure allows for bi-directional control signaling on the necessary basis. It is also possible to serve a direct device-to-device link or provide self-backhauling. A frame structure providing such flexibility is shown in Figure 2.

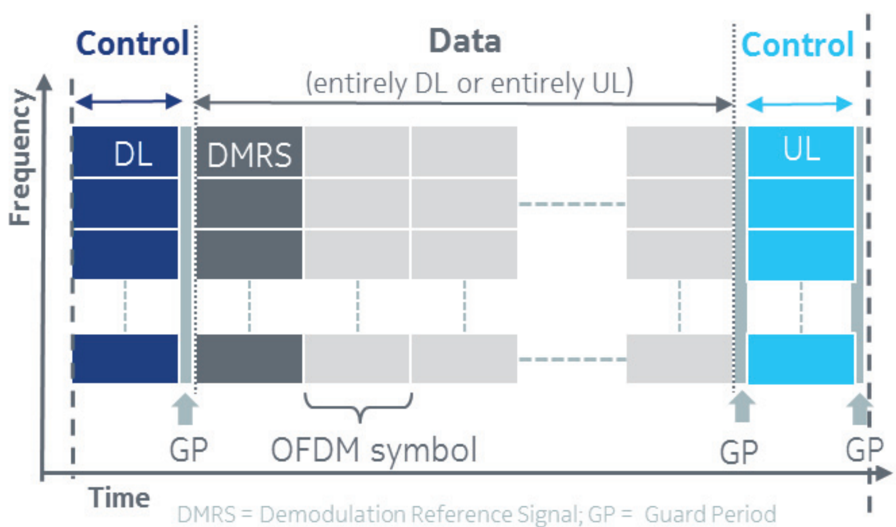

Fig. 2. A frame structure for flexible TDD

The frame length of one 5G Flexible TDD TTI is assumed to be some eight times lower, than LTE. This allows the overall latency target of 1ms to be met to satisfy new use cases such as automotive safety, the tactile Internet or real time control. Transmitting control signals first, followed by the data, allows the processing of the control information during reception of the data part. This pipeline processing is delay- and cost-efficient and fulfills the air interface delay requirement of 1ms, allowing high data rates and good overall system responsiveness. Further, the considered frame structure also supports the flexibility in the HARQ/scheduling latencies, which enables the efficient support of various 5G service scenarios and devices.

Flexible TDD access also means much better spectrum utilization, as the full bandwidth can be allocated to either link direction based on immediate traffic needs, and, with the right design, enables significantly reduced radio layer latency. Furthermore, using the same access technique for both uplink and downlink enables easy multi-hop, self-backhauling and direct device-to-device communication in a cost-efficient way. OFDM and cyclic-prefix single carrier, together with a TDMA component, offer good massive-MIMO and beam forming extension properties and a cost-effective implementation. These techniques will provide a high spectral efficiency and a maximum range, especially with higher frequencies, which allows more antennas in the same space.

Energy efficiency

The air interface and system solutions developed for 5G must be very energy efficient for devices in general and enable years of no-charge operation in support of low-cost wide-area Internet of Things applications. The 5G radio system must be designed with these requirements in mind, and will also benefit from dynamic TDD, particularly in the improvement to device battery consumption resulting from more efficient dormancy cycles.

As well as addressing device energy efficiency, 5G will be the first radio system designed to improve infrastructure energy efficiency, particularly important for reducing environmental impact. It would also be economically impossible to deliver larger and larger amounts of over-the-air traffic without a significant reduction in the energy per bit delivered. Furthermore, when considering ultra-dense network deployments, the power consumed by each base station can only be a small fraction of the power needed in the large wide-area macro base stations of today.

The lower transmit power used by small cells in ultra-dense deployments naturally brings down the power per base station compared to the wide-area base station. As an example, a modern pico cell base station consumes a few Watts or tens of Watts, whereas a large base station consumes several hundred Watts, but of course would also serve a hundred to a thousand times more users over a vastly larger geographical area.

The layered network architecture described below offers a good way to provide coverage and basic capacity with wide area base stations and additional capacity at hot spots when needed. When hot spot traffic requirements are low (for example, at night in a shopping mall or a business district), the small cell layers can be partially powered off and turned on again when needed. The need for such a feature has already been recognized and addressed with LTE Rel 12 small cell on-off switching and can be improved with 5G. An efficient air interface design (like dynamic TDD) that does not require constant transmissions on all carriers for detection purposes allows transmitters and receivers to be switched off even during the shortest instances of zero traffic. The effect of the transmit signal waveform on the power amplifier's power efficiency is another aspect to be considered, especially when looking at the upper end of the frequency range. This is because the high efficiency translates to both lower power consumption and better achievable coverage.

System integration

The ultra-dense network of the future will on average have only a few users per cell for which 5G requirements need to be fulfilled at any given time. However, users are expected to use a wide range of different services and applications with very different traffic requirements. Hence, the network needs to adapt flexibly to the traffic conditions in each cell. The small cell layer or layers providing capacity at above 6 GHz spectrum bands should have features such as dynamic TDD with short TTI and low-overhead frame structure, massive MIMO/beam forming with phased arrays and direct device-to-device links in order to achieve this adaptability.

The integration of the small cell frequency layer to the wide area layer, or, where there are multiple small cell frequency layers, the integration of different frequency layers, is essential for both efficient resource utilization and energy efficiency. Consider a network with a wide area coverage layer deployed at sub-6 GHz frequencies using several tens of MHz of bandwidth, a micro-cellular capacity layer on centimetric wave bands with 100-200 MHz bandwidth and an indoor capacity layer on millimetric wave bands with 1-2 GHz bandwidth. In the simplest case, the device would be connected to one layer at a time, depending on the coverage availability and the needs of the services used. However, in some cases, such as when needing extreme reliability with constant latency, a simple one-layer-at-a-time connectivity is no longer sufficient and a tighter co-operation between the layers is needed to improve the system performance.

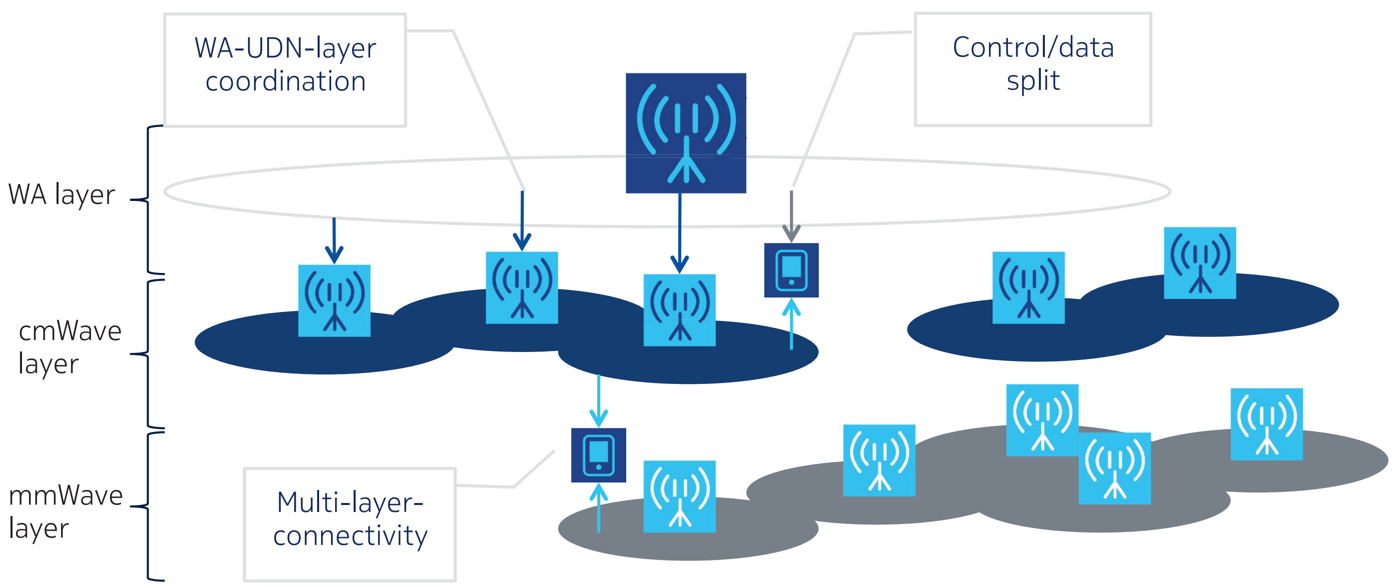

Fig. 3. Illustration of multi-layer 5G network

The wide area layer has the potential to act as the coordination layer, simply by directing the device's connection down to coordinating the scheduling of different cells in the small cell layer(s) for best use of resources. The wide area layer can also act as the signaling connection layer, maintaining control plane connectivity while the user plane is handed over to the small cells. This architecture gives advantages in terms of mobility and reliability, since the device has a fixed anchor point for a large area and the number of mobility events is greatly reduced.

Summary

5G will be an ultra-fast and ultra-versatile communication network including different technologies, but will be transparent for the end user and easy to manage for the operator. Additionally, 5G needs to address the predicted large increase in data traffic and will have to fulfill the capacity, data rate and latency requirements of next-generation devices.

To enable the capacity and data rate requirements for 5G, new spectrum bands are required, along with the massive densification of small cells. Ultra dense small cells will be a key element of 5G deployment and these small cells need to be deployed over a wide frequency range. Hence the design needs to be flexible enough so that the system could be deployed in bands ranging from 2 GHz up to 86 GHz. Both the centimetric and millimetric wave layers will support a set of common features such as dynamic TDD, massive MIMO/beam forming, device-to-device communications and a frame structure with low overhead and shorter frame size. Where the layers differ is on the use of moderate or high bandwidth, implementation of MIMO/beam forming schemes and interference co-ordination and mitigation schemes.

Moreover, flexibility is required to support a wide range of services and requirements. The network needs to support, for example, extreme reliability for critical communications, for example in vehicle-to-vehicle communications, but also very loose reliability requirements for low cost Internet of Things applications, such as reports from humidity sensors. High data rate machine-to-machine applications can be supported with cmWave or mmWave systems but low cost Internet of Things applications require low power, wide area networks. The selection of technology components for 5G needs to carefully consider the energy efficiency, as well as the cost of infrastructure and end user equipment.

The final challenge is to combine the vast variety of solutions for the many 5G use cases as well as multiple previous generation network layers into a uniform user experience with unified control of the network operation. Different layers of 5G will be integrated into one system together with other existing radio technologies and their evolution. All of these radio access layers will collaborate tightly with each other to ensure the best user experience.

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