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Analysis of Spectrum, License Schemes and Network Scenarios in the W-band

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Foreword

This Group Report (GR) has been produced by ETSI Industry Specification Group (ISG) millimetre Wave Transmission (mWT).

Modal verbs terminology

In the present document "**should**", "**should not**", "**may**", "**need not**", "**will**", "**will not**", "**can**" and "**cannot**" are to be interpreted as described in clause 3.2 of the ETSI Drafting Rules (Verbal forms for the expression of provisions).

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Executive summary

The evolution of Mobile Networks towards LTE-A and 5G will in the next few years demand significant challenges of the evolution of microwave technology, especially in terms of transmission capacity and latency.

The interest in millimeter-wave bands has risen significantly in recent years mainly due to new network topologies driving backhaul to the higher part of the spectrum and the enormous amount of under-utilized bandwidth that lies in this part of the electromagnetic spectrum.

The development of new technologies and the use of higher frequency bands allow microwave to remain a fundamental building block of mobile networks even in this framework of ever-increasing demands.

The significant advantages offered by the propagation characteristics in terms of frequency re-usability and large channel bandwidths make millimetre-wave suitable for transmitting multi-Gbps in dense urban scenarios thanks to very compact sizes of the antennas and the extreme low power consumption.

Bands above 90 GHz are prime candidates for large volume applications in the backhaul and fronthaul to support all services requiring high speed wireless transmission.

Standardization activities for the W-band (92 to 114,5 GHz) are published in Recommendation ECC (18)02 [i.2] and Report ECC 282 [i.3], which also includes the D- band (130 to 174,8 GHz).

The present document provides an overview of possible applications and use cases for the W-band, state of the art of the technology at such high frequencies and also possible channel schemes which can be used, including the so called "duplexer-free" scheme.

Information and considerations on the D-band are included where appropriate, to allow comparison for the two high frequency bands.

Introduction

Within the scope of telecommunication, frequency bands above 90 GHz are not yet being commercially exploited nor fully covered by standards from all standards developing organizations (SDOs).

The W-band allocation in Article 5 of the ITU Radio Regulations [i.4] is shown in figure 1, for the Fixed Service, which is allocated as primary in all the three Regions in RF bands 92 to 94 GHz, 94,1 to 100 GHz, 102 to 109,5 GHz, 111,8 to 114,25 GHz.

It should be noted that the bands 94 to 94,1 GHz, 100 to 102 GHz, 109,5 to 111,8 GHz are not allocated for the Fixed Service.

The fragmentation of the bands is a challenging factor for the use of wide continuous RF band to provide very high capacity.

Allocation to services	
Band [GHz]	Region 1 - Region 2 - Region 3
92-94	FIXED
94-94.1	
94.1-95 & 95-100	FIXED
100-102	
102-105 & 105-109.5	FIXED
109.5-111.8	
111.8-114.25	FIXED
114.25-122.25	
122.25-123	FIXED

Figure 1: ITU Table of Frequency Allocation (Radio Regulation 2016)

The common allocation of the bands in the three ITU regions facilitates the scenarios and spectrum usage of any solutions available in the market.

Moreover, new spectrum allows new innovative ways for utilization, new concepts to cope with the increase of capacity and hop lengths are needed. Efficient aggregation of different bands and carriers should be exploited, through BCA together with new mm-wave spectrum made available by regulators.

The proper combination of mm-wave spectrum with traditional microwave spectrum should help to incentivize spectrum efficiency and optimization of spectrum usage, driving the regulators to release unused or under-utilized spectrum portions.

1 Scope

The present document is intended to describe possible scenarios and spectrum usage and proposes, aligned with CEPT Recommendation ECC 18(02) [i.2] - (Radio frequency channel/block arrangements for Fixed Service systems operating in the bands 92 to 94 GHz, 94,1 to 100 GHz, 102 to 109,5 GHz and 111,8 to 114,25 GHz).

Such assumption is aimed to facilitate the deployment of high capacity backhaul systems, able to decongest the network over distances shorter than usual ones for wireless transport.

Considering that the W-band is primarily allocated to FS, part of the scope of the present document is to identify applications for future backhaul networks or similar applications.

Technical propagation characteristics of W-band is considered to analyse system behaviours and evaluate reachable distances and possible achievable throughputs.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

NOTE: While any hyperlinks included in this clause were valid at the time of publication, ETSI cannot guarantee their long term validity.

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] ETSI White Paper No. 15 (July 2016): "mmWave Semiconductor Industry Technologies: Status and Evolution".

NOTE: Available at http://www.etsi.org/images/files/ETSIWhitePapers/etsi_wp15_mwt_semiconductor_technology.pdf.

[i.2] ECC Recommendation (18)02 of 14 September 2018 on radio frequency channel/block arrangements for Fixed Service systems operating in the bands 92-94 GHz, 94.1-100 GHz, 102-109.5 GHz and 111.8-114.25 GHz.

NOTE: Available at https://www.ecodocdb.dk/document/6037.

[i.3] ECC Report 282: "Point-to-Point Radio Links in the Frequency Ranges 92-114.25 GHz and 130-174.8 GHz".

NOTE: Available at https://www.ecodocdb.dk/document/6034.

[i.4] ITU-R Radio Regulation 2016.

NOTE: Available at https://www.itu.int/pub/R-REG-RR-2016.

[i.5] Recommendation ITU-R P.530-16 (07/2015): "Propagation data and prediction methods required for the design of terrestrial line-of-sight systems".

NOTE: Available at https://www.itu.int/rec/R-REC-P.530/en.

[i.6] Recommendation ITU-R P.1411-1: "Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz".

NOTE: Available at https://www.itu.int/rec/R-REC-P.1411/enhttps://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

[i.7] Recommendation ITU-R P.1238-7 (02/2012): "Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz".

NOTE: Available at https://www.itu.int/rec/R-REC-P.1238/enhttps://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

[i.8] Recommendation ITU-R P.838-3: "Specific attenuation model for rain for use in prediction methods".

NOTE: Available at https://www.itu.int/rec/R-REC-P.838/enhttps://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

[i.9] Recommendation ITU-R P.676-11: "Attenuation due to atmospheric gases".

NOTE: Available at https://www.itu.int/rec/R-REC-P.676/enhttps://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

[i.10] IEEE 802.15WPAN™: "60 GHz WPAN Standardization within IEEE 802.15.3c".

NOTE: Available at https://ieeexplore.ieee.org/abstract/document/4294424https://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

[i.11] EIA RS-261-B: "Rectangular Waveguides (WR3 to WR2300)", Standard of the Electronic Industries Association of the United States of America.

[i.12] IEC 60153-2:2016: "Hollow metallic waveguides - Part 2: Relevant specifications for ordinary rectangular waveguides".

NOTE: Available at https://webstore.iec.ch/publication/24898https://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

[i.13] Recommendation ITU-R F.1703: "Availability objectives for real digital fixed wireless links used in 27 500 km hypothetical reference paths and connections".

NOTE: Available at https://www.itu.int/rec/R-REC-F.1703/enhttps://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

[i.14] Recommendation ITU-R F.1668: "Error performance objectives for real digital fixed wireless links used in 27 500 km hypothetical reference paths and connections".

NOTE: Available at https://www.itu.int/rec/R-REC-F.1668/enhttps://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

[i.15] ECC Recommendation (14)01: "Radio frequency channel arrangements for fixed service systems operating in the band 92-95 GHz".

NOTE: Available at https://www.ecodocdb.dk/download/e7d2f0e4-2abe/ECCRec1401.pdfhttps://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

[i.16] Recommendation ITU-R P.530-17 (12/2017): "Propagation data and prediction methods required for the design of terrestrial line-of-sight systems".

NOTE: Available at https://www.itu.int/rec/R-REC-P.530-17-201712-I/enhttps://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

[i.17] Recommendation ITU-R P.1411-9 (06/2017): "Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz".

NOTE: Available at https://www.itu.int/rec/R-REC-P.1411-9-201706-I/enhttps://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

[i.18] Recommendation ITU-R P.1238-9 (06/2017): "Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz".

NOTE: Available at https://www.itu.int/rec/R-REC-P.1238-9-201706-I/enhttps://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

[i.19] Recommendation ITU-R F.2113-0 (01/2018): "Error performance and availability objectives and requirements for real point-to-point packet-based radio links".

NOTE: Available at https://www.itu.int/rec/R-REC-F.2113-0-201801-I/enhttps://www.itu.int/rec/R-REC-P.530-16-201507-S/en.

3 Definition of terms, symbols and abbreviations

3.1 Terms

Void.

3.2 Symbols

Void.

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

5G	Fifth Generation of Mobile Networks
BCA	Band and Carrier Aggregation
BW	Bandwidth
CS	Channel Spacing
DS	Duplex Spacing
FD	Full Duplex
FDD	Frequency Division Duplex
FS	Fixed Service
FWA	Fixed Wireless Access
LOS	Line Of Sight
LTE	Long Term Evolution
LTE-A	LTE-Advanced
nLOS	near Line Of Sight
NLOS	Non Line Of Sight
PmP	Point to Multipoint
PtP	Point to Point
RAN	Radio Access Network
RF	Radio Frequency
SDO	Standard Developing Organization
TCO	Total Cost of Ownership
TDD	Time Division Duplex

4 W band study

4.1 Highlights on W-band

In the search for more spectrum all wireless applications are already using and will use higher frequencies than the traditional microwave bands. The frequency bands above 90 GHz are prime candidates for large volume applications supporting services that require high speed and huge bandwidths.

A schematic diagram of the frequencies from about 6 to 275 GHz, used or of possible use by Fixed Service, is provided in figure 2, where the W and D band are highlighted.

Figure 2: W and D bands spectrum

Ten different portions of spectrum are available (when some contiguous portions are considered), from 92 to 200 GHz, allocated primarily to Fixed Service, covering almost 54 % of the whole band under consideration (92 to 200 GHz).

Overall bandwidth associated to each portion are reported in figure 3.

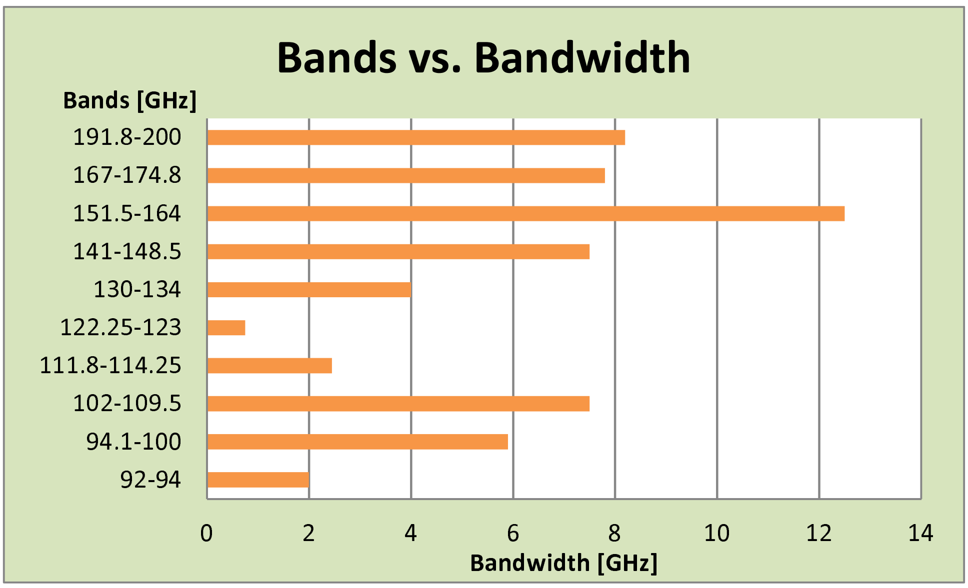

Figure 3: Portions of available spectrum in the range 92 to 200 GHz

In principle, nothing prevents from considering more than one portion of spectrum as a single band, in line with the approach already adopted for the E-band, where 71 to 76 GHz and 81 to 86 GHz were considered together.

Since the portions of the spectrum and bandwidth have not yet been defined, the present document will identify the best way to consider such portions of the spectrum and how to arrange into new bands and how to consider each band into channels, if any.

The existing standards of waveguides [i.11] and [i.12] designate wave guides for RF frequency range considered in the present document, as reported in table 1.

Table 1 Designation of waveguides

Designation EIA/IEC	US commercial designation (see note) & f_{min} - f_{max} [GHz]		Cut-off Frequencies [GHz]	Band
WR8/R1200	RG138 (silver) (see note)	90 to 140	73,8	W-band
NOTE: Example of.				

Activities related to the W band, including possible frequency arrangements, intended to facilitate the deployment of fixed services in the frequency blocks already allocated to fixed services in the bands 92 to 94 GHz, 94,1 to 95 GHz, 95 to 100 GHz, 102 to 109,5 GHz and 111,8 to 114,5 GHz, have been concluded in CEPT.

As a result, ECC Recommendation 18(02) [i.2] containing channel plan and guidelines on deployment, and ECC Report 282 [i.3], including various aspects, such as propagation, regulation, use cases and application, technical characteristics for both W and D bands, are available.

4.2 Characteristics of the W-band

The rain attenuation in the W-band can be derived from figure 4. It should be noted that the rain attenuation in the W-band is higher than in the E-band.

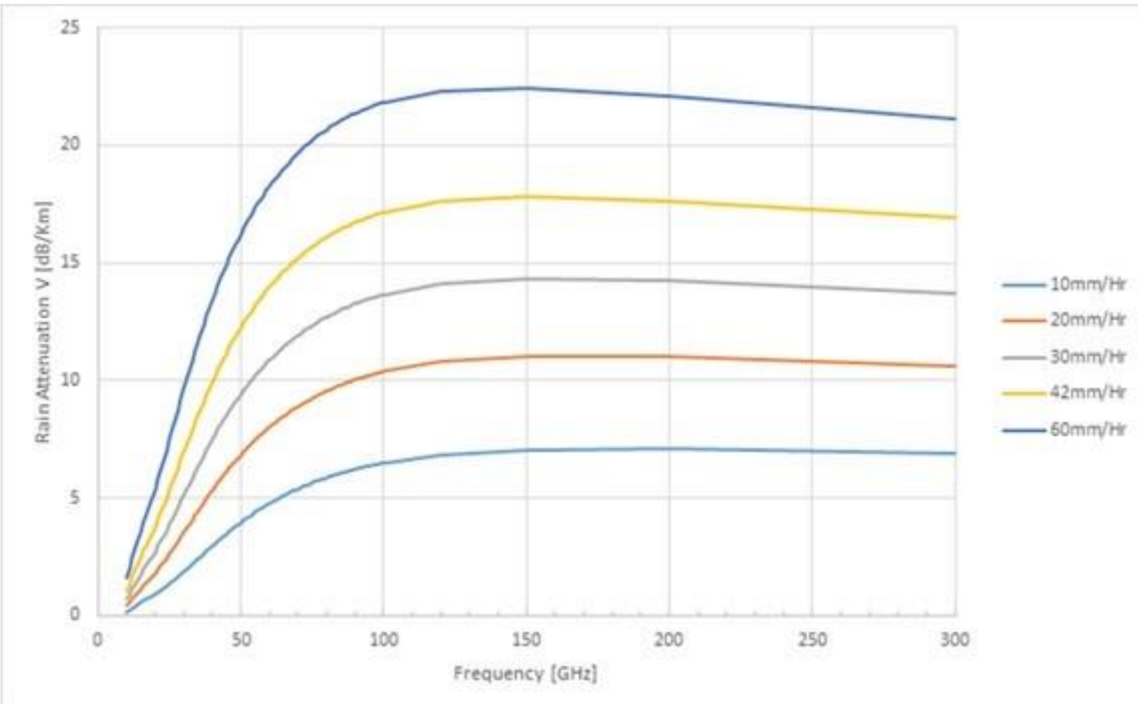

Figure 4: Specific rain attenuation up to 300 GHz (Source: Recommendation ITU-R P.838-3 [i.8])

Gas attenuation is less than 1 dB/km in the W-band (figure 5); is not a dominant factor for the link distance limitation.

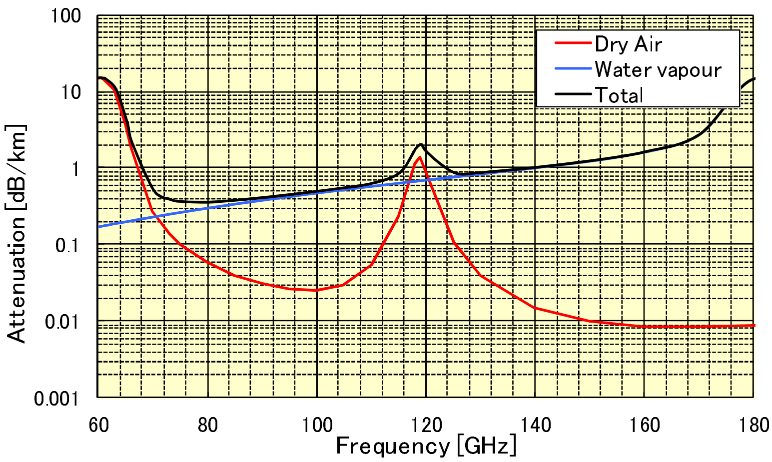

Figure 5: Specific gas attenuation up to 180 GHz (Source: Recommendation ITU-R P.676-11 [i.9])

It can be noted that W-band covers a frequency range which is not affected by Oxygen absorption peaks.

4.3 W-band system simulation

In order to evaluate the covered distances and available throughputs, extensive system simulations have been carried out. As a result, estimation is given of the maximum hop length that can be reached, in the W-band and in the D-band, for different 1 Gbps solutions in different conditions and frequency bands. Moreover the estimation of a maximum hop length that can be reached for a 10 Gbps solution is provided, derived with the same approach used for the 1 Gbps cases.

The model is for pure Line of Sight (LoS) applications where the urban environmental impact has not been taken into account.

Estimation of a reasonable level of system gain to reach 1 Gbps and 10 Gbps throughputs is provided, scaling the solution that is today in place.

The maximum antenna gain considered is up to 40 dBi.

The related standards under which the calculations have been carried out are here reported:

- Recommendation ITU-R P.838-3 [i.8].
- Recommendation ITU-R P.676-11 [i.9]: specific attenuation due to atmospheric gases (dB/km) is derived from figure 5 (Pressure = 1 013,25 hPa; Temperature = 15°C; Water Vapor Density = 7,5 g/m^3).

It should be mentioned that Recommendation ITU-R P.530-17 [i.16] provides models up to 100 GHz, namely "*The prediction procedure ... is considered to be valid in all parts of the world at least for frequencies up to 100 GHz ...*". This means that trials with real equipment at these extremely high frequency bands aim also to validate the ITU models for frequencies above 100 GHz.

The following conditions apply:

- Gross system gain accounts for system gain and antenna gain (estimation of gross system gain range gSyGain to reach 1 Gbps solution).
- Rain rate of 30, 60 and 90 mm/h are taken into account.
- Three cases are considered: 250 MHz, 500 MHz and 1 000 MHz channels.
- Antenna gain is from 30 to 40 dBi.
- No substantial difference between H and V.
- Less than 1 dB (110 GHz) and less than 0,5 dB (150 GHz) of gSYGain for cases 20 to 2 000 meter/ rain rate 10 to 120 mm/h.

The results obtained can be easily scaled for different cases and assumptions. It is also shown that no substantial difference is envisaged between H and V polarizations.

Figure 6 shows the relation between gross system gain and maximum hop length in the W band with different availabilities. Same figure allows comparison with D-band, showing hop length difference of about 20 % with same system gain, rain rate and availability requirement.

Figure 7 provides relation between allowable distances for different rain rates.

Figure 8 provides relation between allowable distances for different availability.

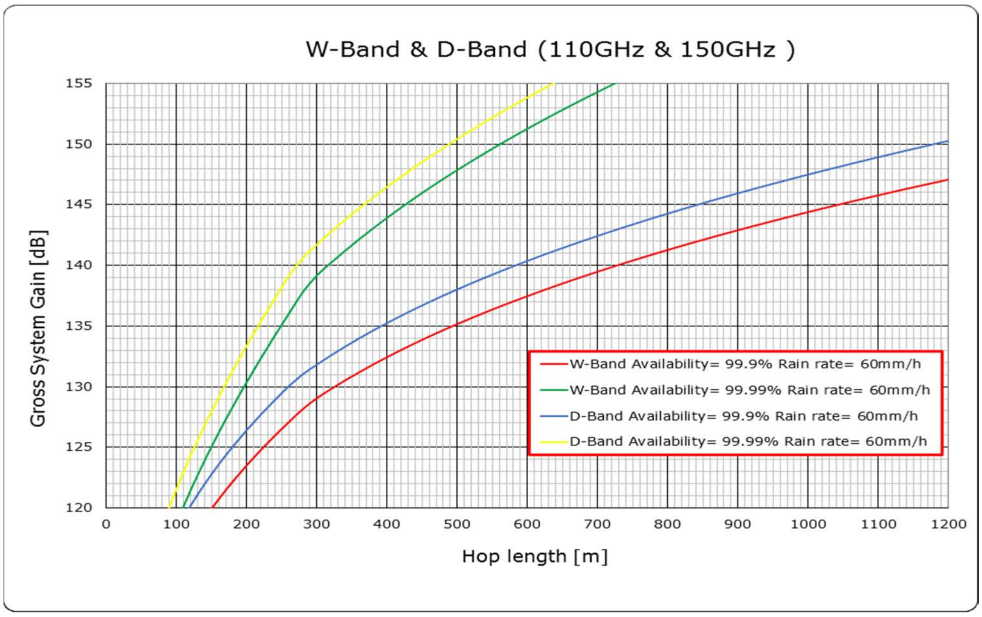

Figure 6: W and D-band - Gross System Gain vs. Max hop length vs availabilities; rain rate 60 mm/h

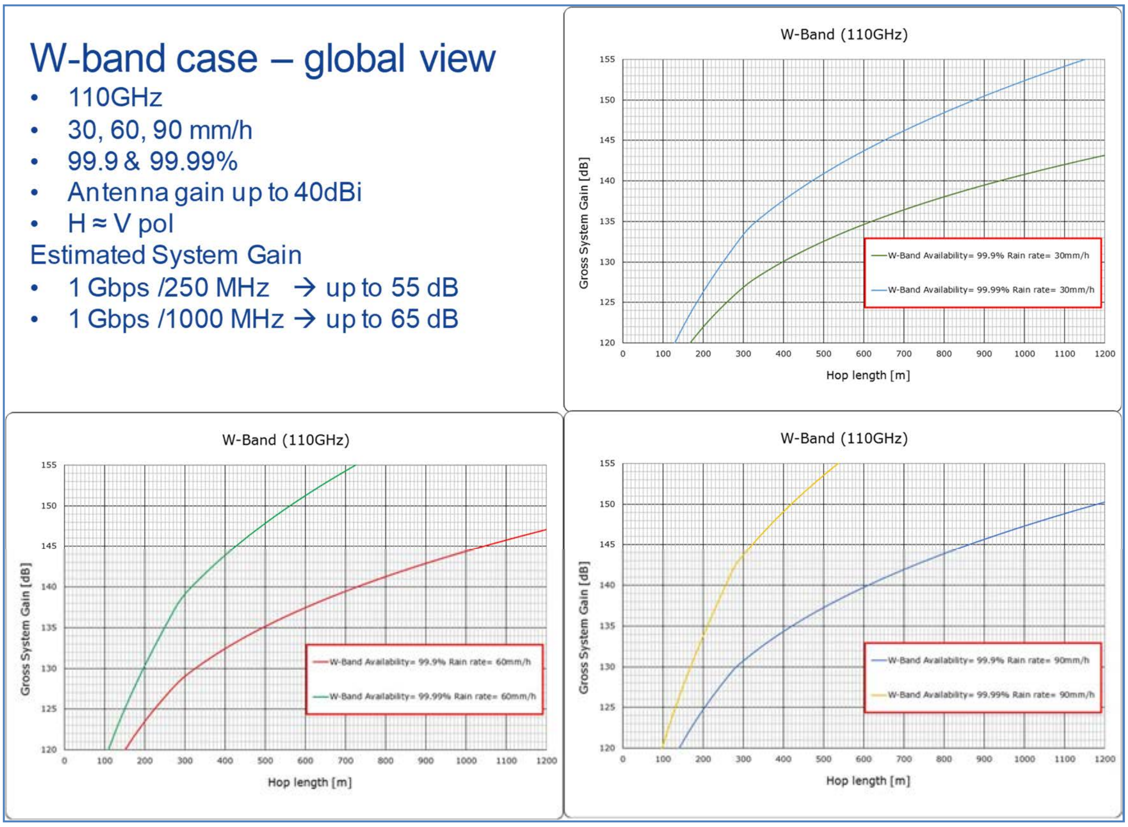

Figure 7: Achievable distances at W-band with 1 Gbps throughput

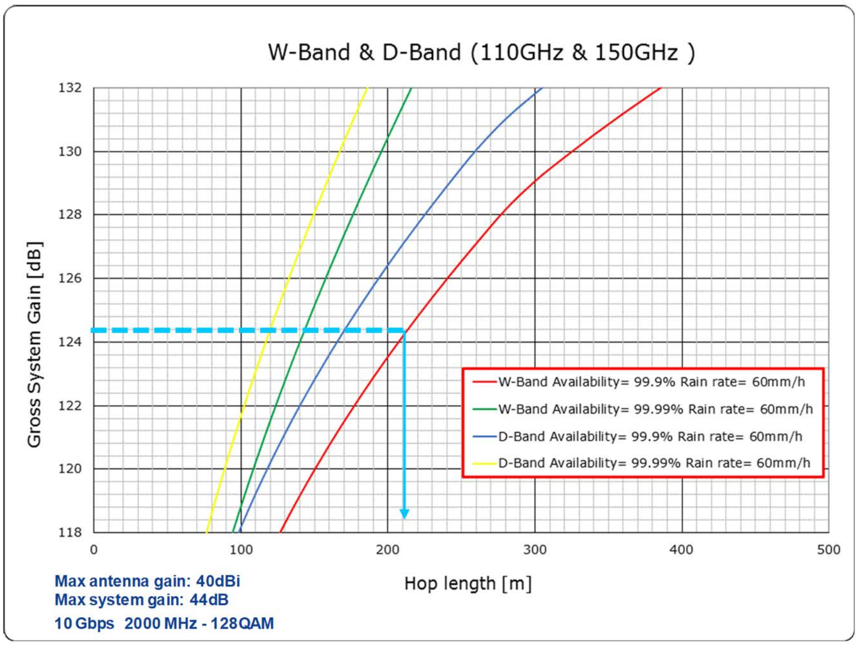

Figure 8: Achievable distances at W and D-band with 10 Gbps throughput

4.4 Regulatory Aspect

4.4.1 ITU-R Regulations concerning W-band

- At the date of publication of the present document, there is no ITU-R deliverable to cover this RF band.

4.4.2 ITU R Radio Regulations concerning Frequency Allocation

- Edition 2016 Vol. 1 Article 5 [i.4].

4.4.3 ITU-R Regulations concerning Propagation Aspects

- Recommendation ITU-R P.530-16 [i.5]: Propagation data and prediction methods required for the design of terrestrial line-of-sight systems.
- Recommendation ITU-R P.530-17 [i.16]: Propagation data and prediction methods required for the design of terrestrial line-of-sight systems.
- Recommendation ITU-R P.1411-1 [i.6]: Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz.
- Recommendation ITU-R P.1238-7 [i.7]: Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz.
- Recommendation ITU-R P.838-3 [i.8]: Specific attenuation model for rain for use in prediction methods.
- Recommendation ITU-R P.1411-9 [i.17]: Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz.
- Recommendation ITU-R P.1238-9 [i.18]: Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz.

Apart from Recommendation ITU-R P.838-3 [i.8], which is valid up to 1 000 GHz, range of validity is up to 100 GHz.

4.4.4 ITU-R Regulations concerning Error Performance and availability objectives

- Recommendation ITU-R F.1668 [i.14].
- Recommendation ITU-R F.1703 [i.13].
- Recommendation ITU-R F.2113-0 [i.19].

Formulas are provided to establish error performance and availability objectives for real links.

4.5 Use Cases and Possible Applications

4.5.0 Introduction

This clause provides an overview of possible applications foreseen in this frequency range.

4.5.1 From Current High Capacity Systems to the Future Systems

In order to be able to identify a subset of requirements for possible future applications in these bands, an overview of the specifications of current available systems in the E-band is herewith reported as a reference in table 2.

Table 2: Current High Capacity System in E-band

Current High Capacity System in E-band	
Capacity	Up to 6 Gbps using Dual Polarization Multiplexing
Channel Separation	250 MHz/500 MHz
Efficiency	Up to 12 bps/Hz
Link Distance	Up to 1,5 km (depending on antenna size and availability)

Given that the estimated required capacities are much higher and involved distances can be much shorter, current specifications do not seem to meet the needs of several future applications as reported in the following clauses.

4.5.2 5G Mobile Backhaul Tail Link

An example of tail link is shown in figure 9, basic requirements are given in table 3.

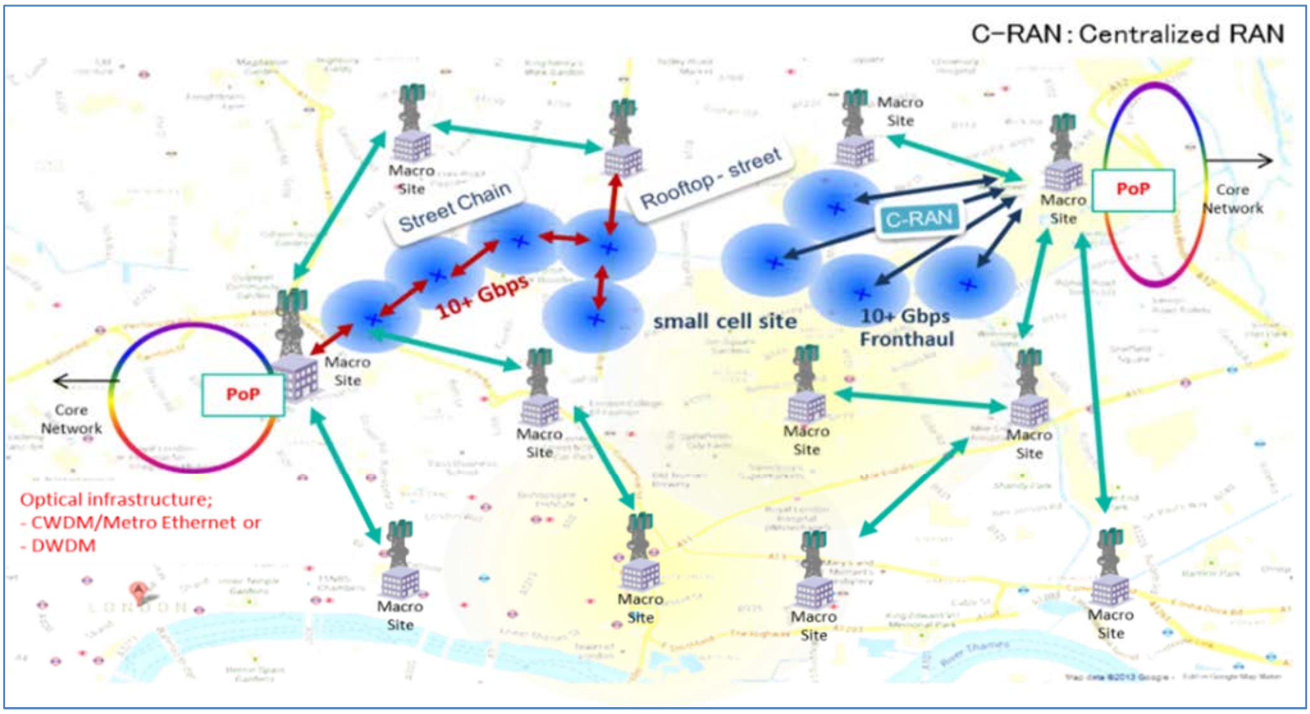

Figure 9: 5G Backhaul Tail Link

Table 3: Tail link basic requirements

Basic requirements for 5G BH Tail Link	
Capacity	> 10 Gbps
Link Distance	< 200 m

4.5.3 Internal Connection of a Data Center (Inter-Server)

An example of internal connection of a data centre is shown in figure 10, some basic description of current systems are given in table 4.

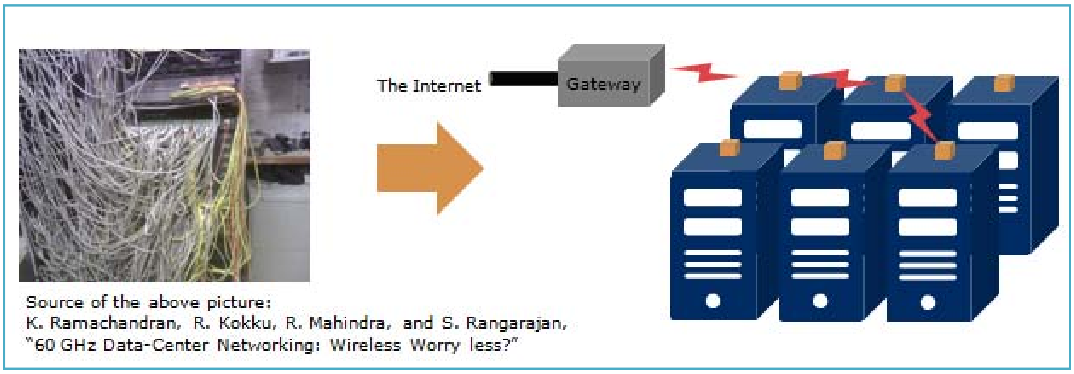

Figure 10: Inter-Server Connection (source : NEC Europe Ltd)

Table 4: Example of basic requirements of Inter-Server Connection

Current System basic requirements	
Media	Optical Fiber 10 GbE (Indoor)
Link Distance	Several tens of meters (Direct Distance)

These capacities are not currently foreseen in any applications related to W band (as IEEE802.15WPAN for 60 GHz [i.10]).

4.5.4 Requirements for Future Applications in mm-wave Radio

Main requirements for future application is summarized in table 5.

Table 5: Future Applications main requirements

	Main Requirements	
High Capacity	> 10 Gbps	Target capacity is 40 Gbps considering 40 GbE for a server connection
Medium Link Distance	Up to several hundreds of meters	Short range is to be covered
High Availability	Up to 99,999 %	As an alternative of fiber cable
		Indoor use is free from rain attenuation
Dual-Directional Communication	Symmetrical/Asymmetrical	
	FDD/TDD	

Example of the above set of requirements implies big changes in the network topology, requiring very high throughputs in very dense networks at an extremely high availability.

Large volume applications in the backhaul and fronthaul, able to support all services requiring very high speed wireless transmission, drive to the higher part of the spectrum.

Given the very stringent capacity, latency and availability 5G targets, combined with sites densification, it is likely that in the access and pre-aggregation network segments, a mix of different transmission technologies (fiber, mmW links, MW links and self-backhaul) will be needed to reach a radio site.

In clause 4.5.5 a table with the applications and use cases relevant to transmission networks evolution is provided. An additional table is included, that points out which use cases can be served by the D-band or which ones need additional support from microwave or lower mmW bands.

4.5.5 First Prototypes and Early Deployment

4.5.5.0 Overview

This clause provides an overview of the first prototypes.

4.5.5.1 The DREAM project

The Nokia Bell Labs conducts the research and innovation in the NOKIA group in various activities. In the specific field of radio, Nokia Bell Labs is researching in frequency bands up to 1 THz covering different fields of applications. Figure 11 shows a W-Band beam steering prototype.

More information about this project, is available on following link: http://www.h2020-dream.eu/.

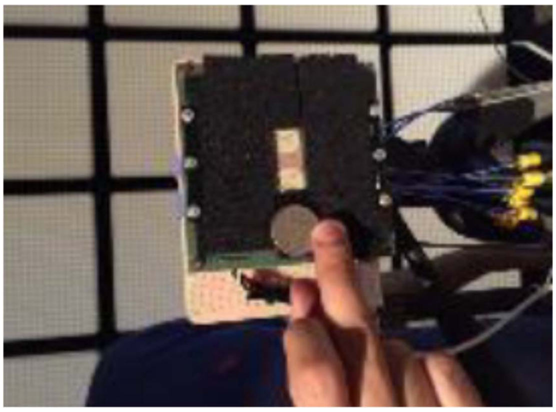

Figure 11: W-Band beam steering prototype

4.5.6 Applications and Use Cases

Clause 5 deals with the foreseen set of requirements aimed to support future 5G transmission networks. Applications and use cases are reported in table 6 for different segments of the network: macro layer, small cell layer and fixed access. Moreover, backhaul and front-haul applications are indicated, even if new generation XHAUL requirements are still to be defined.

Table 6: Applications and Use Cases for 5G Networks

Applications and Use Cases for 5G Networks										
GENERAL REQUIREMENTS		APPLICATIONS								
		5G MACRO CELL LAYER			SMALL CELL LAYER			FIXED ACCESS		
		BACKHAUL	NG XHAUL **	FRONTHAUL*	BACKHAUL	NG XHAUL **	FRONTHAUL*	WttC	WttH	Public Safety (Video-surveillance, etc.)
Network	Area (e.g. urban, sub-urban, rural)	Urban/Sub-urban						Urban/Sub-urban / Clustered Rural		Urban
	Deployment Level (rooftop-to-rooftop/rooftop-to-street/street-to-street)	Rooftop-to-Rooftop			Street-to-Street / Rooftop-to-Street			Rooftop-to-Street	Street-to-Street / Rooftop-to-Street	Street-to-Street
	Network Segment (e.g. access, pre-aggregation, aggregation)	Access, pre-aggregation		Access, pre-aggregation, aggregation	Access (SC layer)		Access (SC layer)	Access/Pre-Aggregation	Access	Access
	RF Path Clearance (LOS/nLOS/NLOS)	LOS		LOS	LOS/nLOS/NLOS		LOS/nLOS/NLOS	LOS/nLOS/NLOS	LOS/nLOS/NLOS	LOS/nLOS/NLOS
	Connectivity (PtP, xtMP)	PtP/xtMP		PtP/xtMP	PtP/xtMP		PtP/xtMP	PtP/xtMP	PtP/xtMP	PtP/xtMP
	Link Density	TBD		TBD	TBD		TBD	TBD	TBD	TBD
Features	Services Capacity (Note 2)	n x 10 / 100 Gbps			20+ Gbps			10 - 40 Gbps	1 - 10 Gbps	1 Gbps
	Capacity for mmW link	n x 10 Gbps		Subject to FH interface (≠CPRI)	1-10 Gbps		Subject to FH interface (≠CPRI)	10 - 40 Gbps	1 - 10 Gbps	up to 1Gbps
	Capacity asimmetry (Downlink/Uplink)	Unknown, however 5G radios will be TDD		1:1	Unknown, however 5G radios will be TDD		1:1	1:1 / 1:2	1:2 / 1:4	1:2 / 1:4
	Transmission Distance (Note 1)	Urban: <2km Sub-urban: 2-10km		Urban: <5km Sub-urban: 3-20km	<300m		<300m	Urban: <1km Sub-urban: <3km	<300m	<300m
	Services Availabilty (Note 2)	TBD (99.999 - 100%)		TBD	TBD (99.999 - 100%)			99.99% - 99.999%	99.9 - 99.99%	99.9%
	mmW link Availability (@ Capacity for mmW link) (Note 2)	99.9 - 99.99%		99.999%	99.5 - 99.9%		99.999%	99.9 - 99.99%	99.5 - 99.9%	99.5%
	Packet Delay (e2e)	Subject to service (e.g. 1ms)		Subject to FH interface (≠CPRI)	Subject to service (e.g. 1ms)		Subject to FH interface (≠CPRI)	Subject to service	Subject to service	Subject to service
	Wireless link latency	< 0.2 ms			< 0.2 ms			< 3 ms	< 1 ms	< 3 ms
	Form Factor	Baseline		Baseline	Very Important		Very Important	Important	Very Important	Very Important
	Automation	Yes, if adds value to system gain and facilitates antenna alignment		Yes, if adds value to system gain and facilitates antenna alignment	Yes		Yes	Yes, if adds value to system gain and facilitates antenna alignment	Yes	Yes
Non-Technical Enablers	Spectrum Licensing	To Be Defined		To Be Defined	To Be Defined		To Be Defined	To Be Defined	To Be Defined	To Be Defined

***** FH interface based on CPRI / ORI / OBSAI

Note 1: In case of mmW links, longer distances than those reachable with D-band could be achieved through BCA: "Where a single hop is not able to cover few km and huge throughput, the BCA could make it viable"

Note 2: Given very stringent Capacity/Latency/Availability 5G targets, plus sites densification, it is likely that in access and pre-aggregation segments a mix of different transmission technologies (fiber, mmW/MW links, self-BH, etc.) are needed to reach a radio site

As a consequence, requirements of Capacity/Availability are described as follows:

· Services Capacity / Availability for the backhaul network; it is likely that the overall services capacity shall not be guaranteed with most stringent availability target (related to mission critical services)

· Technology specific (in our case mmW Link) Capacity/Availability which contributes to deliver service targets depending on technology mix and topology adopted by each Operator.

Services availability could also be achieved by combining mmW link with either fibre or self-BH.

5 Basic Considerations on Channel Arrangements

5.0 Radio Regulations

RF bands allocated to fixed service (FS) by the ITU Radio Regulation 2016 [i.4], are shown in table 7.

Table 7: ITU Table of Frequency Allocation (Radio Regulation 2016)

Allocation to services	
Band [GHz]	**Region 1 - Region 2 - Region 3**
92 to 94	**FIXED** **MOBILE** **RADIO ASTRONOMY** **RADIOLOCATION**
94 to 94,1	
94,1 to 95	**FIXED** **MOBILE** **RADIO ASTRONOMY** **RADIOLOCATION**
95 to 100	**FIXED** **MOBILE** **RADIO ASTRONOMY** **RADIOLOCATION** **RADIONAVIGATION** **RADIONAVIGATION-SATELLITE**
102 to 105 & 105 to 109,5	**FIXED** **MOBILE** **RADIO ASTRONOMY** **SPACE RESEARCH (passive) - 105 to 109,5 only**
111,8 to 114,25	**FIXED** **MOBILE** **RADIO ASTRONOMY** **SPACE RESEARCH (passive)**

CEPT published ECC Recommendation (18)02 [i.2], which specifies possible channel plans for the W band, based on a channelization with 250 MHz wide channels, allowed to be grouped to obtain wider channels; basic subdivision of channels is reported in figure 12 of the present document.

It should be noted that ECC Recommendation (14)01 [i.15] (Radio frequency channel arrangements for fixed service systems operating in the band 92 to 95 GHz) provides a channel plan to be used in the 92 to 95 GHz, partially overlapping with Recommendation ECC (18) 02 [i.2], which includes specific options to address this frequency range

5.1 Radio-frequency channel arrangements in the band 92 to 114,25 GHz

This clause shows the basic channel raster, reported in figure 12, and the related formulas for centre frequencies of single channels, as foreseen by ECC Recommendation (18)02 [i.2].

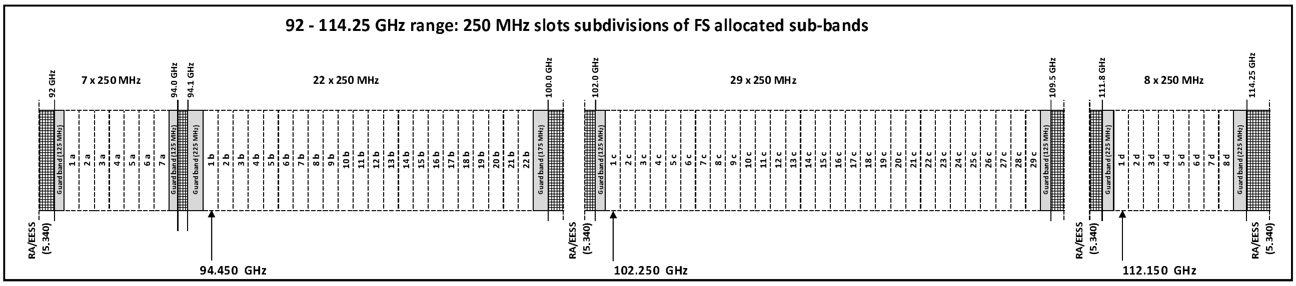

Figure 12: Basic channels raster for FS use in the 92 to 114,25 GHz RF band

Centre frequency of channels can be obtained as follows:

Fn = 92 + N × 0,250 GHz	N: 1 to 7	Sub-band "a"
Fn = 94,1 + 0,1+ N × 0,250 GHz	N: 1 to 22	Sub-band "b"
Fn = 102 + N × 0,250 GHz	N: 1 to 29	Sub-band "c"
Fn = 111,8 + 0,1 + N × 0,250 GHz	N: 1 to 8	Sub-band "d"

6 State of the Art of Technology

6.0 Introduction

This clause examines technological aspects, also addressing the D band.

6.1 Overview of Technological Maturity

This clause provides an overview of technological maturity related to the W-band and the D-band (channel filters width, intelligent antenna availability, expected spectral efficiency, components frequency limitations etc.).

ETSI White Paper No. 15 mmWave Semiconductor Industry Technologies: Status and Evolution [i.1], provides further details on available technology and technology trends.

6.2 Semiconductor technology for W-band: technological maturity and component frequency limitations

Semiconductor technologies for use beyond 100 GHz, covering upper portion of W band, have undergone a very high evolution in the past few decades, driven largely by the space, defence and imaging industries. There are at least six compound semiconductor fabs (III-V) and five silicon based fabs capable of producing ICs for W and D-band. Table 8 gives an overview of semiconductor technologies capable of operating beyond 100 GHz.

Table 8: Overview of semiconductor technologies beyond 100 GHz and their key parameters (Source: Ericsson/ST)

Technology	Feature size (nm)	fMAX (GHz)	Vbr (V)	Nfmin (dB) at 50GHz**	Production or research?
GaAs pHEMT	100	185	7	0.5	P
GaAs mHEMT	70	450	3	0.5	R*
GaAs mHEMT	35	900	2	1	R
InP HEMT	130	380	1	<1	R
InP HEMT	30	1200	1	<1	R
GaN HEMT	60	250	20	1	R
GaN HEMT	40	400	42	1.2	R
SOI CMOS	45	280	1	2-3	P
SiGe-HBT	55	400	1.55	1.5	P
SiGe-HBT	130	400	1.4	2	P
InP DHBT	250	650	4	3	R*
InP DHBT	130	1100	3		R

* Ready to be commercialized in 1-2 years
** Nfmin is proportional to the frequency

The main high frequency transistor technology classes are HBT, HEMT, and MOSFET, where MOSFET is typically implemented in SOI CMOS for high frequency operation. A key property is the feature size, since a transistor with smaller feature size supports higher frequencies. As a rule of thumb circuits are designed to operate below fMAX/3, where fMAX is the frequency at which the transistor's power gain is equal to one.

It is possible to bring the operation frequency much closer to fMAX but, depending on the technology, doing so may result in lower power efficiency and higher design complexity. Other important material properties are the minimum noise figure (NFmin) and the breakdown voltage (Vbr), which determine receiver sensitivity and maximum transmitted power. Flicker noise generation, memory effects and temperature behaviour are not included in table 8, but should also be considered.

The maximum transmitted power and minimum receive noise figure limit the system gain. Research has been published on power amplifiers in GaAs, InP and SiGe technologies delivering more than 10 dBm of output power beyond 130 GHz. GaAs pHEMT provides high breakdown voltage and a low noise figure and, in a few years, is also expected to be able to support the D-band. In GaAs mHEMT and InP pHEMT & DHBT technologies support very high frequencies. These technologies are widely used in aerospace applications but have limited commercial availability, however because of their excellent performance they have been valuable in D-band research and predevelopment activities.

Silicon technologies such as SOI CMOS and SiGe-HBT are today feasible up to W-band (92 to 114,5 GHz) although the maximum output power is limited due to the low breakdown voltage of silicon and the noise figure is worse compared to GaAs and InP technologies. The newer generations of SiGe/BiCMOS technologies have fMAX in the region of 300 to 400 GHz, further increase in fMAX above 400 GHz is under investigation, however as figure 13 shows, nMOS (SOI CMOS) seems to have an optimum of fMAX at 28 nm so may not catch-up with SiGe (BiCMOS).

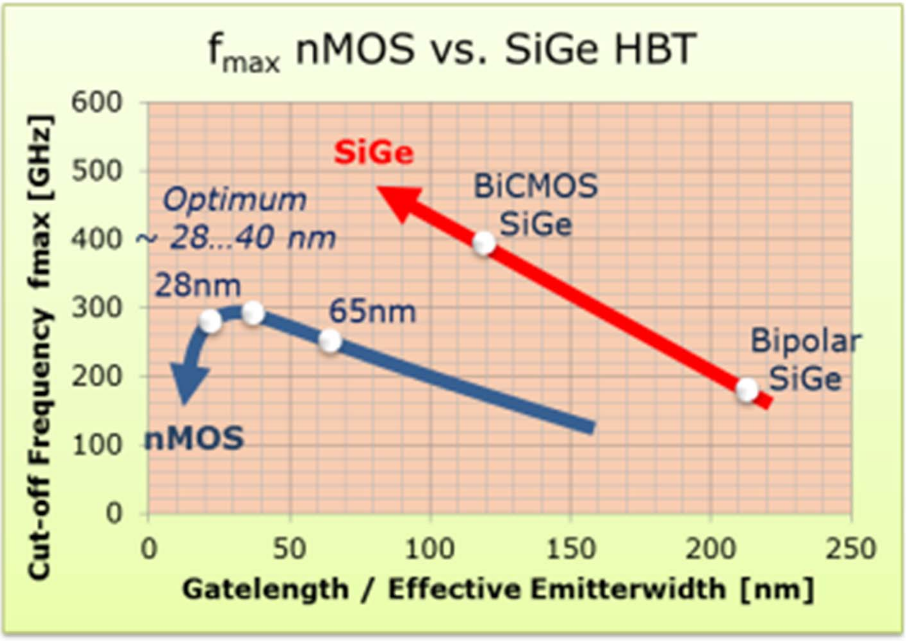

Figure 13: Overview of fMAX for SiGe (BiCMOS/HBT) and nMOS technologies (Source: Infineon Technologies AG)

Silicon technologies are promising for short-range, low-cost applications due to the excellent properties for high integration however performance limitations are expected in the frequency bands above 140 GHz.

Figure 14 shows examples of the performance demonstrated in D-band of power amplifiers and low noise amplifiers manufactured on III-V and Si technologies [i.16].

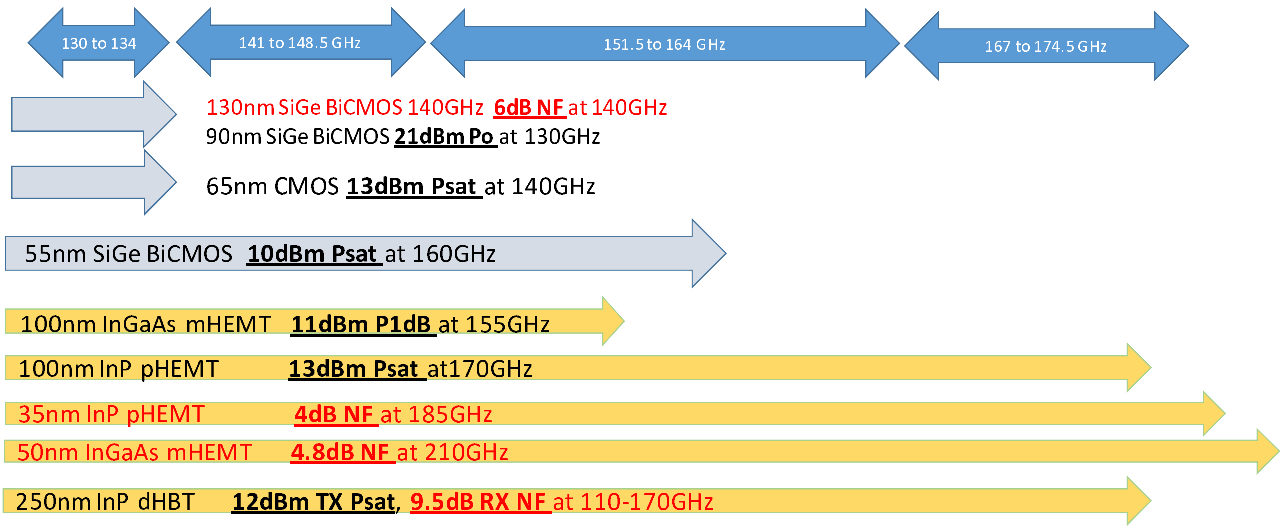

Figure 14: Performance for LNAs (red) and PAs (black) described in the literature (Source: Filtronic/ST)

Packaging and interconnect above 100 GHz are challenging due to the short wavelengths. Parasitic effects are more pronounced and the tolerance requirement is high in design, manufacturing and assembly, especially when considering wide bandwidths. Crosstalk and unwanted resonances are additional issues since the typical MMIC size is of the order of the wavelength. This makes traditional interconnects, such as wire bonding and flip chip, difficult to use with high yield.

7 Summary and Conclusions

The millimetre wave spectrum allows new scenarios and pushes to identify the most suitable bands for future transmission networks within 5G scenarios. Moreover, the 5G requirements imply major changes in the network topology, requiring very high throughputs in very dense networks at an extremely high availability.

The development of new technologies and the use of higher frequency bands allow microwave to remain a fundamental building block of mobile networks even in this framework of ever-increasing demands in terms of coverage, capacity, latency and reliability.

More than 16 GHz of spectrum is available in the W-band. The gas attenuation in the band is almost flat and so is the rain attenuation.

Possible use of the W band in dense urban scenarios to allow capacities up to few Gbps is observed as less capable than the D-band, due to the minor amount of available spectrum, and the higher fragmentation compared to D band.

However, the propagation characteristics allows good frequency re-usability which, together with the large channel bandwidths available make W-band suitable for transmitting significant high capacity with using very compact antennas and low power, potentially useful in proper sections of future 5G networks, to support overall expected capacity increase.

Optimized trade-off between very wide channels and spectrum efficiency allows achieving very compact form factors and low power consumption even in case of very wide capacity applications, such as FWA, backhaul and front-haul.

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NOTE: Available at https://www.etsi.org/deliver/etsi_en/302200_302299/30221703/.

- ETSI EN 302 217-4-2 (V1.4.1): "Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 4-2: Antennas; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive".

NOTE: Available at https://www.etsi.org/deliver/etsi_en/302200_302299/3022170402/01.04.01_60/en_3022170402v010401p.pdf.

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