Mobile and wireless communications Enablers for the Twenty-twenty Information Society-II

Report R3.1
Preliminary spectrum scenarios and justification for WRC Agenda Item for 5G bands above 6 GHz

Version: v1.0

2015-10-02

Report R3.1
Preliminary spectrum scenarios and justification for WRC Agenda Item for 5G bands above 6 GHz

Grant Agreement Number:	671680
Project Name:	Mobile and wireless communications Enablers for the Twenty-twenty Information Society-II
Project Acronym:	METIS-II
Document Number:	METIS-II/R3.1
Document Title:	Preliminary spectrum scenarios and justification for WRC Agenda Item for 5G bands above 6 GHz
Version:	v1.0
Delivery Date:	2015-10-02
Editor(s):	Rauno Ruismäki (NOK-T), Thomas Rosowski (DT)
Authors:	Thomas Rosowski (DT); Du Ho Kang, Sachin Sharma (ERI); Jian Luo (HWDU); Changqing Yang (HWHQ); Ingolf Karls (IMC); Ki Won Sung, Yanpeng Yang (KTH); Eiman Mohyeldin (NOK-N); Rauno Ruismäki, Mikko A. Uusitalo (NOK-T); Milos Tesanovic (SAM); Giovanna D'Aria (TI); Luis M. Campoy (TID).
Keywords:	5G, Spectrum above 6 GHz, WRC.
Status:	Final
Dissemination level:	Public

Abstract

This document presents technical aspects of 5G in spectrum bands above 6 GHz including e.g. spectrum demand, coverage provision and benefits of contiguous bands and aligned with METIS-II use cases.

Executive summary

The World Radiocommunication Conference 2015 (WRC-15) will recommend items to the ITU Council for inclusion in the agenda for the next WRC which will be held in 2019 (WRC-19). It is important that consideration of additional spectrum allocations to the mobile service and identification of additional frequency bands for International Mobile Telecommunications (IMT) is included in the WRC-19 agenda, aiming in particular at frequency bands above 6 GHz. The scope of this Report is to provide elements in order to update, consolidate, and reinforce results and findings of research projects (e.g., METIS), standardization groups and organizations (e.g., ITU-R) which have extensively investigated the need and opportunity of spectrum for 5G above 6 GHz.

The variety of 5G services, scenarios and use cases puts high demands on future mobile networks with regard to coverage, capacity and reliability, for which the availability of a spectrum amount of several GHz is required, to be sought in a combination of different suitable frequency bands in different spectrum parts in the whole range up to 100 GHz. An example in this Report with an assumed traffic increase of Extreme Mobile Broadband (xMBB) application 4K video up to 70 Gbps/km^2 in the year 2025 shows that additional bandwidth of at least 500 MHz per operator is needed if, as an example, the 10 GHz band is used. Another example presented in this Report shows that ultra-reliable Machine Type Communication (uMTC), also need similar bandwidths as xMBB, i.e. in the order of several hundreds of MHz due to the overall impact of latency and reliability requirements and the amount of devices at the same time.

The capacity of wireless networks can be basically increased by network densification, higher spectrum efficiency (e.g. multi-antenna techniques), and larger spectrum bandwidth. It is analyzed that these three elements are exchangeable in macro-cell environments. However, in dense networks, spectrum becomes the most effective solution for providing high capacity.

Contiguous spectrum bandwidth offer advantages with regard to device complexity, signaling, guard bands and interference.

The suitability of bands above 6 GHz in different scenarios is demonstrated by channel and propagation measurements. Due to the fact that building penetration depth strongly decreases with increasing frequency, the lower part of the spectrum between 6-30 GHz is suitable for outdoor to indoor coverage. Outdoor to outdoor mobile coverage, on the other hand, is worthwhile to be investigated across the full range of spectrum up to 100 GHz. For instance, channel and propagation measurements performed at 28 GHz have demonstrated the suitability of centimetric wave spectrum for outdoor mobile communications. Furthermore, current wireless technology implementations enable the use of millimetric waves, e.g. for ultra-high capacity P2P/low mobility applications in line of sight (LOS) conditions.

In summary it can be stated that additional spectrum in the order of several GHz is required to cope with the expected traffic demand of various use cases of 5G. In order to allow for an efficient service provision for all 5G scenarios, frequencies in the whole range from 6 GHz to 100 GHz should be investigated.

Contents

List of Abbreviations and Acronyms

3GPP	Third Generation Partnership Project
4G	Fourth Generation
4K	Resolution of 4096 x 2160 pixels
5G	Fifth Generation
5G-PPP	5G Private Public Partnership
BOM	Bill of Materials
BS	Base Station
CMOS	Complementary Metal Oxide Semiconductor
C-RAN	Centralized RAN
CSI	Channel State Information
dBi	Decibels (dB) relative to an isotropic antenna
dBm	Decibels (dB) referenced to 1 milliwatt
DL	Downlink
ECC	Electronic Communications Committee
EIRP	Equivalent Isotopically Radiated Power
EMF	Electromagnetic Field
FCC	Federal Communications Commission
Gbps	Gigabits per second
IEEE	The Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
ISD	Inter Site Distance
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
LNA	Low-noise amplifier
LoS	Line of Sight
MAA	Modular Antenna Array
MBB	Mobile Broadband
MIMO	Multiple-Input and Multiple-Output
mm	Millimeter
mMTC	Massive MTC
MTC	Machine-Type Communications
MWC	Mobile World Congress
NFV	Network Functions Virtualization
NLoS	Non LOS
P2P	Point-to-Point
PA	Power Amplifier
PAPR	Peak-to-Average Power Ratio
PDF	Power Flux Density
PPDR	Public Protection and Disaster Relief
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RF	Radio Frequency
Rx	Receiver
SAR	Specific Absorption Rate
SDN	Software-Defined Networking
SIG	Special Interest Group
SMT	Semiconductor Manufacturing Technology
TRS	Technical Rate of Substitution
Tx	Transmitter
UE	User Equipment
UL	Uplink
uMTC	Ultra-reliable MTC
W	Watts
WiGig	Wireless Gigabit Alliance
WRC-15	World Radiocommunication Conference, held in year 2015
WRC-19	World Radiocommunication Conference, held in year 2019
xMBB	Extreme MBB

1 Introduction

In order to ensure a smooth and successful introduction to the telecommunications market of 5G networks and applications, the adoption of a regulatory framework in line with technological progress and market requirements is of the utmost importance. For the telecom industry, one of the main regulatory areas is spectrum regulation.

The envisioned 5G/IMT networks will span a wider applications area than the current IMT networks and will accomplish 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.

Such new demands will mainly be achieved by the combination of three broad categories of improvements: more efficient technology, denser deployments, and increased availability of spectrum. The relative weight of each improvement category in fulfilling each usage and application demand depends on a number of factors deriving from that particular usage and application case. In particular, as to spectrum availability, it is foreseen that contiguous and broader channel bandwidths than available to current IMT systems would be desirable to support continued growth. At the same time, the benefits of spectrum harmonization should be strongly pursued to facilitate economies of scale, enable global roaming, reduce equipment design complexity, preserve battery life, improve spectrum efficiency and potentially reduce cross border interference [IMT-2083].

On a global scale, decisions on 5G spectrum are expected to be made in the World Radiocommunication Conference in 2019 (WRC-19). In order to assist the decision making at this conference there is a need to motivate well before WRC-15 (where the Agenda Items for WRC-19 will be decided) why additional spectrum should be allocated to mobile services and identified for IMT (5G) and also to estimate how much spectrum is needed.

METIS-II will provide rationale, justification and good arguments for the Agenda Item negotiations at WRC-15 and finally for WRC-19.

1.1 Objective of the document

Technical, market and usage related rationale is needed to justify why spectrum above 6 GHz is needed for 5G. Also, there is a need to show technical evidence and feasibility that mobile communication systems can be implemented in bands above 6 GHz.

This Report provides the overall view on future needs and usage scenarios, resulting in requirements for spectrum (including technical justification and rationale), combining information from the wireless industry as well as vertical industries. Spectrum scenarios describe the requirements and opportunities for enabling sufficient spectrum, whereas end user scenarios describe the end user needs. This Report builds on results from the spectrum work in the previous METIS project. The METIS results are re-evaluated and updated and aligned with METIS-II end user scenarios.

Results and findings of this Report intent to justify why an Agenda Item for 5G for bands above 6 GHz is needed at WRC-19.

1.2 Structure of the document

This Report is structured as follows:

5G services and use cases and their impact on requirements with regard to spectrum are considered in section 2. Spectrum demands for the 5G generic services xMBB and uMTC are elaborated from different perspectives in section 3. Existing technologies are looked into in section 4. Finally in section 5, technical studies related to 5G implementation in spectrum above 6 GHz are considered. The results and findings of this Report are concluded on in section 6.

2 5G services and use cases and their impact on spectrum

5G networks will support a wide range of applications with differing requirements with regard to connectivity. Thus, access to different spectrum bands with corresponding characteristics so as to address the requirements on coverage, throughput and latency is essential in order to maximize the efficiency in spectrum usage as well as to minimize operational expenditure. Although it is expected that additional bands for IMT will be identified at WRC-15 that will become available for mobile communications, it is evident that further spectrum is needed to enable the services described in the 5G vision, in particular to facilitate broadband access in very dense mobile traffic areas. Hence, bands at higher frequencies (i.e. above 6 GHz) which allow for wide channel bandwidths (e.g. 500-1000 MHz of contiguous spectrum per network) to support very high data rates and short-range mobile connectivity will be required. The increasing densification of mobile networks will also require associated backhaul solutions, including wireless backhaul solutions using in-band or out-of-band spectrum.

Generally, spectrum for 5G should be globally harmonized as far as possible in order to avoid technical complexity, both, in networks and in terminals.

2.1 METIS 5G generic services

The key design principle for the envisioned 5G systems is flexibility and diversity in order to serve diverse applications and usage scenarios. The system concept proposed by previous METIS project [MET15-D66] focused on three generic 5G services:

- **Extreme Mobile Broadband (xMBB)** provides both extreme high data rates and low-latency communications, and extreme coverage improving the Quality of Experience by providing reliable moderate rates over the coverage area.

- **Massive Machine-Type Communications (mMTC)** provides wireless connectivity for tens of billions of network-enabled devices. Scalable connectivity for an increasing number of devices, wide area coverage and deep penetration are prioritized over peak rates as compared to xMBB.

- **Ultra-reliable MTC (uMTC)** provides ultra-reliable low-latency communication links for network services with extreme requirements on availability, latency and reliability, e.g. V2X communication and industrial control applications.

In Figure 2-1 an illustration of 5G generic services is depicted.

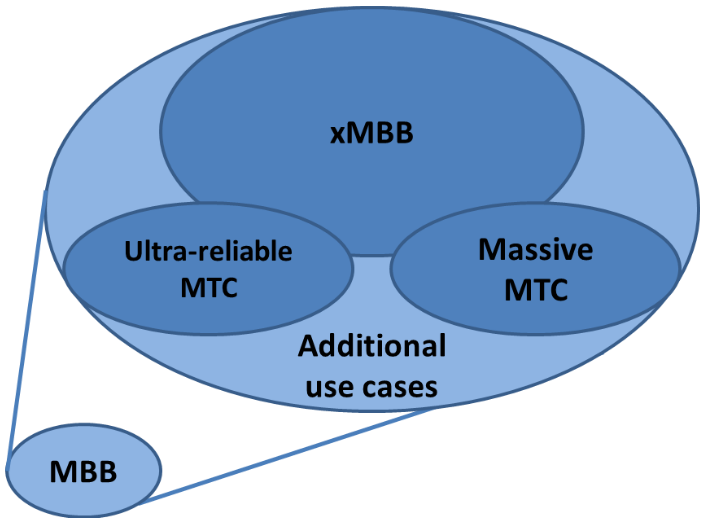

Figure 2-1: Development from today's MBB services to the beyond-2020 mix of xMBB, uMTC and mMTC. Additional use-cases enabled by 5G systems are to be expected.

2.2 METIS-II 5G use cases

In order to keep the simulation efforts within a reasonable framework, the intention is to span the relevant 5G space with a low number of use cases. Thus, METIS-II has selected five use cases that will be analyzed in detail during the project term. These use cases are four METIS Test Cases, two of them supplemented by NGMN use cases, and one NGMN use case supplemented by a METIS Test Case. With these five use cases all three generic services (xMBB, uMTC, mMTC) are addressed.

An overview of the METIS-II 5G use cases, including the generic service(s) these use cases belong to, is given in Figure 2-2. Furthermore, the scopes in terms of requirements and services are stated as well as the use case origin.

	Use case	Scope of Requirements (Network/User Perspective)	Scope of Services (Service Perspective)	
xMBB mMTC	Dense Urban Information Society	Experienced user data rate / Traffic vol. per subscriber / Nb. of users & devices / Energy efficiency	Broad range of communication services covering needs related to both indoor and outdoor urban daily life (excl. office and factory)	*METIS-I UC enriched by NGNM Mobile Video Surveillance UC*
xMBB	Virtual Reality Office	Experienced user data rate/Traffic volume per subscriber/ Latency	Broad range of communication services in in the (indoor) office context	*METIS-I UC*
xMBB	Broadband Access Everywhere	Experienced user data rate / Availability / Mobility / Energy efficiency	Full coverage topic addressing outdoor/indoor communication needs especially in rural areas	*NGNM Use-Case 50+ Mbps everywhere incl. METIS-I Blind Spot TC*
mMTC	Massive Distribution of Sensors and Actuators	Availability / Number of devices / Energy efficiency	Broadest range of IoT services covered	*METIS-I UC Massive Deployment of Sensors and Actuators*
xMBB uMTC	Connected cars	Latency/ Reliability / Mobility	Strong expectation from the (automotive) industry Belong to the first uMTC services expected to be commercialized	*METIS-I UC on traffic efficiency and safety completed by MBB aspects*

Figure 2-2: METIS-II 5G use cases.

The requirements of the METIS-II 5G use cases concerning spectrum can be roughly categorized into three main groups:

- **Capacity** to cope with high traffic per cell / area, including large contiguous spectrum → high bandwidth.
- **Coverage** to ensure the availability of 5G everywhere → lower frequencies.
- **Reliability** to fulfil the demands of critical services, requiring stable and predictable operation conditions → dedicated spectrum.

The relationship – focusing on the main KPIs – between the METIS-II 5G use cases and the three categories is illustrated in Figure 2-3.

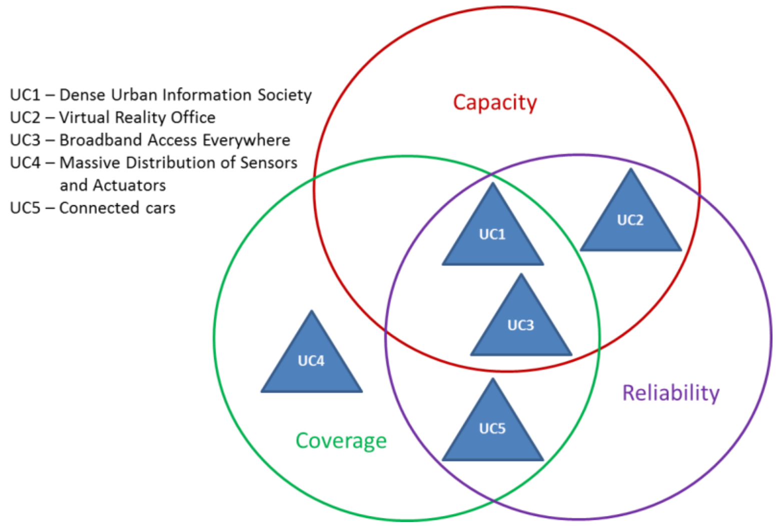

Figure 2-3: Relation between METIS-II 5G use cases and categories.

These relations highlight the need for a combination of different suitable frequency bands for 5G network operation.

2.3 5G spectrum considerations of spectrum above 6 GHz from METIS and ITU-R

2.3.1 Initial spectrum considerations from the studies in METIS

In [MET13-D51] and [MET14-D53] initial investigations on spectrum opportunities for 5G systems were undertaken. The performed inventory was European centric. Material used as reference comprised the ITU Radio Regulations 2012 (for regional frequency allocations), ERC Report 025 (for European National frequency allocations), ECC Report 173 (Fixed Service in Europe) and available non-European information (e.g. from FCC and China). The assessment took into consideration the physical propagation conditions of the bands and evaluated the possibilities to coexist with existing services in the bands.

Spectrum in the range 5.925-31 GHz is important to leverage on more suitable propagation conditions for outdoor deployments. Thus a second study was carried out with a lower requirement on minimum contiguous bandwidth, and focus was given to outdoor deployments [MET14-D53]. This smaller target bandwidth significantly increases the opportunities of finding suitable spectrum bands in the range 5.925-31 GHz.

Spectrum opportunities for terrestrial mobile 5G were identified in different bands within the frequency range 6-95 GHz, although the overall spectrum amount was larger in higher frequency bands than in lower ones. This is partly a consequence of the propagation conditions, i.e. the increased isolation between co-existing systems in higher bands. It is also a result of the applied search criteria, in particular by focusing on very wide bands of contiguous spectrum. There may be other search criteria that would lead to different results.

2.3.2 ITU-R Report on "Technical feasibility of IMT in bands above 6 GHz"

This ITU-R Report [IMT-2376] investigates the technical feasibility of IMT in the frequencies between 6 GHz and 100 GHz. It is based on studies carried out by a large number of ITU-R sector members in different organizations globally.

The theoretical assessment, simulations, measurements, technology development and prototyping described in this ITU-R Report indicate that utilizing the bands between 6 and 100 GHz is feasible for those IMT deployment scenarios described in the ITU-R Report.

In particular, the ITU-R Report collects measurement data on some examples and reference points in ranges from 10 GHz to above 70 GHz in several different environments and refers to a number of other publications on the matter. Both, LoS and NLoS as well as outdoor-to-indoor measurement cases have been studied in this ITU-R Report. Further, several different deployment scenarios for systems operating in the frequencies between 6 and 100 GHz have been envisioned and some of these simulated for performance. Generally the results are as expected; the lower bands have better propagation characteristics for coverage and outdoor-to-indoor penetration, whereas the higher bands are useful for outdoor hot-spot and indoor deployments but with relatively poor outdoor-to-indoor penetration capabilities.

3 Aspects related to spectrum demand for 5G

3.1 xMBB service aspects

The spectrum scenarios requiring the highest available bandwidth are associated to xMBB generic services, as analyzed in [MET14-D53], due mainly to the high data rate individually associate to each User Equipment (UE), and also to the high density. The final value of the required bandwidth depends on:

- Targeted objectives, in terms of percentage of users with different service level achievements, accordingly with the different quality class specified for them.
- SINR achievable in each BS-UE links involved in the communication. This of course will depend on:
    - The radio propagation characteristics of the environment considered
    - The transmitted power of all transmitters involved in the radio communication
    - The physical location of UEs and BS. Taking into account that the number of BS (density of deployment) is one of the key factors impacting the economic suitability
- Spectral efficiency associated to BS-UE radio link
- Spectral efficiency increase associated to the coordinated action of several BS in the coverage area
- Traffic pattern associated to the UE service

There are then three parameters which need to be coordinated to provide the required QoS, available BW (shaped by regulation), system spectral efficiency (limited by physical laws) and network deployment density (limited by cost). It should be taken into account that there is a market pressure for 5G to reduce exploitation costs, in order to match the consumer willing to pay for new 5G services /performances. Increasing the density of network accesses should not come at high unsustainable cost (including backhaul, energy, complexity for interference management, etc.)

The ITU-R document [IMT-2083] is targeting individual peak data rates greater than 10 Gbps for the xMBB services. Since the efficiency of new deployments is decaying in ultra-dense environments (as shown in [MET14-D53]), and the envisioned limits of spectral efficiency achievable, this data rate value could only be achieved with the use of several hundred MHz bandwidth.

This vision is also shared with 4G Americas [4G-AME], which is proposing that spectrum license blocks in the order of several hundred MHz per operator should be made available, with the stipulation of accommodating multiple operators per band. Adding that, sufficient bandwidths of several GHz should be made available for 5G at WRC-19 in frequency bands of 6 GHz and above.

Results of studies estimate the total global spectrum for IMT to be in the range of 1340 (for lower user density settings) up to 1960 MHz (for higher user density settings) for the year 2020 [ITU-2290].

3.2 Spectrum bandwidth demand analysis for the xMBB application 4K video

Video services are identified as one of the key drivers of MBB traffic in the future [ERI14]. In this section, the spectrum demand in the 6-30 GHz range is assessed by system-level simulations for an example scenario of 4K video. In this analysis, the lower part of 6-30 GHz frequency range is focused on for future spectrum demand and existing frequency ranges below 6 GHz are also included as baseline spectrum.

For the simulation, the xMBB traffic demand is extrapolated for the year 2025 based on [ERI14] with 25% penetration of video users. It is assumed that 4K video is used over 3 hrs per evening. Data rate requirement per video user is gradually increasing from 2 Mbps up to 25 Mbps from 2015 to 2025 resulting in 60-70 Gbps/km^2 at the end of that period. Each macro site has 1500 subscribers both indoors and outdoors.

Existing cellular bands at 2.6 GHz and 3.5 GHz are included for this evaluation purpose. In total 160 MHz downlink bandwidth below 6 GHz is assumed to be available for a given operator, noting that this is considerably more than what is currently available in these bands. The lower part of 6-30 GHz range is aggregated for expanding system capacity and coverage and is for simplicity assumed to be operated at 10 GHz in this example evaluation. As traffic demand increases, a macro network is densified with an increase in bandwidth above 6 GHz to meet the future traffic demand. A generic low-rise building scenario similar to a typical European city is chosen. A 3D ray tracing based propagation model is used for spectrum above 6 GHz which explicitly models both, diffraction and reflection. Carrier aggregation is implemented to jointly serve traffic from multiple frequency ranges. High gain beamforming with multiple antenna arrays is used.

Figure 3-1 illustrates traffic demand increase per area for the xMBB application 4K video until 2025. It is determined (see Table 3-1) that from 2025 each operator needs at least 500 MHz bandwidth in the lower part of 6-30 GHz (at 10 GHz in this example evaluation) in order to cope with the spectrum demand for xMBB 4K video.

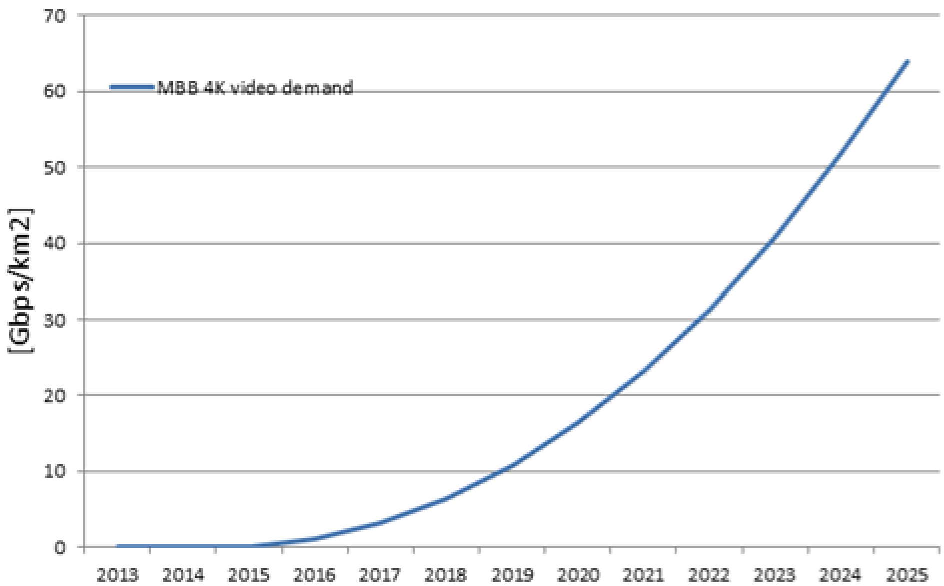

Figure 3-1: xMBB 4K video traffic estimate used for the simulations.

Table 3-1: xMBB 4K video bandwidth demand.

Year	Gbps/km^2	Spectrum bands used in the simulation	Bandwidth required for the DL
2015	2	2.6 GHz, 3.5 GHz	80 + 80 MHz
2025	60-70	2.6 GHz, 3.5 GHz, 10 GHz	80 + 80 + 500 MHz

3.3 Relative effectiveness of spectrum for xMBB services

In the previous section, spectrum requirements with specific network deployment scenarios have been illustrated. This section will depict a more general picture of the spectrum demand. As aforementioned, a general consensus is that three fundamental ingredients are available for increasing the capacity of wireless networks: densification of networks, better transmission technology, e.g., multi-antenna techniques, and more spectrum bandwidth. Different from the first two elements necessitating infrastructure investment, spectrum is considered a virtual resource. Thus, the question of "how much spectrum is needed for future xMBB" should be looked into in the context of "how effective spectrum is compared with infrastructure investment."

The relative effectiveness of spectrum can be measured by technical rate of substitution (TRS), a concept from microeconomics [VAR10]. TRS is defined as the rate at which a firm will have to substitute one input for another in order to keep the output constant. Suppose that we have two factors, e.g., spectrum bandwidth and BS density, and are operating at some point (W, λ_b) with the output of experienced user data rate r_a. Consider a change in W and λ_b while r_a remains constant:

$$r_a = f(W, \lambda_b) = f(W + \Delta W, \lambda_b + \Delta\lambda_b)$$

Then the TRS of the factor 1 (spectrum bandwidth) with regard to the factor 2 (BS density) at the point (W, λ_b) is defined as

$$TRS(W, \lambda_b) = |\frac{\Delta\lambda_b}{\Delta W}|$$

which indicates the substitutability of spectrum bandwidth. If the TRS of W is low, it means that spectrum can be replaced by more BSs. Higher value for TRS of W indicates that the densification of BSs is less effective than increasing spectrum bandwidth at the particular operating point.

Similar analysis can also be performed between the spectrum bandwidth and the number of antennas per BS. Let M denote the number of antennas that each BS has. Then, the TRS of spectrum with regard to multi-antenna is given by

$$TRS(W, M) = |\frac{\Delta M}{\Delta W}|$$

Likewise, spectrum and multiple antennas are equivalently effective under low TRS of W, and spectrum should be preferred when TRS of W is high.

Table 3-2 and Table 3-3 provide TRS of spectrum bandwidth in regard to antenna number and BS density, respectively. Two types of deployment environments are considered, namely sparse and dense deployment.

- Sparse: the density of active user at an instantaneous moment is higher than the BS density. Therefore, the users have to share BS's radio resource. User data rate of 15 Mbps is set as a requirement.
- Dense: the density of active user at an instantaneous moment is lower than the BS density. Therefore, the users most probably receive exclusive services from their own BSs. User data rate of 420 Mbps is considered to be a requirement.

Note that the active users account for only a fraction of total subscribers, and the portion depends on the daily usage pattern of the users. Also, note that the TRS values have been normalized by the lowest value in each table. Thus, the absolute values do not carry a meaning. Rather, relative comparison of the TRS values should be considered meaningful in each table. Further details of the numerical experiments are available at [YS15].

Table 3-2 shows that TRS keeps increasing as the BSs employ more antennas. This means that adding more antennas is getting less and less effective when multiple antennas are already used. Therefore, spectrum acquisition becomes a more preferred option for multi-antenna wireless networks. The same trend is observed for both sparse and dense environment.

The relationship between the spectrum and the BS density is more extreme. See Table 3-3. In the sparse regime, TRS increases as with the BS density, but the increment is modest. An interpretation of the result is that the densification of BSs is a conceivable option in the sparse regime although its effectiveness diminishes. On the contrary, in the dense regime, the TRS skyrockets with the increasing BS density. We can conclude that the further densification of already dense network is not effective at all. Then, the spectrum will be the only solution to fulfil the requirement of xMBB services.

Figure 3-2 gives a hint on how to cope with increasing service requirement in the dense deployment regime. Suppose that a wireless network needs to provide twice user data rate than the basic service of 420 Mbps. The figure shows the densification-spectrum indifference curves, i.e., combinations of the bandwidth and the BS density satisfying the old and new requirements. The curves become almost parallel as the BS density increases. This means that it is nearly impossible to increase the user data rate with the densification alone. On the contrary, acquiring more bandwidth is always effective.

In summary, spectrum and the other two elements are exchangeable in the current macro networks with single or few antenna configurations. However, the densification of infrastructure continues losing its merit, and the spectrum becomes the most effective solution for providing the xMBB services in dense wireless networks.

Table 3-2: TRS between spectrum and antenna number.

Sparse	M=1	M=4	M=8	M=16
$\lambda_u = 100$ $\lambda_b = 10$ $R_a = 15Mbps$	1.0	6.7	18.7	49.7
Dense	**M=1**	**M=4**	**M=8**	**M=16**
$\lambda_u = 100$ $\lambda_b = 1000$ $R_a = 420Mbps$	1.5	9.7	23.6	57.2

Table 3-3: TRS between spectrum and BS density.

Sparse	$\lambda_b = 1$	$\lambda_b = 5$	$\lambda_b = 10$
$\lambda_u = 100$ $R_a = 15Mbps$	1.0	15.0	55.6
Dense	$\lambda_b = 100$	$\lambda_b = 500$	$\lambda_b = 1000$
$\lambda_u = 100$ $R_a = 420Mbps$	145.8	4370.6	11643.3

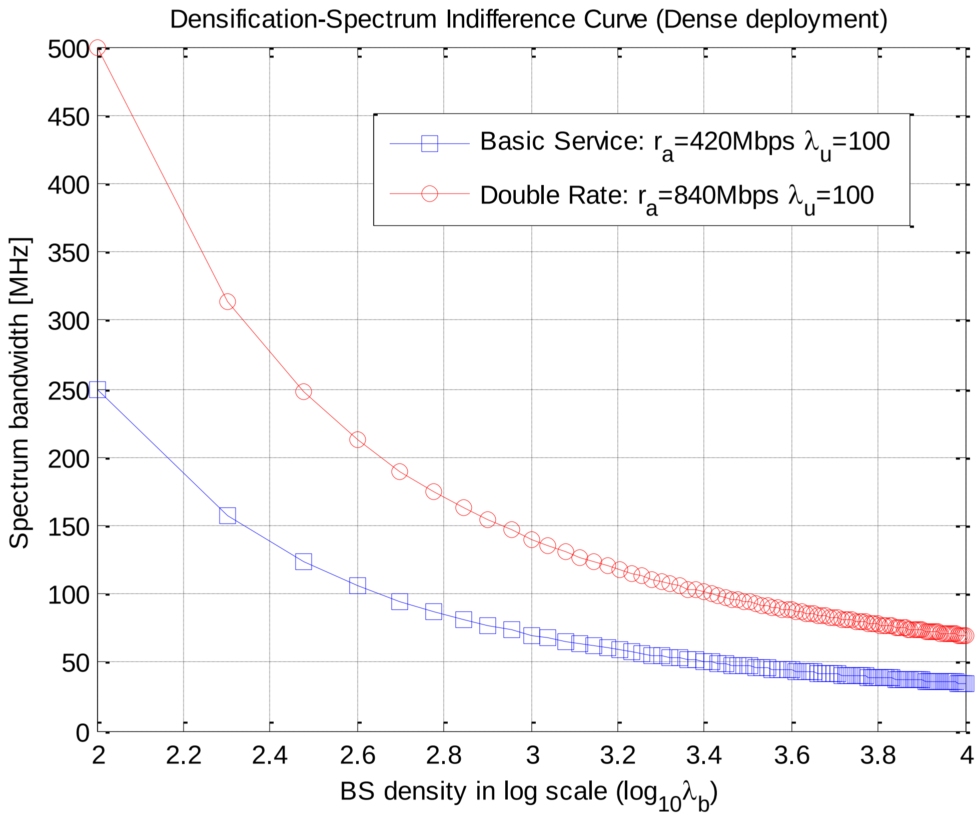

Figure 3-2: Relation between spectrum and BS density (M=1).

3.4 Spectrum bandwidth demand analysis of uMTC services

xMBB is not the only usage type requiring a large amount of spectrum bandwidth. uMTC services can also demand orders of magnitude higher bandwidth than today's MTC applications depending on the extent of requirement on ultra-high reliability and ultra-low delay. Of particular interest is remote tactile interaction, or tactile internet, including remote surgery, remote driving, factory automation, virtual reality, and many other use cases [ITU-1432], [MET15-D15].

The tactile internet applications typically require end-to-end delay of less than one millisecond (1 ms), which translates into the radio interface delay of 0.2 ms or less. They also require extremely high reliability particularly for life-critical services such as remote surgery.

Spectrum demand for remote tactile applications can be characterized by several parameters as listed below.

- Radio interface delay requirement (D_{req}): It depends on the network architecture and user interface. When the communicating nodes are far away from each other, radio interface delay should be lower to compensate the transport delay. Note that light travels

300 km during 1 ms. User interface delay should also be deducted from the total delay budget of 1ms.

- Access probability (p_a): When there are multiple nodes contending for the radio resource, random access delay or scheduling delay should be considered. It can be modelled by access probability for simplicity.
- Packet size (L_{pkt}): The size of packet largely depends on the application type. A few bytes would suffice if only control messages are to be delivered, for example, for an automated factory. However, much larger packet size would be needed to deliver real-time image for, e.g., remote surgery and virtual reality.
- Baseband Spectral efficiency (S_{eff}): It is a function of modulation order and coding rate employed for the transmission. Since some of the remote tactile applications have very high reliability requirement, low-order modulation and high-rate coding may be needed in order to combat fading effects.

Let (W) denote the required spectrum bandwidth for a remote tactile application. Then, it can be expressed as below in a simplistic manner.

$$W = \frac{L_{pkt}}{P_a S_{eff} D_{req}}.$$

Table 3-4 shows two different but plausible set of requirements and their corresponding bandwidth demands. Example 1 represents a tactile game between friends in the vicinity of each other. Relatively larger radio interface delay is allowed, and control message are mostly to be delivered in a favorable propagation environment. Even less than the bandwidth of 1 MHz would be enough to run such a service. On the contrary, Example 2 depicts a remote manipulation of a machine/vehicle with real time vision and sound. Packet size is thus bigger, and low-order modulation should be used to allow for a fading margin. There could be a contention for radio resource if there are several machines. Then, bandwidth demand approaches several hundreds of MHz in this case due to the overall impact of latency and reliability requirements and the amount of devices at the same time.

Table 3-4: Examples of bandwidth demand for uMTC services.

Parameters	Example 1	Example 2
Radio interface delay (D_{req})	200 µsec	100 µsec
Access probability (p_a)	50%	10%
Packet size (L_{pkt})	10 Byte	1000 Byte
Baseband Spectral efficiency (S_{eff})	5 bps/Hz	1 bps/Hz
Bandwidth demand	**160 kHz**	**800 MHz**

In summary, there would be a variety of uMTC applications requiring extremely low delay and high reliability in the future. Although the average data volume seems to be much lower than that of xMBB, the nature of the service requirements can demand very high instantaneous data rate. It is possible for some uMTC applications to require spectrum bandwidth of 1 GHz or even more.

4 Existing technologies above 6 GHz

4.1 Field trial at 28 GHz

Debilitating path loss in bands above 6 GHz can render any communication impossible if it is assumed that the antenna aperture decreases with decreasing wavelength (i.e. increasing frequency), such as a standard half-wave dipole. If the antenna gain is increased through smart antenna techniques, which are additionally more easily implementable on small surface areas at higher frequencies, then this effect can be successfully combatted. Additionally, advances in HW detailed below coupled with inventive hybrid beamforming techniques [PK11] have produced functioning hand-held solutions [R14].

More specifically, a prototype of a beamforming antenna at the 28 GHz band has recently been developed [R14], [SAM15]. The prototype antenna is comprised of 48 antenna elements arranged in the form of a uniform planar array with eight horizontal and six vertical elements, confined within an area of 45 mm by 42 mm. Based on a 58 dBm EIRP limit, satisfactory communications links were attained even in non-line-of-sight scenarios more than 200 meters away. Thus, enhanced coverage solutions may prove necessary in some deployments, including optimized cell deployment, inter-cell coordination, relays, or repeaters. The test-bed in question revealed a potential antenna array architecture that provides simultaneous flexibility in form factor choice, beam steering, and high array gain in a cost-effective manner. This architecture involves constructing modular, composite antenna arrays [R14].

The RF components for this band have been developed on a prototype basis to conduct 28 GHz trials. Similarly adaptive antenna systems and beam-forming algorithms/components have been developed. 1.2 Gbps data transmission was achieved at user speeds of just over 100 km/h. Considering the commercial availability of satellite and Local Multipoint Distribution System (LMDS) wireless components in this band, it will not be a huge challenge to produce mobile cellular components in this frequency range. Key HW achievements are the development of cost-effective implementations of Silicon-based CMOS nano-scale process under 100nm, widespread availability of GaAs Monolithic Microwave Integrated Circuits, or MMICs, and improved reconfigurable phased antenna arrays.

4.2 WiGig at 60 GHz

WiGig delivers a first example of a wideband system with 2 GHz bandwidth, deploying modular antenna arrays (MAA), power amplifiers (PA), low noise amplifiers (LNA) etc. Given its similarity of expected operation modes across the millimetric wave spectrum, it is anticipated that technologies like WiGig can be re-applied in other millimetric wave bands, supporting bandwidths from less than 100 MHz up to 2 GHz. But it has to be stated that many of the system components used in WiGig systems must be re-banded and re-designed to operate in other than 60 GHz millimetric wave bands. This has to be accomplished at bill-of-materials

(BOM) costs affordable for mobile devices. So the readiness of electronic components, antenna designs, and affordable cost of deployment will be crucial for successful commercial systems.

For outdoor operation a maximization of inter-site distances (ISD) typically between 100-200 m shall be accomplished to minimize deployment costs assuming that successful link budgets can be achieved for all millimetric wave bands. Overcoming these link budget challenges will involve the development and deployment of multi-element modular antenna arrays (MAA) providing sufficiently large beam forming gains. In addition this allows advanced spatial multiplexing techniques like single-user and multi-user MIMO as well as massive MIMO to get implemented. To meet cost, volume and power constraints, antenna-on substrate array implementations will be key for MAAs. Technical challenges are the reduced captured energy at the antenna subsystem due to millimetricic wave and the wider bandwidth with increased noise ingress and lower total SNR compared to microwave. WiGig shows that both challenges can be met by using a MAA including small 16, 32, 64 element arrays and beyond, arranged in horizontal rows/vertical columns, and possibly realizing polarization diversity at both the transmitter and receiver. From the first experience of WiGig products, it is anticipated that the realization of such arrays is technically feasible.

There will be significant indoor deployments (stadiums, public transportation centers, shopping malls etc.), where the widespread use of beam forming shall minimize inter-cell and intra-cell interference resulting in deployments to be thermal noise-limited rather than interference-limited. Together with significant penetration losses between outdoor and indoor deployments there will be substantial isolation between individual cells and between individual deployments. Therefore these self-contained, localized millimetric wave access networks could be seen in strong relationship with the roll out of software defined networks (SDN) and network function virtualization (NFV). The deployment of both indoor and outdoor base stations utilizing millimetric wave bands will not just be for access but also for back- and front haul.

4.3 E-band (71-76/81-86 GHz) equipment

There are already a number of RF components and chips available for the E-band. Examples include the 40 nm CMOS direct transmitter [ZR14] and the E-band Doherty power amplifier [KZR14], the 90 nm CMOS transceiver at 77 GHz [MOH10], and the SMT-ready E-band radio frontends [INF14,INF15].

Furthermore, multiple demonstrations have been conducted on E-band transmissions. One demonstration is the E-band trial with the RTN 380 [HW13]. The trial has been carried out with sites in LoS with a common hub in the outdoor scenario. The aim of the trial was to investigate the performance of the E-Band technology. In addition, ITU-R propagation models have been also investigated by using the weather information retried during the trial.

Another demonstration is the 100+ Gbps transmission in the 71-76 GHz and 81-86 GHz bands at Mobile World Congress (MWC) 2014 [HW14] in indoor scenario. This is a 5G prototype which utilized a novel transceiver architecture operating on the 70-90 GHz spectrum band, as well as advanced transmission technologies, especially, multi-antenna precoding technology. The prototype demonstrated that it could overcome out-of-band emission leakage for flexible spectrum utilization, while also reducing peak-to-average power ratio (PAPR) for improved energy efficiency, which allows for longer terminal battery life.

5 Technical aspects of 5G in spectrum above 6 GHz

5.1 Mobile coverage provisioning in different frequency ranges

In this section, 5G mobile coverage is analyzed in the frequency range 1-100 GHz. As shown in Figure 5-1, the considered scenario mainly focuses on the outdoor to indoor case which is one of the most challenging situations due to expected high building penetration loss in high frequency ranges. Indoor coverage is provided by a macro base station deployed above rooftop. Two analyses are provided for this scenario. First, in Section 5.1.1, no practical limits are assumed for antenna gain, transmit power and Electromagnetic Field (EMF) exposure, which give us the best possible outdoor to indoor coverage of using spectrum above 6 GHz. Then, in Section 5.1.2, these limits are briefly discussed and considered in the analysis, as well as other more realistic assumptions.

5.1.1 Ideal macro-cell coverage analysis

The considered scenario, illustrated in Figure 5-1, has the above rooftop base station 150 m away from the intended user. NLOS conditions prevail and diffraction loss from rooftop to street level user is added on the top of free space path loss. Coverage is provided to a depth of 10 m into the building. The building penetration loss of different materials has very different frequency-dependencies. Buildings with exteriors composed of multiple materials are introduced further variability. Two frequency dependent models representing a modern office building with high loss metal coated glass and an older office building with untreated windows are used to span some of the range [SHF+14]. Table 5-1 summarizes the assumed key parameters such as maximum transmit power, available antenna area, and solid angle to cover.

Table 5-1: Key parameter assumptions for the macro-cell BS

Max. transmit power [W]	Antenna area [m^2]	Solid angle to cover	Distance from BS [m]	Coverage type
40	1 x 0.1	120° x 10 °	150	NLOS, outdoor to indoor

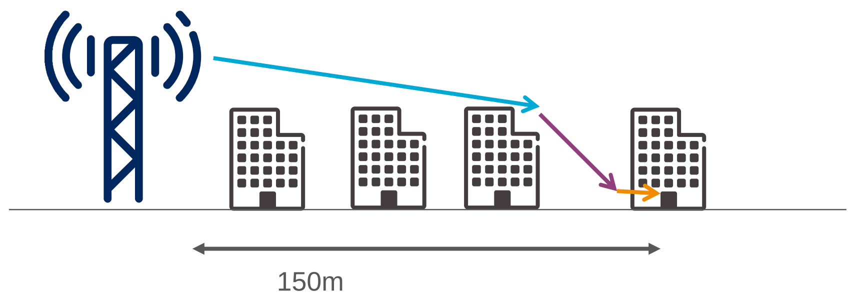

Figure 5-1: Outdoor to indoor coverage analysis for 5G spectrum.

In this study, the antenna gain will increase as a function of frequency due to the increased directivity as shown in Figure 5-2. It is assumed that there are no practical limitations on antenna gain.

Another aspect of high gain beamforming is mobility. Even if such CSI is available at Tx and Rx allowing optimal beamforming, finding and tracking the optimal beams due to Tx and/or Rx mobility would become increasingly challenging with smaller beamwidths in higher frequency ranges. The use of antenna beamwidths that are smaller than the angular extent of the intended coverage area requires beam steering and tracking functionality. A high number of beams, in particular if needed at both Tx and Rx, would necessitate very advanced algorithms to maintain communication in a non-static scenario, which increase complexity and costs. The relationship between frequency and the number of beams needed to cover an area is illustrated in Figure 5-3.

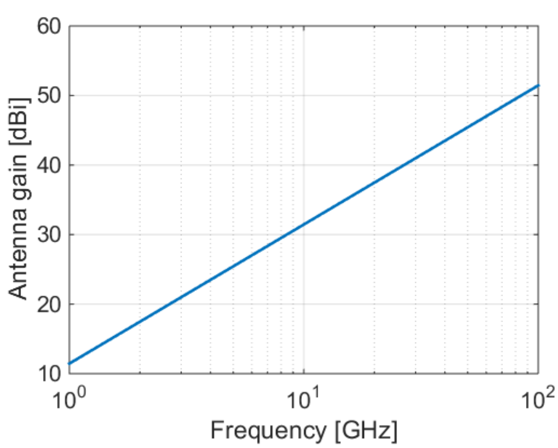

Figure 5-2: Assumed ideal beamforming gain for a fixed antenna area.

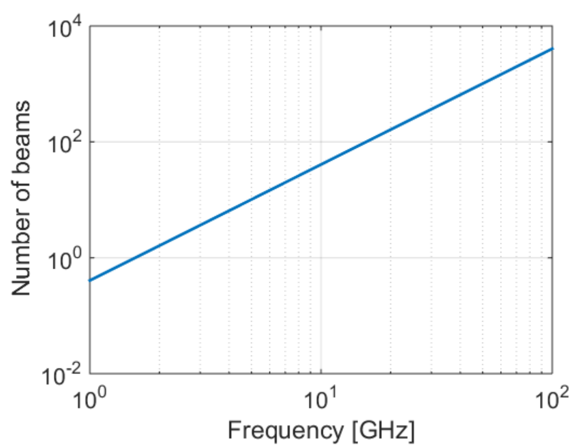

Figure 5-3: The number of beams needed to cover cell area of interest.

Figure 5-4 illustrates the DL received power from the macro-cell BS as a function of frequency. The received RF power for the low loss building case first slightly increases and then rapidly decreases from a certain frequency. For the high loss building, it always decreases over frequency although ideal antenna gain is assumed. Based on this, Figure 5-5 provides the rough estimate of downlink cell coverage. The received power relative to 1 GHz is used to calculate a relative cell range assuming exponential path loss dependence. This indicates that the network densification required to compensate the excessive propagation loss also grows quickly after a certain frequency.

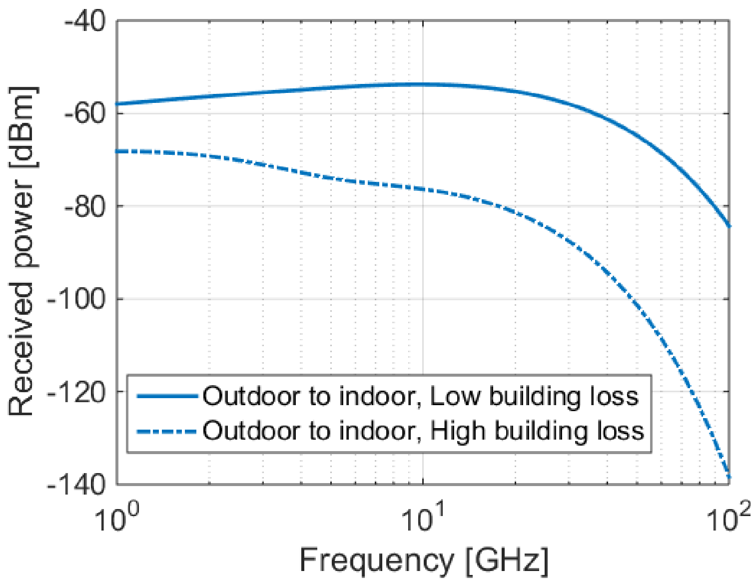

Figure 5-4: Downlink received power at cell edge versus frequency. Received power decreases even with ideal antenna gain after a certain frequency range.

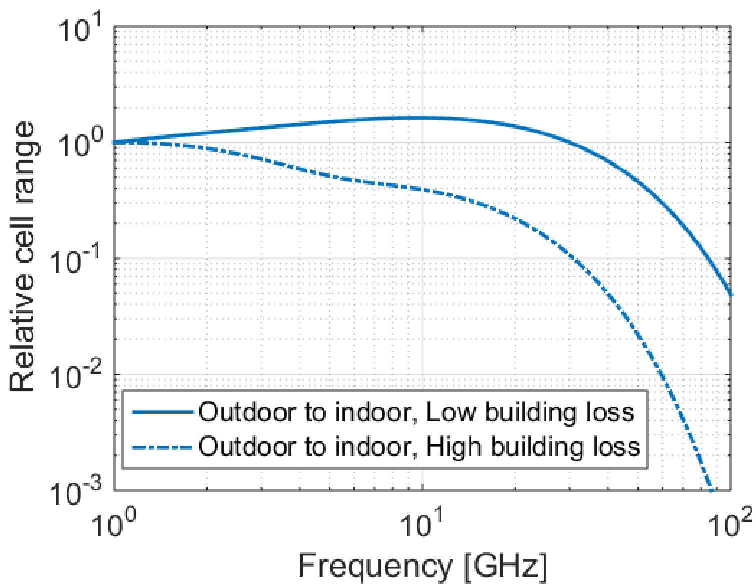

Figure 5-5: Downlink cell range versus frequency. This indicates that network densification required to cover the area grows with increasing frequency.

5.1.2 Macro-cell coverage analysis with practical limits and assumptions

Practical limitations on antenna gain and transmit power, and regulatory limitations on EMF exposure have direct impact on the Equivalent Isotopically Radiated Power (EIRP), a key parameter for the coverage range.

Antenna gain

Antenna gain in high frequency ranges is one of active research areas which still need further investigations. Nominally this gain increases with the square of the frequency. However, as the lobewidth decreases at the same rate, it becomes increasingly challenging to utilize the full gain in practice. The angular spread in the channel puts a limit to the achievable antenna gain unless coherent channel state information (CSI) is available.

In the analysis, the achievable antenna gain has been capped at 30 dBi at the base station and 20 dBi at the terminal, as shown in Figure 5-6.

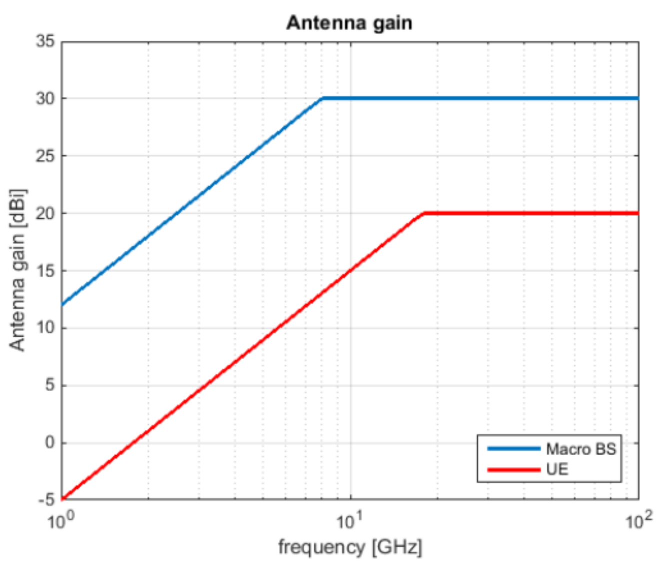

Figure 5-6: Antenna beamforming gain for a fixed antenna area: Extremely high antenna gains may not be achievable due to challenging management of antenna beams.

Transmit power

Transmit power levels at frequencies above 6 GHz can be considerably reduced compared to transmit powers of current cellular networks. The main reason for that is the poor efficiency of power amplifiers for high frequencies. Without techniques as linearization or pre-distortion, power amplifier efficiency is below 10% for frequencies above 10 GHz. It is still not clear how much the power amplifier efficiency can be improved at high frequencies by applying such or other techniques, but considering that one important aspect for 5G deployment is energy efficiency, it is expected that transmit powers at above 10 GHz will be far below currently common BS power levels of 40 Watts. In this analysis, a transmit power of 30 dBm is considered for the base station transmission at any frequency. This can be conservative for frequencies below 20 GHz and optimistic for frequencies above 30 GHz.

EMF exposure limits

According to International Commission on Non-Ionizing Radiation Protection (INCIRP), basic restrictions for EMF exposure are based on established health effects and biological considerations [ICNIRP]. Basic restrictions below 10 GHz are expressed as Specific Absorption Rate (SAR) values whereas Power Flux Density (PFD) is used for frequencies above 10 GHz. Basic restrictions for the general public are [ETSI08] :

- For 10 MHz < f < 10 GHz: SAR = 2 W/kg.
- For f > 10 GHz: PFD = 10 W/m^2.

Reference levels for the general public exposure are expressed as PFD from 2 GHz to 300 GHz, covering almost all frequencies used for fixed radio services. These reference levels determine a maximum PFD = 10 W/m^2. Then, compliance to the basic restrictions can be achieved by compliance to the reference levels throughout that frequency range. In cases where necessary, the basic restrictions can be used below 10 GHz to demonstrate compliance.

The PFD expression for far-field region is given by:

$$PFD = \frac{EIRP}{4 * \pi * d^2} \; [W/m^2]$$

where *d* is the distance from the transmit antenna in meters. As the far-field calculation overestimates the near-field, PFD for the far-field region can be used to determine the maximum allowed EIRP at any given distance *d*, such that the PFD = 10 W/m^2 limit is not crossed. Figure 5-7 illustrates the maximum EIRP as a function of the distance from the transmit antenna.

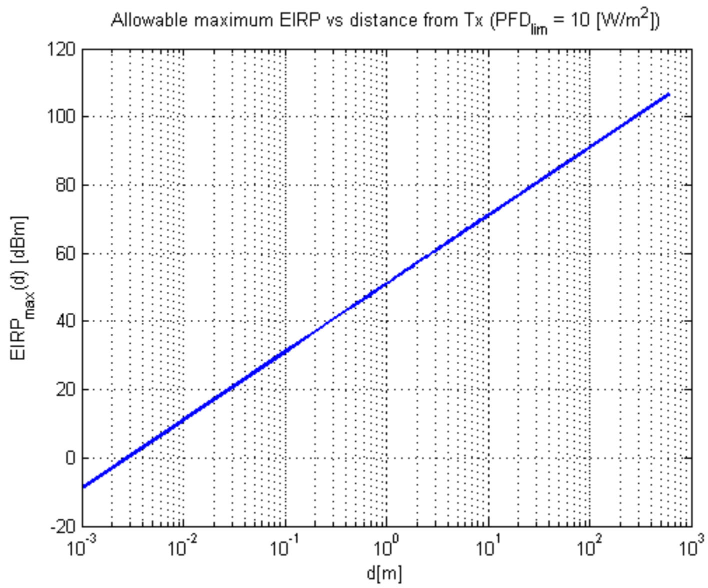

Figure 5-7: Maximum permitted EIRP as a function of the distance from the transmitter, such that EMF exposure limit given by PFD = 10 W/m^2 is not crossed.

Coverage evaluation under practical limits and assumptions

From EMF exposure limits and by assuming 10 m as the protection distance for the considered macro-cell deployment, the EIRP limit is 71 dBm. This limit is valid for the whole frequency range of interest (2 GHz < f < 300 GHz). More restricted EIRP can be considered in some frequency ranges because of the mentioned antenna gain and transmit power limitations. In this analysis, EIRP = 60 dBm is used for any frequency to reflect the high frequency limitations in base station antenna gain (30 dBi) and transmit power (30 dBm). Additionally, the propagation model used in the analysis is the current version of the 5G channel model under development for the frequency range 6-100 GHz.

Figure 5-8 illustrates the DL received power as a function of frequency for an indoor UE just behind a modern window. Three different distances between base station and UE are considered: 25 m, 150 m, and 300 m. As in the ideal analysis for the low loss building case, the received RF power slightly increases and rapidly decreases after a certain frequency range.

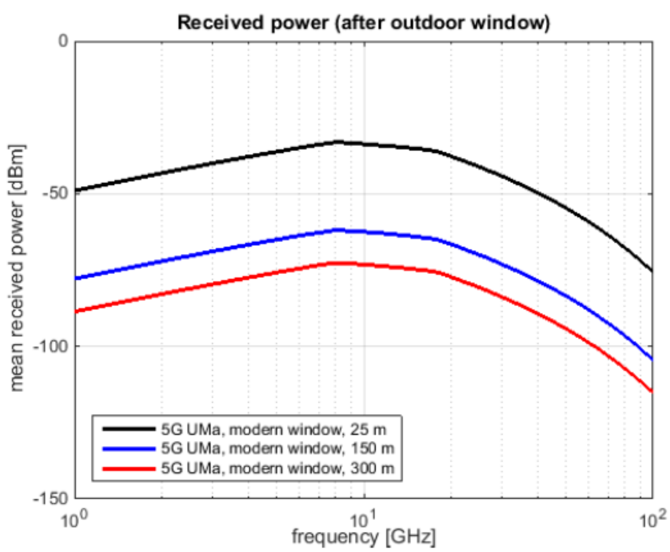

Figure 5-8: Downlink received power versus frequency.

The throughput gain can be assessed for these scenarios under the realistic assumption of using wider channel bandwidths for higher operation frequencies. In this analysis, channel bandwidth is assumed as 2% of the center frequency, e.g. 20 MHz channel bandwidth at 1 GHz, 2000 MHz channel bandwidth at 100 GHz. Then, by using Shannon capacity to estimate the throughput and having throughput at 1 GHz operation frequency as reference, Figure 5-9 shows the throughput gain as a function of frequency. The observed behavior of received power degradation after a certain frequency is also present for throughput in the macro-cell outdoor-to-indoor coverage, even by considering wider channel bandwidths for higher frequencies.

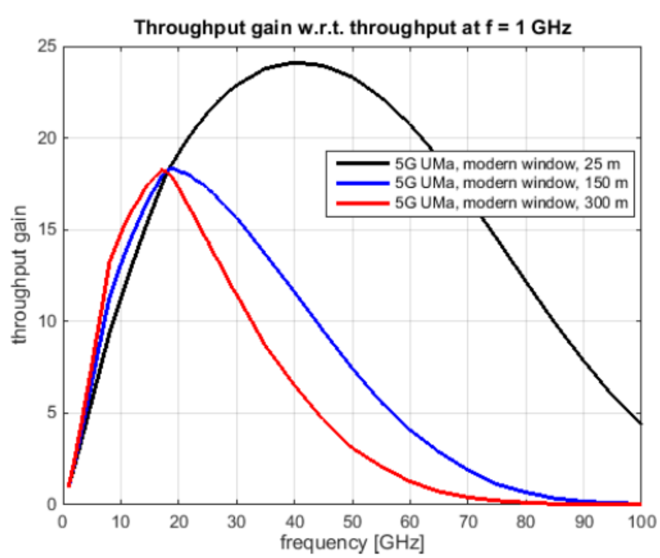

Figure 5-9: Throughput gain (with respect to throughput at f = 1 GHz) versus frequency.

5.2 Benefits of contiguous spectrum bands

When assessing the suitability of new bands, the key aspects (in addition to technical challenges such as propagation characteristics and HW availability and cost listed above) are potential for international harmonization of selected bands [IMT-2083], and ability of a band to host multiple operators. Contiguous spectrum would also have advantages for device supply and for consumers (e.g. changing service provider), ensuring economies of scale.

Device transmitter and receiver architecture

In context of LTE Carrier Aggregation (CA), lot of evaluation work has been carried out to understand the trade-offs in terms of complexity and performance when introducing support of non-contiguous inter-band aggregation. In Figure 5-10, the high level transceiver architecture is shown for the case when a UE supports contiguous intra-band aggregation of 100 MHz (assuming five 20 MHz component carriers) in both DL and UL. In Figure 5-11 the same is illustrated assuming that five non-contiguous frequency bands are required to achieve the aggregation of the 100 MHz bandwidth. In the architecture shown in Figure 5-11 it has been assumed that the frequency bands are split to different frequency ranges so that three of the bands are located for substantially higher frequencies than the other two making it possible to combine all 5 bands to single antenna trough diplexer component. If more than 3 bands would be categorized either low frequency or high frequency bands, the aggregation might not be practically feasible anymore. It is also to be noted that in order to support UL CA in five separate bands, an individual power amplifier (PA) is needed for each individual band, increasing further the cost, power consumption and the complexity of transceivers. In context of 5G, higher order multi-antenna schemes have been considered, thus increasing the amount of needed components further.

In Figure 5-12 and Figure 5-13, transceiver architectures are shown for TDD.

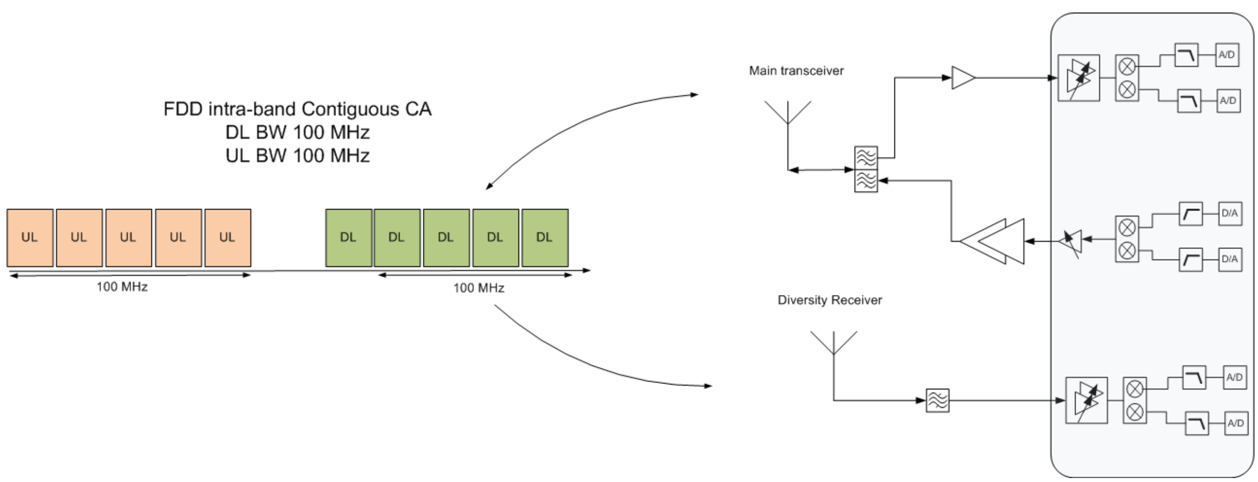

Figure 5-10: FDD transmitter/receiver implementation for one contiguous band.

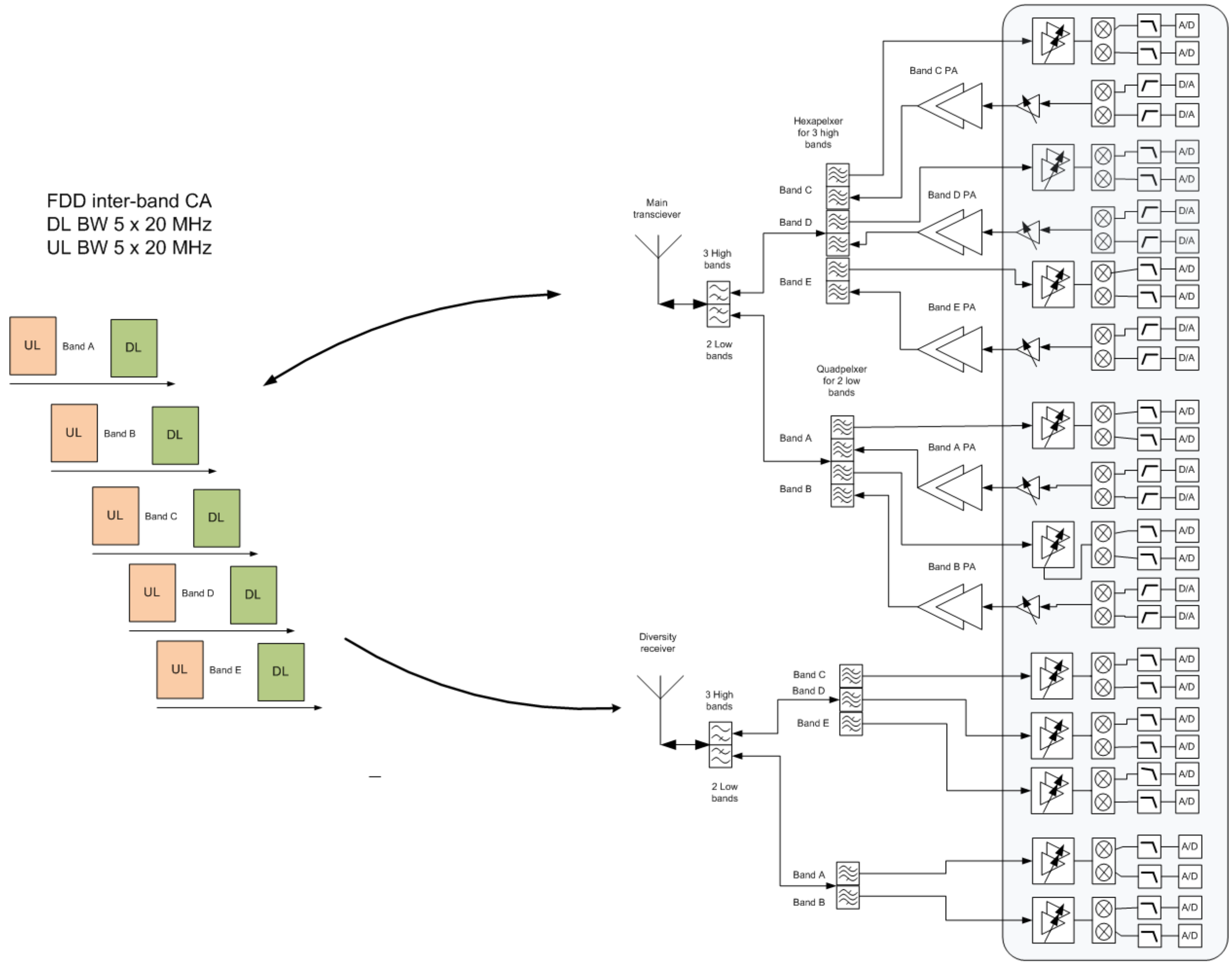

Figure 5-11: FDD transmitter/receiver implementation for five fragmented bands.

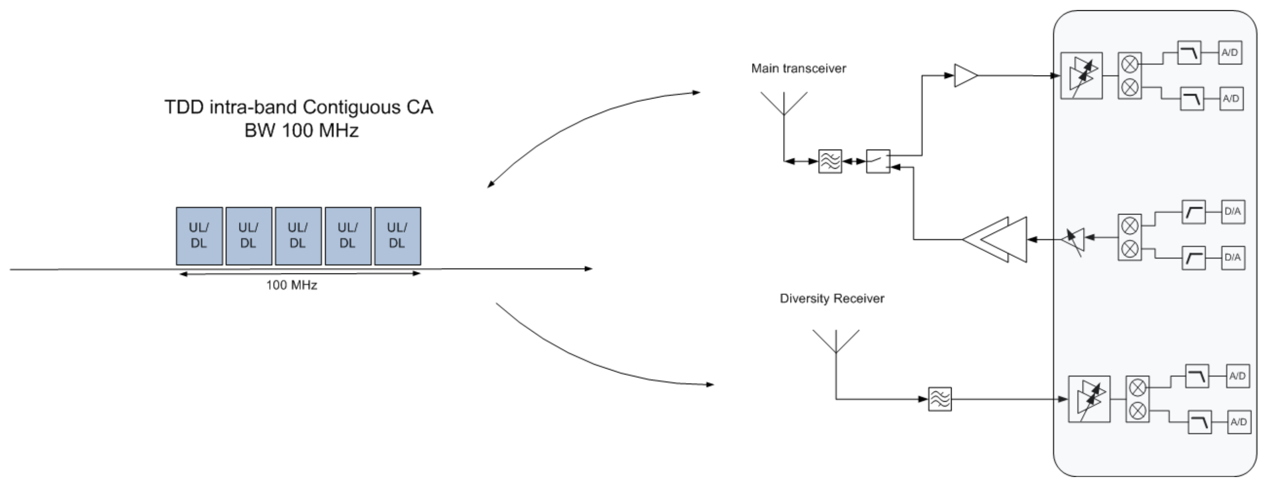

Figure 5-12: TDD transmitter/receiver implementation for one contiguous band.

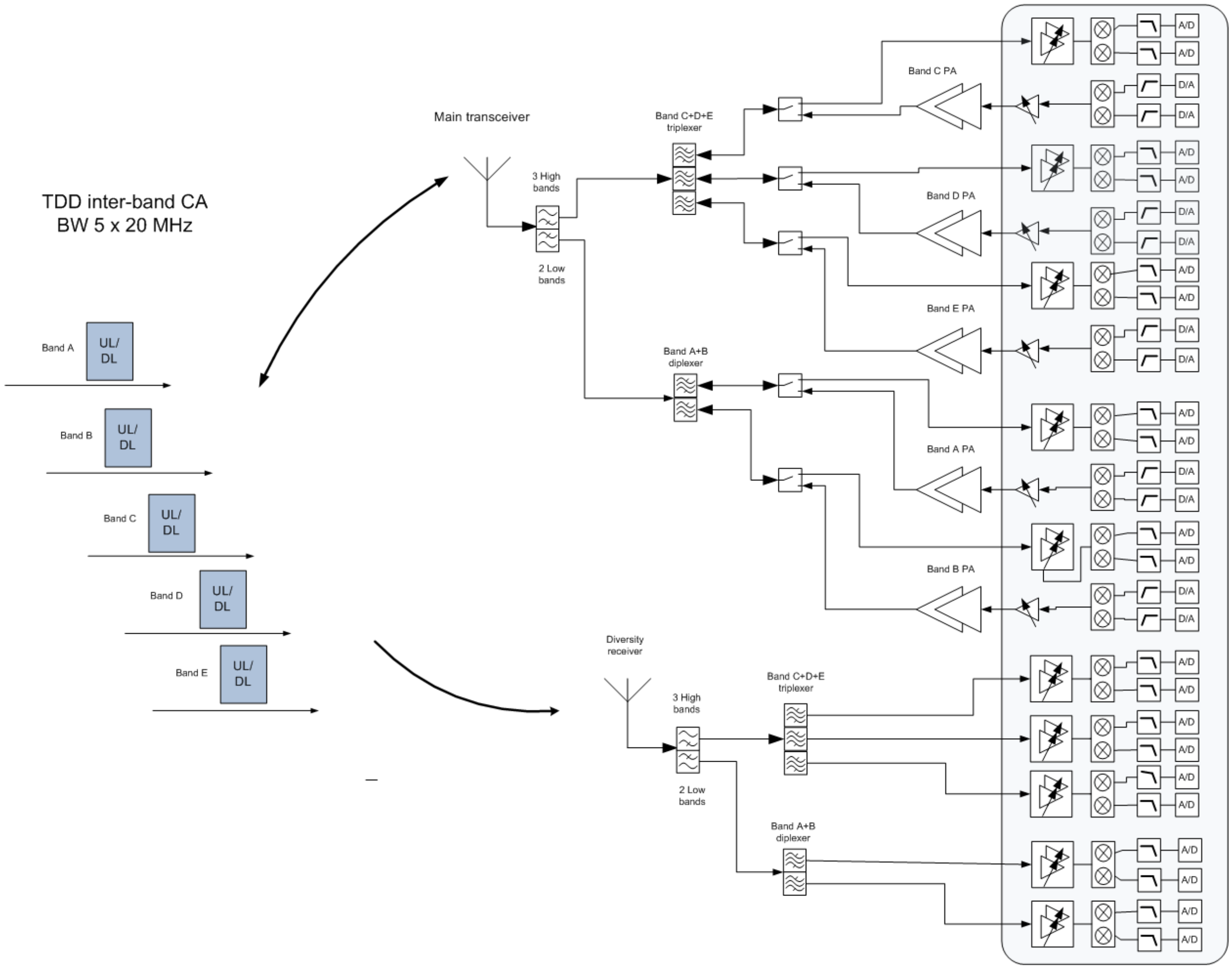

Figure 5-13: TDD transmitter/receiver implementation for five fragmented bands.

Control signal overhead

One aspect to be considered when comparing contiguous or non-contiguous frequency bands is the required signaling overhead due to control information. In typical cellular radio systems the control information required by UE's to camp and register to the system is broadcasted on all active frequency bands. This is done because the device capabilities and coverage areas of different frequency bands (and cells) may be different. Thus in order to ensure more contiguous service coverage in various deployments, certain amount of control overhead is required. Although the final details of the 5G system design are still open and there are several different deployment scenarios considered, it is very likely that if several bands are assigned (and used in cellular type of operation), each individual non-contiguous frequency band will require the control information to be broadcasted individually. When comparing this with using a single contiguous frequency band it is obvious that considering the similarities achievable over the band, the overall overhead can be reduced (compared to several non-contiguous bands). Naturally the relative amount of control overhead will decrease as wider system bandwidths are considered, but as the maximum amount of system information is likely to be restricted, there will be smaller overhead when wider system bandwidth is considered.

Guard bands

Guard bands are implemented in edges of each contiguous frequency bands to facilitate the emission and interference requirements to and from the adjacent bands. The size of a guard band depends on the requirements but in case of multiple fragmented bands there is a need for a higher number of guard bands as each band will need its own individual guard bands. Currently, there are also guard bands between carriers (like 5 MHz LTE carrier includes 2x 250 kHz internal guard bands) to mitigate interference in reception, however, depending how this will be specified for 5G, there is a possibility to reduce those internal guard bands.

Inter-modulation interference

An additional aspect is that in case of support of large number of simultaneous non-contiguous and fragmented frequency bands, the inter-modulation interference scenarios may become more challenging, when considering the emission requirements. With a contiguous band, this kind of inter-modulation interference can be avoided.

Testing

Also one aspect is that fragmented spectrum introduces the requirement to support several different bands and system bandwidths which increases complexity and time for testing.

5.3 Sharing with existing services

5.3.1 Fixed Satellite Service and 5G in Ku/Ka-band (20-30 GHz)

For IMT and FSS UL case, preliminary study [ITU-2367] shows that co-existence between IMT and FSS UL in this band is feasible, and the interference margin is large enough. In [ITU-2367], it's concluded that indoor IMT and FSS UL can co-exist under a certain condition and aggregated interference from IMT cannot interference FSS satellite in 6 GHz band. Compared with 6 GHz band, the propagation loss of millimetric wave band signal in free space loss is larger. For example, 28 GHz free space loss will be 13.4 dB larger than 6 GHz. In addition, the atmosphere attenuation will be also larger than 6 GHz. If the density of 28 GHz IMT system is the same as that of 6 GHz system, 28 GHz sharing between IMT and FSS UL is expected to be much easier.

For IMT and FSS DL case, based on ITU-R Recommendation S.1432 [ITU-1432] and S.465 [ITU-465], the protection criterion for FSS earth station is similar to that for C-band. In addition, the millimetric wave propagation including atmosphere attenuation, rain attenuation, building entry loss and other loss will be larger. Besides, the IMT bandwidth in millimetric wave will be at least 500 MHz, and this will make the power spectrum density lower. Therefore, IMT and FSS earth station sharing is expected to be easier than C-band [ITU-2368]. Meanwhile, high frequency IMT system will be mainly deployed in dense urban area to provide high traffic service. When the FSS earth stations are deployed in rural or suburban, the nature distance between different deployment scenarios is benefitting spectrum sharing. When the FSS earth station is deployed in urban scenario, it's likely deployed above roof top to avoid the signal obstacle of surrounding buildings. In this case, IMT system can adopt some isolation method and mitigation technique to avoid interference to FSS earth station.

5.3.2 Fixed Service and 5G in E-band (60-90 GHz)

Existing fixed links in the E-Band are typically deployed at height and above local clutter (typ. > 25 m) to achieve maximum range and line-of-sight propagation. These fixed links also use high-gain antennas with very highly-directional (0.5°-3° beam width) beams (see Figure 5-14).

IMT in the E-band will be for high-capacity small cells, with base stations deployed below roof top (typ. < 10 m). These will use antenna arrays (e.g., 32×32) to create large numbers of directional (3°-6° beam width) beams with down tilts of typically 10° or more.

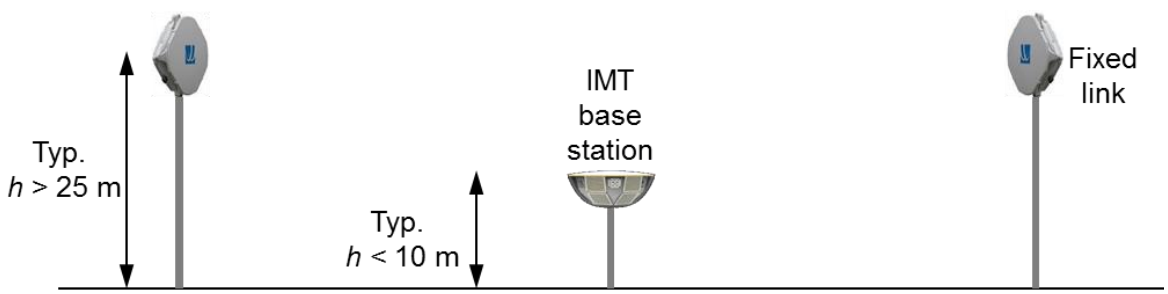

Figure 5-14: Angular discrimination mitigates interference.

In [ITU-2327], IMT and fixed service sharing study below 6 GHz is evaluated. The results show that certain geographic separation or frequency separation can facilitate spectrum sharing. The study done in the band 5925-6425 MHz show that 20-200 meters protection distance is enough for co-channel in most directions, except for the main and first side lobes of the antenna pattern. Compared to frequency bands below 6 GHz, the prorogation loss above 6 GHz including the free space loss, atmosphere loss, rain loss, building entry loss and other losses will be larger. In addition, the bandwidth of IMT systems is expected be at least several GHz, and this make IMT small cell system's PSD (power spectrum density) very low in E-band. Therefore, the sharing condition is expected to be more favorable.

IMT-systems in E-band will be mainly deployed in dense urban scenario. If it's indoor IMT systems, the building entry loss in E-band will be very large. Measurements in [IMT-2376] show that building entry loss will be nearly 18 dB for standard window, 40 dB for coated window and up to 280 dB for concrete wall. The overall building entry loss from IMT transmitter to the fixed service station will be even larger when considering the inner wall and other obstacle loss. Therefore, the sharing between indoor IMT and outdoor fixed service station is feasible. If the IMT station is deployed in outdoor scenario, the below roof top IMT station and above roof top fixed service station will have large antenna discrimination. In this case, evaluation results show that even in free space condition, IMT station can co-exist with fixed service station with 15 m apart from each other for co-channel case. For relative larger distance, because of the large E-band clutter loss in urban scenario, the propagation loss will be very large when the signal faces the obstacle, and the sharing is expected to be feasible.

Calculations [IMT-2376] indicate that, for typical deployment geometries, and cautious parameters and protection criteria, the protection distances between IMT base stations and fixed link receivers can vary between 10 m to 100 m, depending on the frequency adjacency.

6 Conclusions

Results and findings in this Report are based on work done in other projects (e.g. METIS) and organizations (e.g. ITU-R) which are re-evaluated and updated with the aim to provide a sound justification – as far as possible in this early stage of 5G developments – for the need of spectrum above 6 GHz.

System-level simulations have been carried out for an example scenario with traffic corresponding to the Extreme Mobile Broadband (xMBB) application 4K video. It is assumed that the traffic load increases to 60-70 Gbps/km^2 by the year 2025. In order to cope with this demand, at least 500 MHz additional bandwidth per operator would be needed if, as an example, the 10 GHz band is used. It is also determined that even ultra-reliable Machine Type Communication (uMTC) applications could require such high bandwidths due to the overall impact of latency and reliability requirements and the amount of devices at the same time. Generally, the capacity of wireless networks can be increased by (1) network densification (i.e. more access points), (2) higher spectrum efficiency (e.g. with multi-antenna techniques), and (3) larger spectrum bandwidth. With an analysis of the relative effectiveness of spectrum utilization it is demonstrated that network densification is a conceivable option in sparse network deployments although its effectiveness diminishes, but not effective at all in already dense deployments, and the effectiveness of using multiple antennas decreases with the number of antennas, both for sparse and dense network deployments. Therefore, the capacity demand can be covered finally only with larger spectrum bandwidths. It is analyzed that contiguous spectrum bands offer advantages with regard to device complexity, signaling, guard bands and interference.

The suitability of bands above 6 GHz in different scenarios is demonstrated by channel and propagation measurements. Due to the fact that building penetration depth strongly decreases with increasing frequency, the lower part of the spectrum between 6-30 GHz is suitable for outdoor to indoor coverage. Outdoor to outdoor mobile coverage, on the other hand, is worthwhile to be investigated across the full range of spectrum up to 100 GHz. For instance, channel and propagation measurements performed at 28 GHz have demonstrated the suitability of centimetric wave spectrum for outdoor mobile communications. Furthermore, current wireless technology implementations enable the use of millimetric waves, e.g. for ultra-high capacity P2P/low mobility applications in line of sight (LOS) conditions.

In summary it can be stated that additional spectrum in the order of several GHz is required to cope with the expected traffic demand of 5G. In order to allow for an efficient service provision for all 5G scenarios, frequencies in the whole range from 6 GHz to 100 GHz should be investigated for 5G.

7 References

[4G-AME] 4G Americas, 5G Spectrum recommendations, August 2015.

[ERI14] Ericsson, "Ericsson Mobility Report". 2014.

[ETSI08] ETSI TR 102 457 V1.1.1; Transmission and Multiplexing (TM);Study on the electromagnetic radiated field in fixed radio systems for environmental issues; 2006-08.

[ETSI15] ETSI ISG mWT response to Ofcom consultation on "Spectrum above 6 GHz for future mobile communications": http://stakeholders.ofcom.org.uk/binaries/consultations/above-6ghz/responses/ETSI_ISG_mWT_Response.pdf

[HW13] "Huawei E-Band RTN380-Field Trial Report", http://carrier.huawei.com/en/static/HW-314533.pdf.

[HW14] "Huawei Named Key Member of New 5G Association, Announces Faster than 100 Gbps Speed Achievement at Mobile World Congress 2014", http://pr.huawei.com/en/news/hw-328622-ictmwc.htm.

[ICNIRP] ICNIRP Guidelines For Limiting Exposure to Time-varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHz); Published in: Health Physics 74 (4):494-522; 1998.

[IMT-2083] Recommendation ITU-R M.2083,IMT-Vision, "Framework and overall objectives of the future development of IMT for 2020 and beyond" June 2015.

[IMT-2376] Report ITU-R M.2376, Technical feasibility of IMT in bands above 6 GHz, June 2015.

[ITU-2368] Report ITU-R S.2368-0, Sharing studies between International Mobile Telecommunication – Advanced systems and geostationary satellite networks in the fixed-satellite service in the 3400-4200 MHz and 4500-4800 MHz frequency bands in the WRC study cycle leading to WRC-15, Jun. 2015.

[ITU-2327] Report ITU-R F.2327-0, Sharing and compatibility study between International Mobile Telecommunication systems and point-to-point fixed wireless systems in the frequency band 4400-4990 MHz, Dec. 2014.

[ITU-2367] Report ITU-R S.2367-0, Sharing and compatibility between International Mobile Telecommunication systems and fixed-satellite service networks in 5850-6425 MHz frequency range, Jun. 2015.

[INF14]	"E-Band Radio Frontend – Reference Design", https://www.infineon.com/dgdl/Infineon-E-Band+Radio+Frontend+%E2%80%93+Reference+Design-PB-v01_00-EN.pdf?fileId=5546d4624933b8750149802fb82c4ba5.
[INF15]	"SMT-Ready E-Band Radio Frontend – Reference Design", http://www.infineon.com/dgdl/Infineon-SMT_Ready_E_Band_Radio_Frontend_Design-PB-v01_00-EN.pdf?fileId=5546d4624d6fc3d5014dd79f3a6649e6.
[ITU14]	ITU-T Technology Watch Report, "The Tactile Internet", August 2014
[ITU-1432]	Recommendation ITU-R S.1452-1, Apportionment of the allowable error performance degradations to fixed-satellite service (FSS) hypothetical reference digital paths arising from time invariant interference for systems operating below 30 GHz, Jan. 2006.
[ITU-2290]	Report ITU-R M.2290, Future spectrum requirements estimate for terrestrial IMT, Dec. 2013.
[ITU-465]	Recommendation ITU-R S.465-6, Reference radiation pattern for earth station antennas in the fixed-satellite service for use in coordination and interference assessment in the frequency range from 2 to 31 GHz, Jan. 2010.
[KZR14]	Kaymaksut, E.; Dixian Zhao; Reynaert, P., "E-band transformer-based Doherty power amplifier in 40 nm CMOS," Radio Frequency Integrated Circuits Symposium, 2014 IEEE , vol., no., pp.167,170, 1-3 June 2014
[MET13-D51]	ICT-317669 METIS, Deliverable 5.1 Version 1, "Intermediate description of the spectrum needs and usage principles", August 2013.
[MET14-D53]	ICT-317669 METIS, Deliverable 5.3 Version 1, "Description of the spectrum needs and usage principles", August 2014.
[MET15-D15]	ICT-317669 METIS, Deliverable 1.5 Version 1, "Updated scenarios, requirements and KPIs for 5G mobile and wireless system with recommendations for future investigations", April 2015.
[MET15-D66]	ICT-317669 METIS project, Deliverable 6.6 Version 1, "Final report on the METIS 5G system concept and technology roadmap", April 2015.
[MOH10]	Mitomo, T.; Ono, N.; Hoshino, H.; Yoshihara, Y.; Watanabe, O.; Seto, I., "A 77 GHz 90 nm CMOS Transceiver for FMCW Radar Applications," Solid-State Circuits, IEEE Journal of , vol.45, no.4, pp.928,937, April 2010.
[PK11]	Z. Pi and F. Khan, "An Introduction to Millimetric-Wave Mobile Broadband Systems", IEEE Communications Magazine, June 2011.

[R14] W. Roh et al., “Millimetric-Wave Beamforming as an Enabling Technology for 5G Cellular Communications: Theoretical Feasibility and Prototype Results”, IEEE Communications Magazine, February 2014.

[SAM15] Samsung 5G Vision White Paper, March 2015 (available at http://www.samsung.com/global/business-images/insights/2015/Samsung-5G-Vision-0.pdf).

[SHF+14] E. Sem, F. Harrysson, A. Furuskär, H. Asplund, ”Outdoor-to-Indoor Coverage in High Frequency Bands”, The First International Workshop on Mobile Communications in Higher Frequency Bands, IEEE GLOBECOM December 2014, Austin, TX, USA, pp. 393-398.

[TN15] M. Tesanovic and M. Nekovee, “mmWave-based mobile access for 5G: key challenges and projected standards and regulatory roadmap”, accepted for publication at IEEE GLOBECOM 2015.

[VAR10] H. R. Varian, Intermediate Microeconomics: A modern approach, 8th ed. W. W. Norton & Company, 2010.

[YS15] Y. Yang and K. W. Sung, “Technical Rate of Substitution of Spectrum in Future Mobile Broadband Provisioning,” in proc. IEEE DySPAN, Stockholm, Sweden, 30 Sept-2 Oct, 2015.

[ZR14] Dixian Zhao; Reynaert, P., "A 3 Gb/s 64-QAM E-band direct-conversion transmitter in 40-nm CMOS," Solid-State Circuits Conference (A-SSCC), 2014 IEEE Asian, vol., no., pp.177, 180, 10-12 Nov. 2014.