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millimetre Wave Transmission (mWT); Analysis of Spectrum, License Schemes and Network Scenarios in the D-band

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Contents

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Foreword

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

All Companies referenced in the present document have given the consensus of all the material provided herewith.

Modal verbs terminology

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Executive summary

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

Interest in millimetre-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 a very compact antenna size and extreme low power.

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

Standardization activities are now under way of the so-called W-band (92 - 114,5 GHz) and D-band (130 - 174,8 GHz).

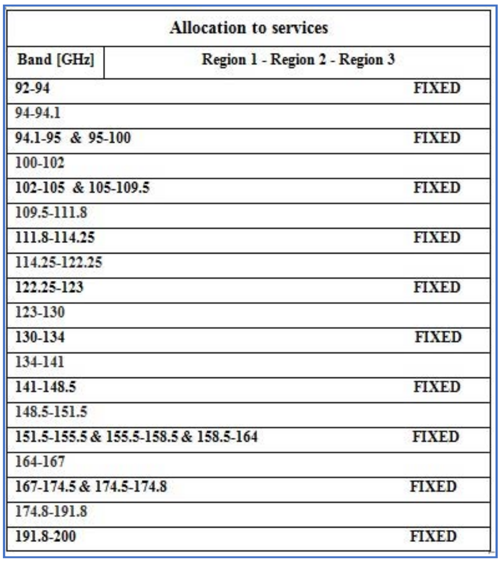
The present document provides an overview of the possible applications and use cases for the D-band, state of the art of the technology at such high frequencies and also possible channel schemes which can be used, including the so called "duplexer-free" scheme.

Although the present document is focused on the D-band, information and considerations on the W-band are included where appropriate and beneficial to the readers.

Introduction

Frequency bands above 100 GHz have not been commercially exploited yet and have not been regulated yet by specific recommendations.

The W-band and D-band are already considered in the table of frequency allocation issued by the ITU-R Radio Regulation 2016 [i.5].



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
123-130	
130-134	FIXED
134-141	
141-148.5	FIXED
148.5-151.5	
151.5-155.5 & 155.5-158.5 & 158.5-164	FIXED
164-167	
167-174.5 & 174.5-174.8	FIXED
174.8-191.8	
191.8-200	FIXED

Figure 1: ITU Table of Frequency Allocation (Radio Regulation 2016) [i.5]

The table indicates fixed service (FS), and that covers all the applications of interest to ISG mWT, and which have a primary status, when considering the frequency band from 92 up to 200 GHz.

The allocation between 92 and 200 GHz is common for all three ITU regions, which facilitates the scenarios and spectrum usage solutions covering these bands.

Moreover, new spectrum and innovative ways to use the bands, new concepts related to availability 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 regulation.

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

1 Scope

The present document describes possible scenarios and spectrum usage and proposes, aligned with CEPT ECC SE19 Working Item 37 [i.3], the channelization of the D-band (130 - 174,8 GHz) 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 and the D-band are 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 and D-band are considered to analyze system behaviours and evaluate reachable distances and possible achievable throughputs.

In the absence of standardized channel plans for both the W-band and D-band, guidelines for efficient deployment in terms of spectrum, license schemes and other relevant aspects in those bands are being proposed, also considering non-operator services, in the vision of significant market share.

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: "mmWave Semiconductor Industry Technologies: Status and Evolution".

NOTE: Available at mmWave Semiconductor Industry Technologies: Status and Evolution.

[i.2] Abhiram Chakraborty, Saverio Trotta (Infineon Technologies AG) and Robert Weigel (Lehrstuhl für Technische Elektronik, FAU Erlangen-Nürnberg):"A Low Power Multichannel Receiver for D-Band Sensing Applications in a 0,13 µm SiGe BiCMOS Technology (*here defined up to 132 GHz)".

[i.3] SE19(17)16A09: "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".

[i.4] SE19(17)16A10: "Radio frequency channel/block arrangements for fixed service systems operating in the bands 130 - 134 GHz, 141 - 148,5 GHz, 151,5 - 164 GHz and 167 - 174,8 GHz".

[i.5] ITU-R Radio Regulation 2016.

[i.6] Recommendation ITU-R P.530-16 (07/2015): "Propagation data and prediction methods required for the design of terrestrial line-of-sight systems".

[i.7] 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".

[i.8] 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".

[i.9] Recommendation ITU-R P.838-3: "Specific attenuation model for rain for use in prediction methods".

[i.10] Recommendation ITU-R F.1703: "Availability objectives for real digital fixed wireless linksused in 27 500 km hypothetical reference paths and connections".

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

[i.12] IEEE 802.15™: "WPAN for 60 GHz".

[i.13] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman: "Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes", Physical Review A, vol. 45, no. 11, 1992.

[i.14] N. Bozinovic, et al: "Terabit-scale orbital angular momentum mode division multiplexing in fibers", Science, vol. 340 no. 6140 pp. 1545-1548, 2013.

[i.15] F. Tamburini, et al.: "Encoding many channels on the same frequency through radio vorticity: first experimental test", New Journal of Physics 14, 2012.

[i.16] J. Butler and R. Lowe: "Beamforming matrix simplifies design of electronically scanned antennas", Electronic Design, vol. 9, pp. 170-173, 1961.

[i.17] EIA RS-261-B: "Rectangular Waveguides (WR3 to WR2300)".

[i.18] IEC 60153-2:2016: "Hollow metallic waveguides - Part 2: Relevant specifications for ordinary rectangular waveguides".

[i.19] Yuan-Hung Hsiao, Zuo-Min Tsai, Hsin-Chiang Liao, Jui-Chih Kao and Huei Wang: "Millimeter-Wave CMOS Power Amplifiers With High Output Power and Wideband Performances", IEEE Transactions on microwave theory and techniques, Vol. 61, NO. 12, December 2013.

[i.20] Recommendation ECC REC (18)01: "Radio frequency channel/block arrangements for Fixed Service systems operating in the bands 130 - 134 GHz, 141-148,5 GHz, 151,5-164 GHz and 167 - 174,8 GHz".

[i.21] Recommendation ITU-R F.1668: "Error performance objectives for real digital fixed wireless links used in 27 500 km hypothetical reference paths and connections".

3 Abbreviations

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

5G	Fifth Generation of Mobile Networks
BCA	Band and Carrier Aggregation
BER	Bit Error Rate
BH	BackHaul
BW	BandWidth
CMOS	Complementary Metal Oxide Semiconductor
DHBT	Double Heterojunction Bipolar Transistor
DS	Duplex Spacing
EM	ElectroMagnetic
FDD	Frequency Division Duplex
FS	Fixed Service
FWA	Fixed Wireless Access
Gbaud	Giga baud
HBT	Heterojunction Bipolar Transistor
HEMT	High Electron Mobility Transistor
LOS	Line Of Sight

LTE	Long Term Evolution
LTE-A	LTE-Advanced
MAG	Maximum Available Gain
MMIC	Microwave Monolithic Integrated Circuit
MOS	Metal Oxide Semiconductor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MW	MicroWave
OAM	Orbital Angular Momentum
PA	Power Amplifier
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuit
RX	Receiver
SOI	Silicon On Insulator
TCE	Thermal Coefficient of Expansion
TDD	Time Division Duplex
TX	Transmitter
VBE	Base-Emitter Voltage
VCB	Collector-Base Voltage
VCO	Voltage Controlled Oscillator
XHAUL	generic (X) split within LTE/5G protocol stack between fronthaul and backhaul

4 Introduction to the W-band and the D-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 all services that require high speed and very large bandwidths.

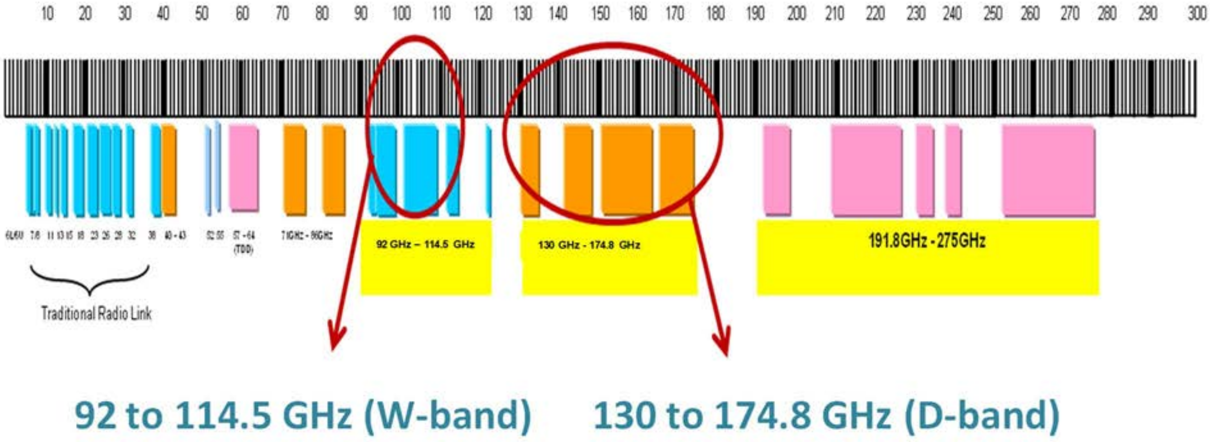


Figure 2: W and D bands spectrum

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

These portions have the following bandwidth (size in GHz), ranging from 1 GHz - 12,5 GHz.

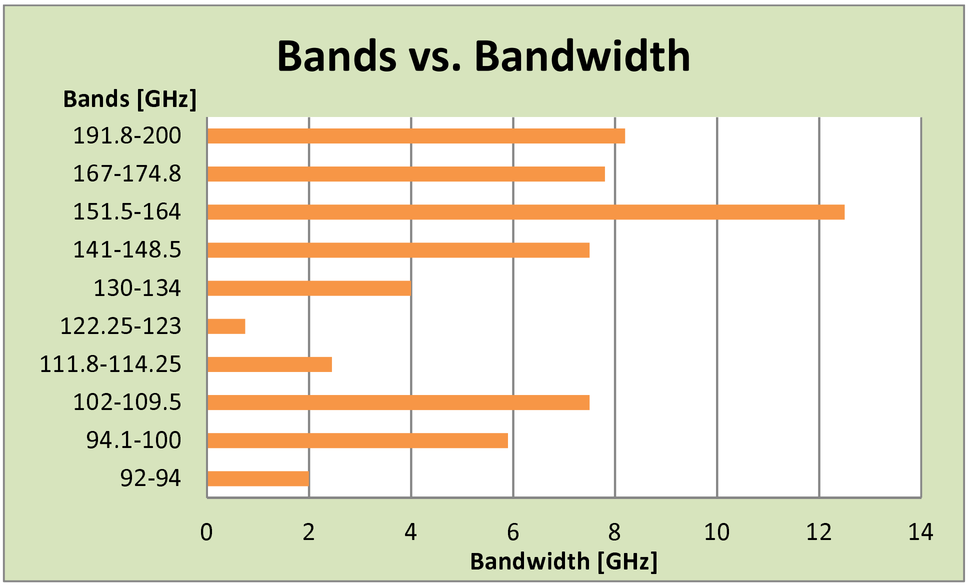


Figure 3: Portions of available spectrum in the range 92 - 200 GHz (Source: Nokia)

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 - 76 GHz and 81 - 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 it into new bands and how to consider each band into channels, if any.

The existing standard of waveguides [i.17], [i.18] allows the following use:

Table 1: Designation of waveguides

Designation EIA/IEC	US commercial designation & f_{min} - f_{max} [GHz]		Cut-off Frequencies [GHz]	Band
WR8/R1200	RG138 (silver)	90,00 - 140,0	73,8	W-band
WR7/R1400	RG136 (silver)	110,0 - 170,0	90,8	D-band

Regarding the activities related to the W-band and the D-band, including possible frequency arrangements, two Work Items have been opened in CEPT ECC SE19, the Work Item on W-band (SE19 37) [i.3] and the Work Item on D-band (SE19_38) [i.4], with the scope to facilitate the deployment of fixed services in the frequency blocks already allocated to fixed services in the bands 92 - 94 GHz, 94,1 - 95 GHz, 95 - 100 GHz, 102 - 109,5 GHz and 111,8 - 114,5 GHz for the W-band and in the bands 130 - 134 GHz, 141 - 148,5 GHz, 151,5 - 164 GHz and 167 - 174,8 GHz for the D-band.

These work items aim to provide ECC Recommendation(s) guidelines on the deployment of fixed services operating in the mentioned bands.

The outcome of this analysis has been liaised to CEPT WG SE19, and may be liaised to other relevant groups for discussion.

5 ITU Regulations concerning the W-band and the D-band

5.1 ITU Regulations concerning Frequency Allocation

- Recommendation ITU-R Radio Regulation 2016 [i.5].

5.2 ITU-R Regulations concerning Propagation Aspects

- Recommendation ITU-R P.530-16 (07/2015) [i.6]: Propagation data and prediction methods required for the design of terrestrial line-of-sight systems.
- Recommendation ITU-R P.1411-1 [i.7]: 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 (02/2012) [i.8]: 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.9]: Specific attenuation model for rain for use in prediction methods.

Apart from Recommendation ITU-R P.838-3 [i.9], which is valid up to 1 000 GHz, the range of validity is up to 100 GHz.

5.3 ITU-R Regulations concerning Error Performance and Availability objectives

- Recommendation ITU-R F.1668 [i.21].
- Recommendation ITU-R F.1703 [i.10].

Formulas are provided in Recommendation ITU-R F.1703 [i.10] to establish availability objectives for real links.

6 Characteristics of the W-band and the D-band

The rain attenuation in the W-band and in the D-band can be derived from figure 4. It should be noted that the rain attenuation in the D-band is around 2 dB larger than in the E-band. In addition it should be noted that the rain attenuation in the D-band is almost flat.

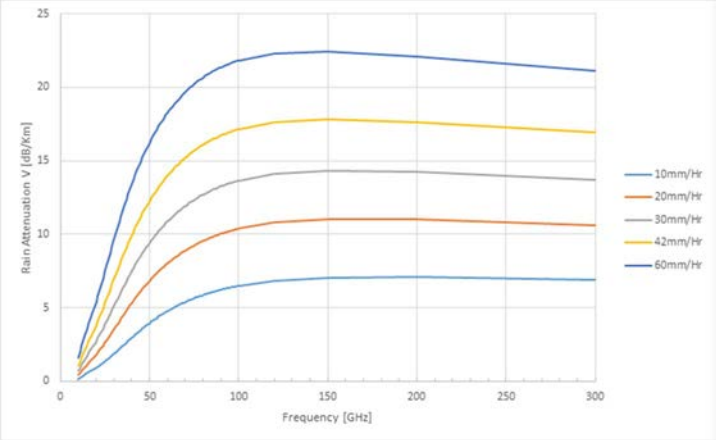


Figure 4: Specific rain attenuation up to 300 GHz (Source: Recommendation ITU-R P.838-3 [i.9])

Regarding gas attenuation, it is 1 - 2 dB/km in the D-band. This is not a dominant factor for the link distance limitation.

The gas attenuation in the D-band is almost flat. In the W-band it is lower than 1 dB/km.

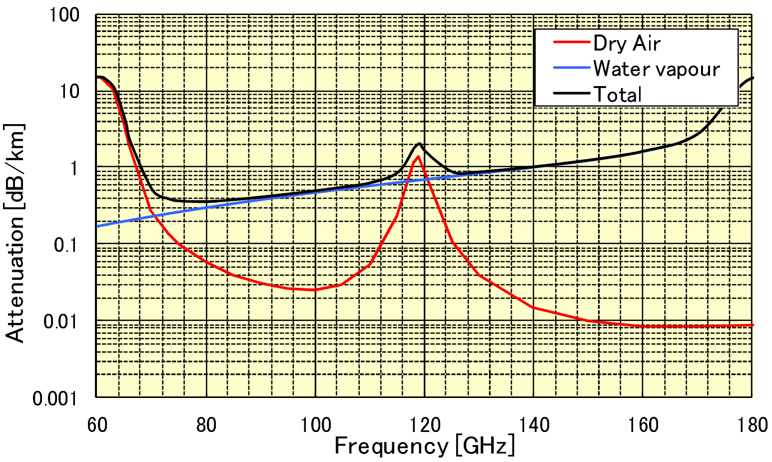


Figure 5: Specific gas attenuation up to 180 GHz (Source: Recommendation ITU-R P.676-11 [i.11])

Compared to the V-band, both the W-band and the D-band, similarly to the E-band, are in the part of spectrum which is not affected by the Oxygen absorption peaks.

7 System Behaviour

7.1 D-band system simulation

In order to evaluate 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 the 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. 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:

- Recommendation ITU-R P.530-16 [i.6].
- Recommendation ITU-R P.838-3 [i.9].
- Recommendation ITU-R P.676-11 [i.11]: specific attenuation due to atmospheric gases (dB/km) is derived from figure 5 in Annex 2 (Pressure = 1 013,25 hPa; Temperature = 15 °C; Water Vapor Density = 7,5 g/m3).

It should be mentioned that Recommendation ITU-R P.530-16 [i.6] 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 - 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 - 2 000 meter/rain rate 10 - 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.

The first graph in figure 6 shows the relation between the gross system gain and the maximum hop length in the W-band and in the D-band with different availabilities.

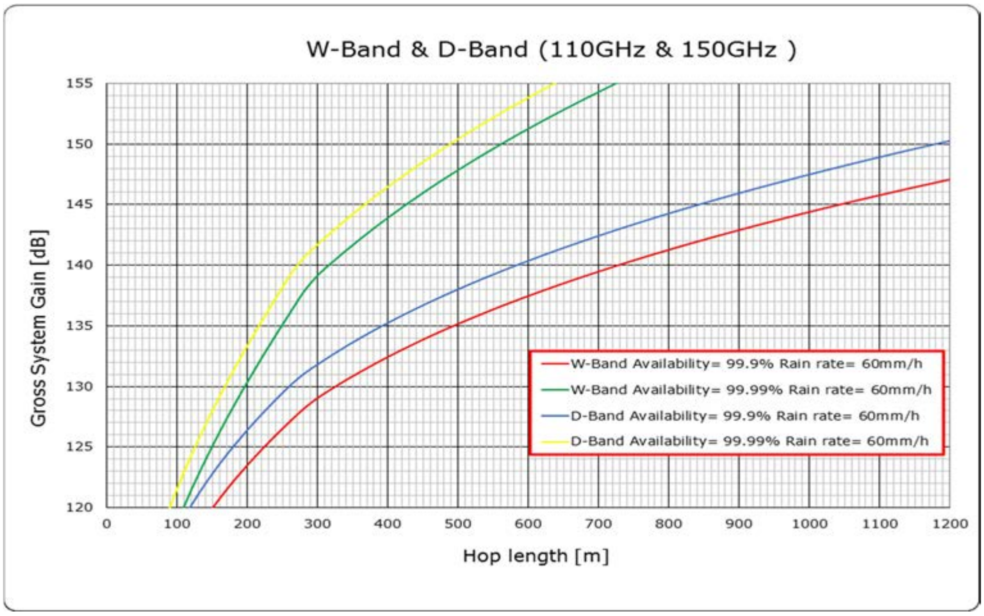
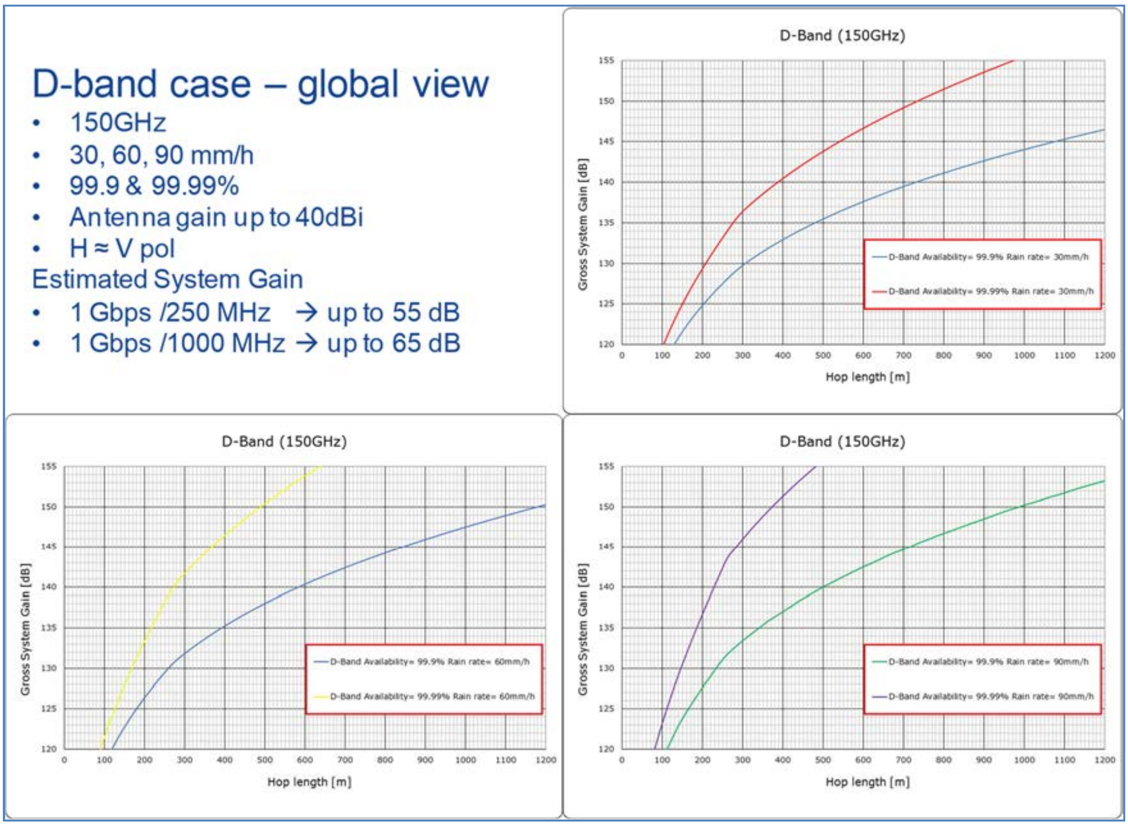


Figure 6: W and D-band - Gross System Gain vs. Max hop length for different availabilities and 60 mm/h rain rate

Under the same conditions, antenna and system gain, the differences in hop length are close to 20 %.

Figures 7, 8, 9 and 10 provide an overview of the W-band and the D-band reachable distances for different rain rates and availabilities.



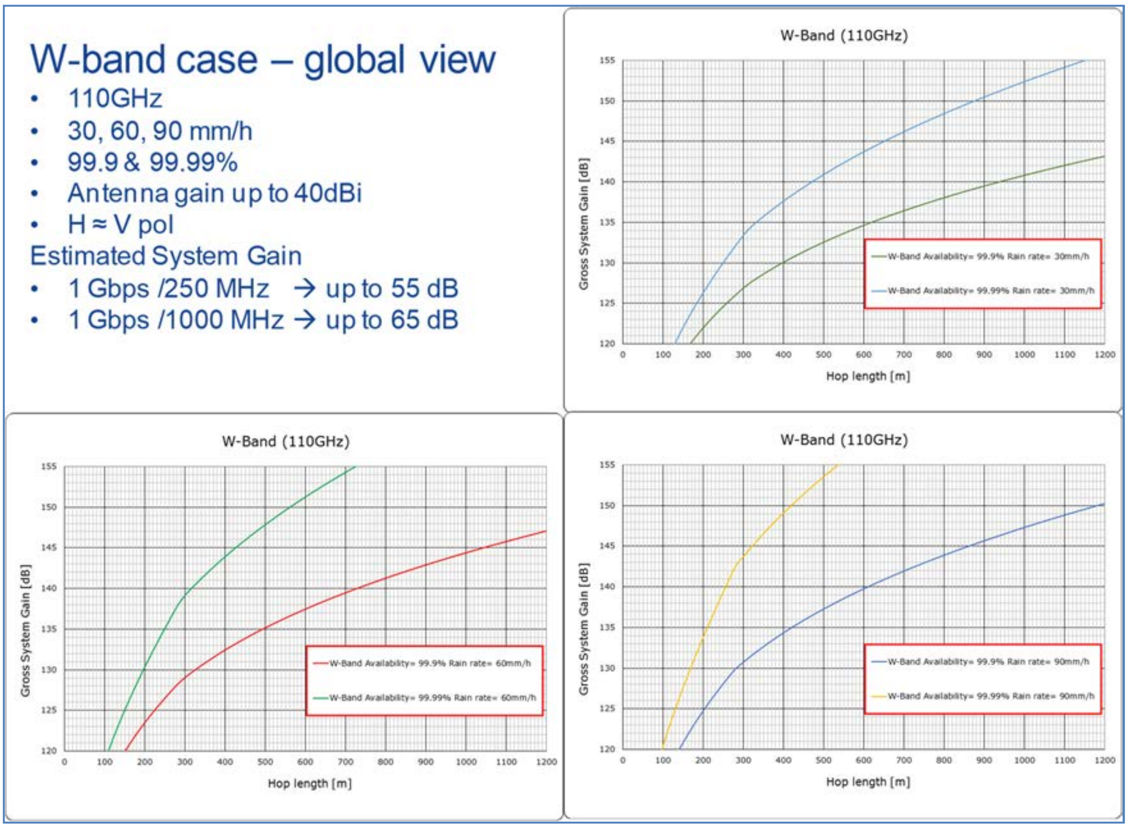
D-band case – global view

- 150GHz
- 30, 60, 90 mm/h
- 99.9 & 99.99%
- Antenna gain up to 40dBi
- H ≈ V pol

Estimated System Gain

- 1 Gbps /250 MHz → up to 55 dB
- 1 Gbps /1000 MHz → up to 65 dB

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



W-band case – global view

- 110GHz
- 30, 60, 90 mm/h
- 99.9 & 99.99%
- Antenna gain up to 40dBi
- H ≈ V pol

Estimated System Gain

- 1 Gbps /250 MHz → up to 55 dB
- 1 Gbps /1000 MHz → up to 65 dB

Figure 8: Achievable distances at W-band with 1 Gbps throughput

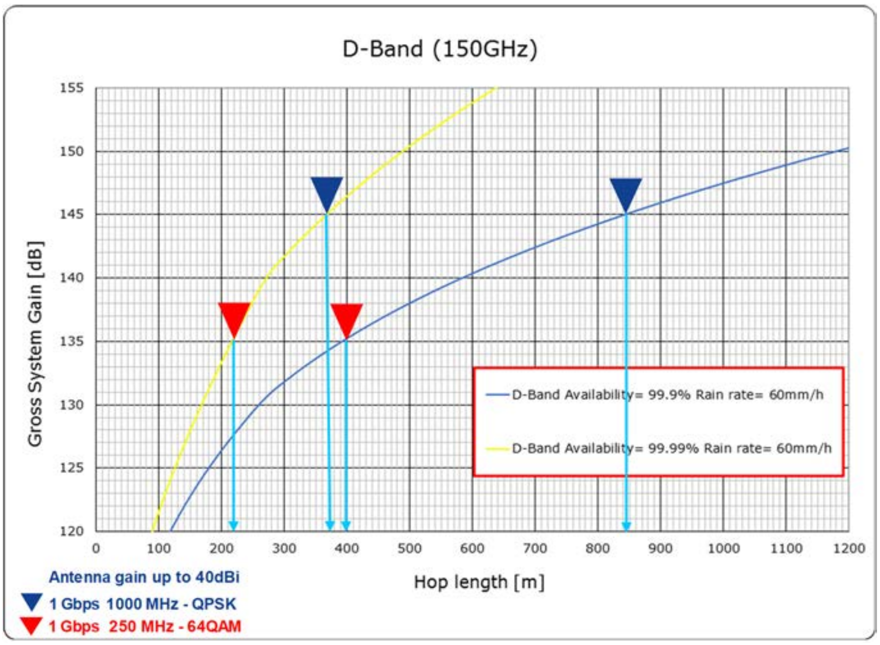


Figure 9: Achievable distances at D-band with 1 Gbps throughput and different modulation schemes

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

8 Use cases and possible applications

8.1 From current high capacity systems to 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.

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.

8.2 D-band: Backhaul, fronthaul and fixed wireless access

More than 30 GHz of spectrum is available in the D-band. Optimized trade-off between very wide channels and spectrum efficiency allows achieving very compact and low power consumption for fixed wireless applications and ultra-high capacity for backhaul and front-haul.

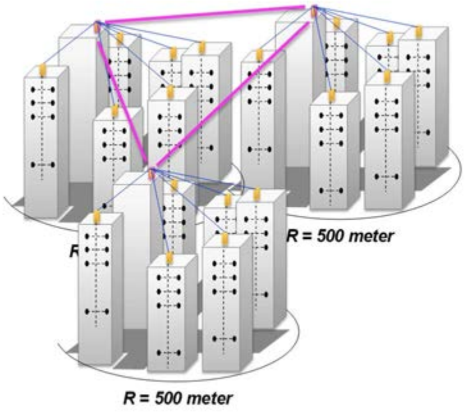


Figure 11: D-band possible application scenario (blue lines; E-band represented by the pink lines)

8.3 5G Mobile Backhaul Tail Link

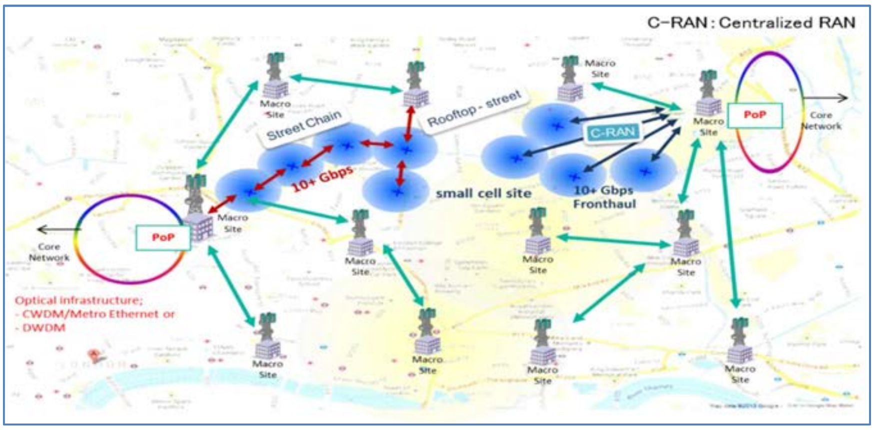
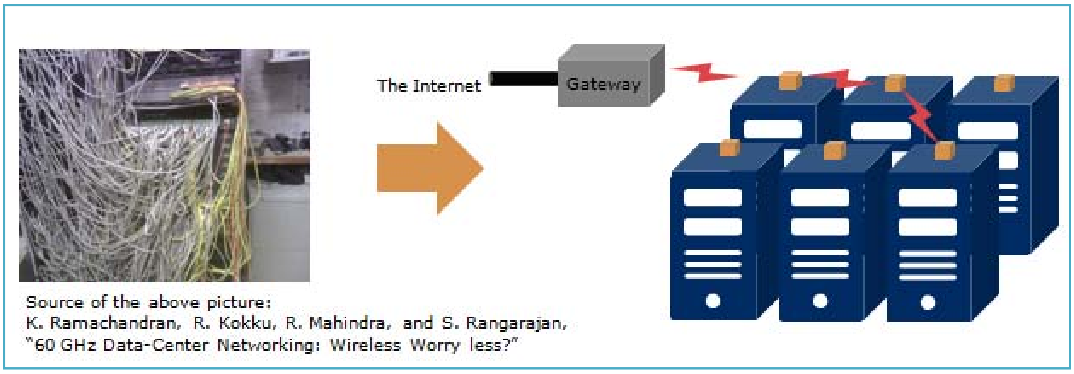


Figure 12: 5G Backhaul Tail Link

Table 3: 5G BH tail link requirements

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

8.4 Internal Connection of a Data Centre (Inter-Server)



Source of the above picture:
K. Ramachandran, R. Kokku, R. Mahindra, and S. Rangarajan,
"60 GHz Data-Center Networking: Wireless Worry less?"

Figure 13: Inter-Server Connection (Source: NEC Europe Ltd)

Table 4: Inter-server connection requirements

Current System	
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 the W-band and the D-band (as IEEE 802.15 [i.12] WPAN for 60 GHz).

8.5 Requirements for future applications in mm-wave radio

Table 5: Prospect of Requirements for Future Applications in mmW Radio

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 fibre cable
		Indoor use is free from rain attenuation
Dual-Directional Communication	Symmetrical/Asymmetrical	
	FDD/TDD	

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

In the next clause 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.

8.6 Applications and Use Cases

The following is the foreseen set of requirements aimed to support future 5G transmission networks. Applications and use cases are reported 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 have still to be defined.

The second table distinguishes which use cases can be served by the D-band only and which ones can be covered by other mmW, possibly also taking advantage of BCA.

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.

Table 7: D-band Solution Mapping within Applications and Use Cases for 5G Network

D-band Solution Mapping										
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
	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
	Transmission Distance (Note 1)	Dense urban: <1km Urban: <2km Sub-urban: 2-10km		Urban: <5km Sub-urban: 3-20km	<300m		<300m	Urban: <1km Sub-urban: <3km	<300m	<300m
	mmW link Availability (@ Capacity for mmW link)	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
Solution Mapping	**D-band mapping**	D-band (<1km) (1)		---	D-band		D-band	D-band (3)	D-band	(D-band) (2)

(1) possible longer distances based on enhanced technology

(2) the solution into parentheses is not the preferred one

(3) depending on different rain rates

* FH interface based on CPRI (CPRI Specification V7.0) / ORI / OBSAI

** not addressed here

9 First Prototypes and Early Deployment

9.0 Introduction

This clause provides an overview on the first prototypes available in the market, the early field trials and preliminary evaluations of propagation ITU models.

9.1 Huawei

9.1.1 First prototype and field trial in cooperation with Politecnico di Milano

The first prototype has been designed and developed in Huawei R&D centre in Milan and has been tested in September 2016.

The antenna, providing a gain of 34 dBi, the TX and RX MMICs, implemented in GaAs, and the RF transceiver chains have been part of the design activity.

The lab test has shown error-free transport of 1 Gbps over 750 MHz channel in QPSK, up to 7 Gbps over 1 600 MHz in 32 QAM.

Moreover, the prototype was aimed to show that usage of separated antennas for Tx and Rx is possible and provide sufficient and good isolation. This achievement can be reflected in a new definition of channel arrangements, the so called "flexible duplexing" or duplexer-free architecture. The results have been taken into account in the definition of channelization in CEPT SE19 Work Item 37 [i.3].

The working bandwidth of the prototype is from 140 GHz to 160 GHz. The architecture is made of separated TX and RX antennas, without duplexers. The antenna dimension is a 4 cm x 4 cm square, while the outdoor unit dimension is a 21 cm x 21 cm square. The channel bandwidth is 250 MHz and its multiples.

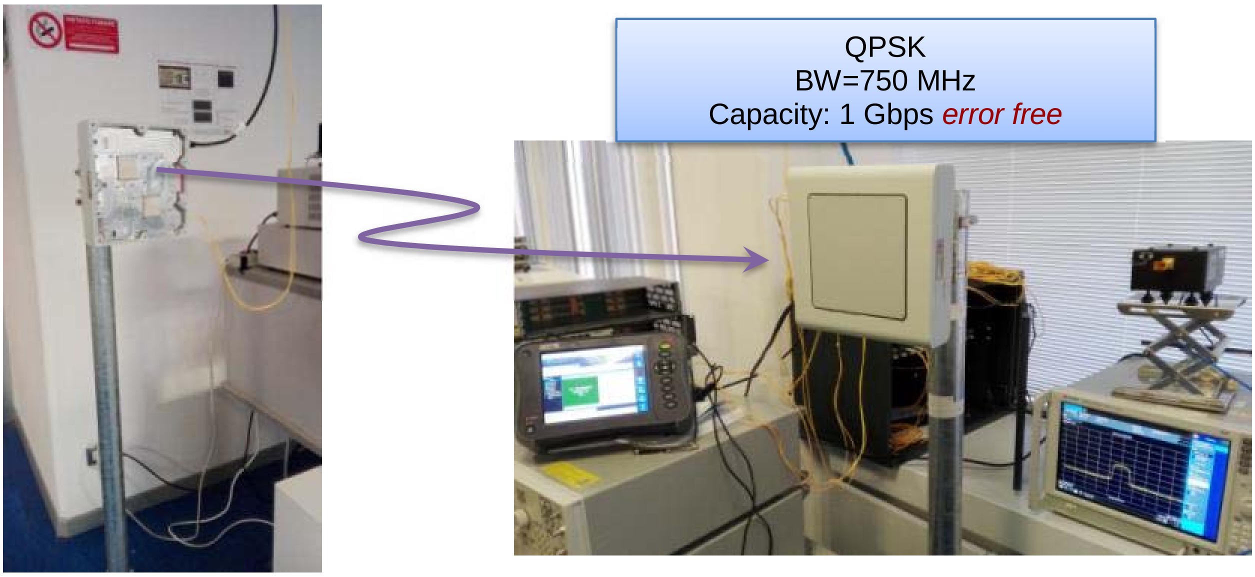


Figure 14: First D-band prototype in Huawei labs in Milan

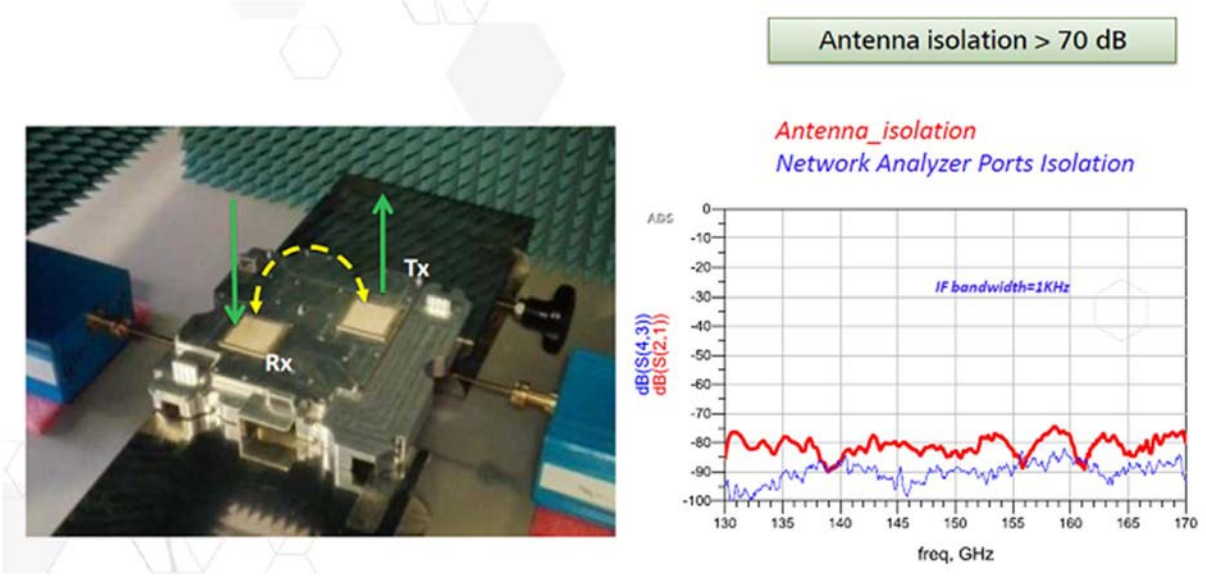


Figure 15: Antenna isolation measurements, to enable "duplexer-free" architecture

The early field trial aims to test the equipment in real environment for a sufficiently long period and under different propagation conditions, and also to extend the propagation ITU models that are so far valid up to 100 GHz.

The trial has been set-up in cooperation with the Italian University Politecnico di Milano and has been up and running since November 2016.

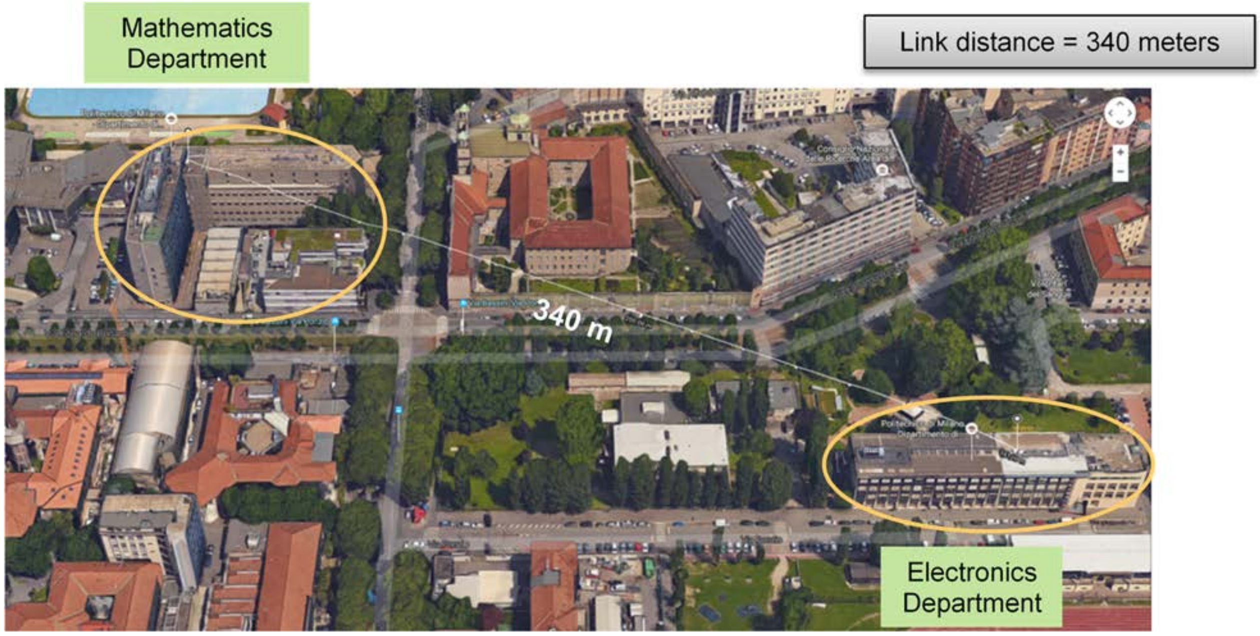


Figure 16: First D-band live trial at Politecnico di Milano University

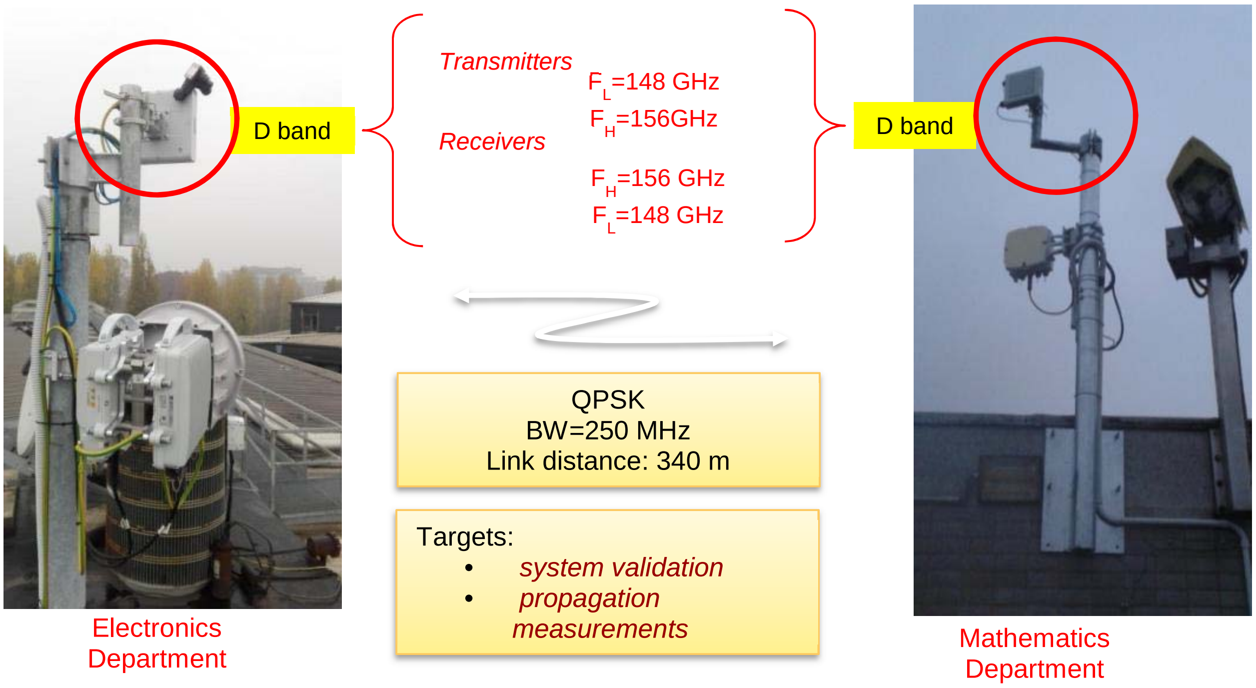


Figure 17: Details of first D-band live trial at Politecnico di Milano University

The first propagation measurements show good correlation between the link behaviour and the atmospheric conditions, as reported in the figure 20.

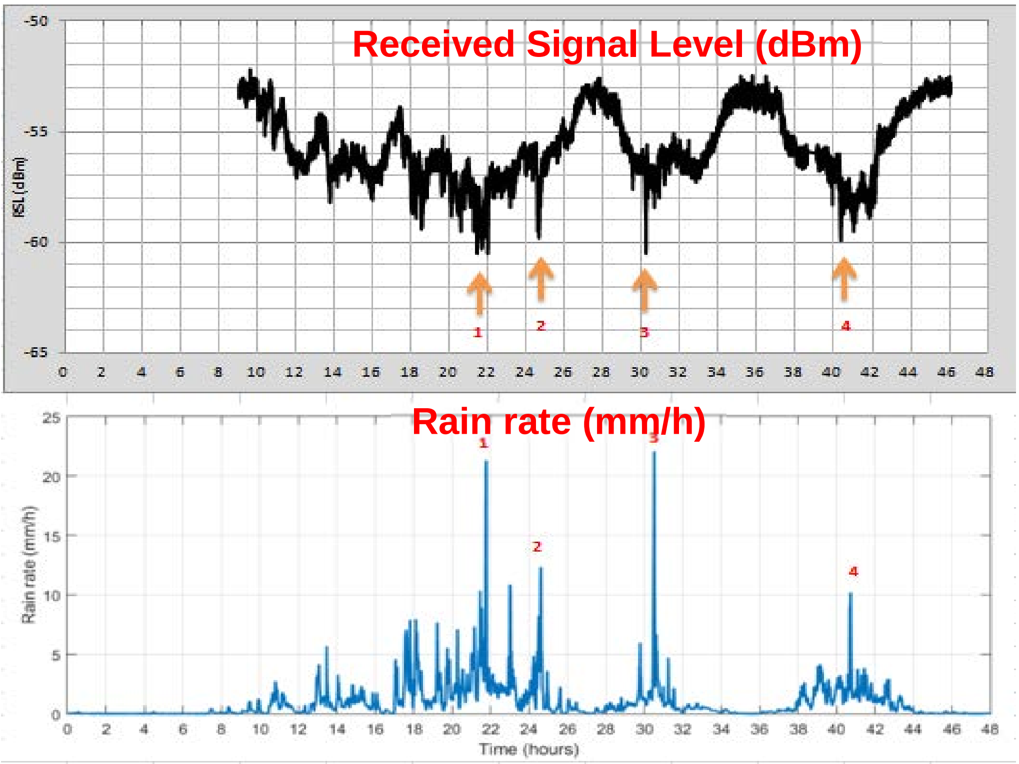


Figure 18: First propagation measurements results

9.1.2 Preliminary evaluation of ITU model

A preliminary evaluation of the attenuation due to rain has been done with reference to the Recommendation ITU-R P.530-16 model [i.6], showing good accordance, even taking into account that the measurement sensitivity of the radio decreases as long as the RX threshold is approached.

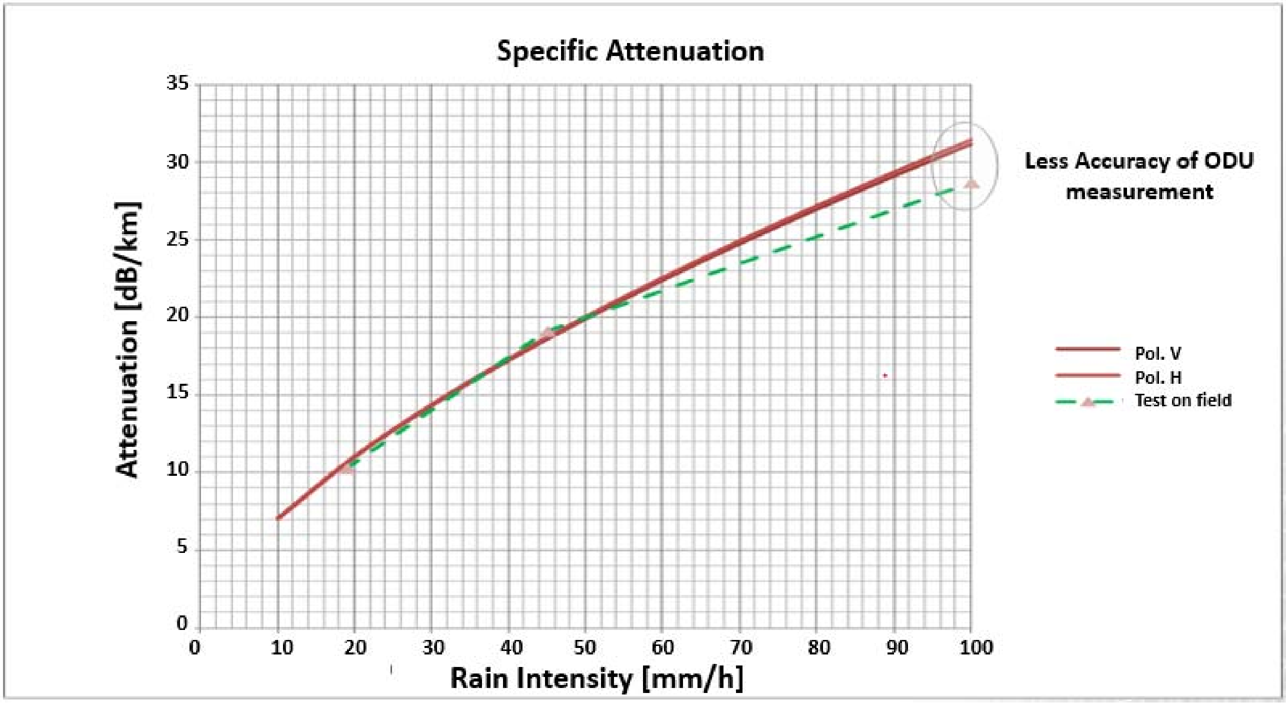


Figure 19: Preliminary evaluation of specific attenuation with reference to the Recommendation ITU-R P.530-16 model [i.6]

Nevertheless a significant statistical evaluation will require the collection of data throughout at least one year of measurements.

9.1.3 D-band trial with Telecom Italia for highly dense 5G backhaul network scenarios

The target of the trial is the study links working in the range 140 - 160 GHz, in a highly dense urban scenario. Moreover, easiness of setup and alignment are also evaluated.

The live trial collects radio data performance and throughput in different weather conditions. Log data available from a weather station are also used.

The trial is carried out using Huawei D-band link prototypes.

It was deployed in July 2017, at Telecom Italia premises in Turin, in via Reiss Romoli and lasted about five months.

NOTE: **D-band Link Characteristics:**
Band: 140 - 160 GHz
Frequency: 148 GHz low site
156 GHz High site
Channel: 500 MHz
Distance: 90 m
P_{tx}: +4 dBm
Antenna gain: 34 dBi
RX threshold: -64 dBm
System gain: 136 dB
RX power (clear sky): -45 dBm
Fading margin: 19 dB

Figure 20: Location of the D-band link and its characteristics

This is an installation with very compact footprint which consists of a full outdoor unit with integrated antennas, physically separated for TX and RX on each side of the link.

This type of equipment is suitable for dense urban environment because it allows simple alignment procedure and good disguised deployment.

The setup and alignment of the link, shown in figure 23, was carried out easily and without major issues.

Figure 21: Setup and Alignment of the link

During this period no significant rainfall events were registered, and the running link had shown the expected performance and robustness with no errors.

During the trial, one significant rainfall event (about 50 mm/h) happened in the area but no significant degradation had been registered and the link performance continued to be error-free.

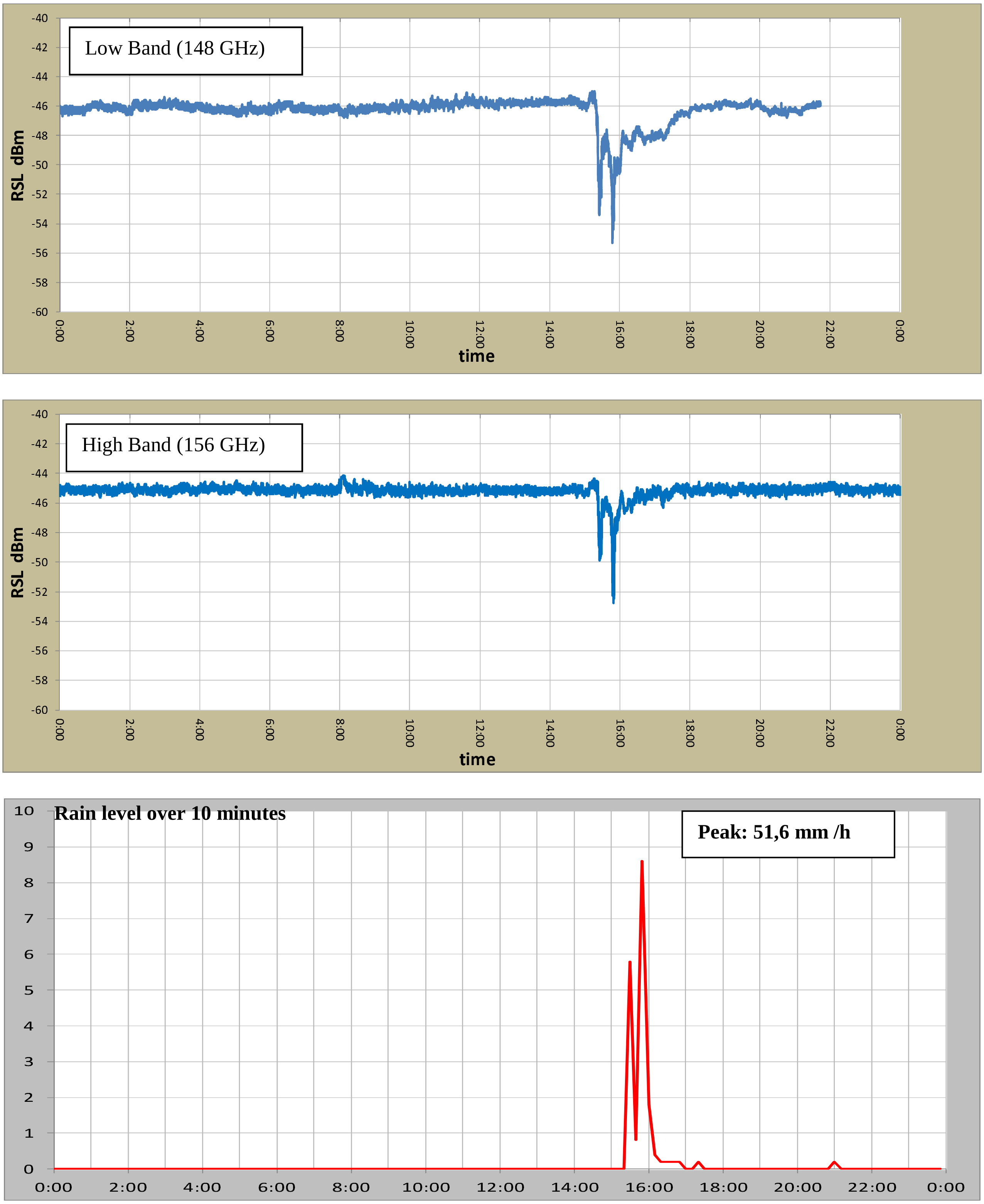


Figure 22: Graphs of the link behaviour

Through Ethernet traffic measurement, notwithstanding the significant rain event, the performance of QPSK at 750 MHz continued to be error-free.

9.2 Ericsson

Ericsson together with researchers at Chalmers University of Technology, have developed a D-band transceiver module, shown in figure 25. The module contains an InP DHBT Tx MMIC and an Rx MMIC and a separate circuit board for bias control and connectors. The MMICs cover the entire D-band. Figure 26 (top) shows a block diagram of the radio prototype. The module contains the blocks shown in dashed lines. Both transmitter and receiver MMICs contain a Gilbert cell mixer for up or down conversion and a frequency tripler for local oscillator generation. A low-noise amplifier is implemented in the receiver having approximately 15 dB of gain, while a medium-power amplifier is implemented in the transmitter MMIC supporting a saturated output power of more than 10 dBm.

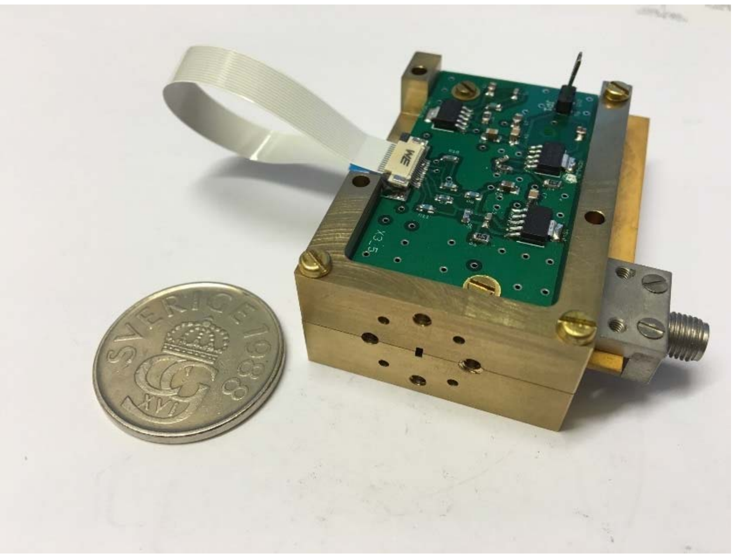


Figure 23: D-band transceiver module based on InP chipset (Source: Ericsson)

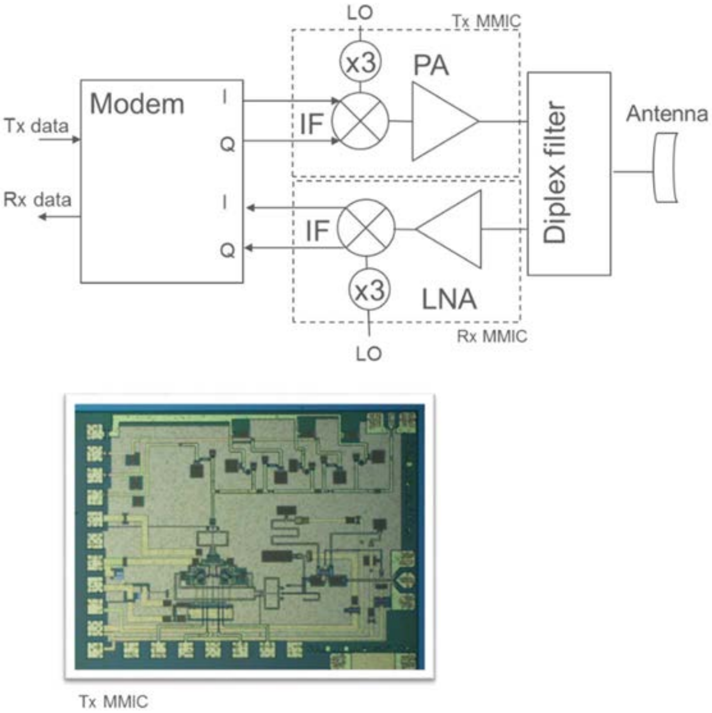


Figure 24: (top) block diagram of D-band radio. (bottom) photo of transmitter MMIC (Source: Ericsson)

The MMICs are assembled in a slot inside a 50 µm thick soft substrate that also extends into a waveguide as an E-plane probe. The waveguide connects to a diplex filter that interfaces with an antenna.

The transmitter and receiver modules were measured back-to-back before being assembled into the radio prototype. Figure 27 shows the measured bit error rate (BER) versus received signal power for a 125 MHz channel at 143 GHz. The modules supported up to 5 GHz channels and the inset in figure 27 shows the measured error-free constellation for a symbol rate of 4Gbaud using 16QAM for in total 16 Gbps. A noise figure of 9,5 dB was measured for the receiver MMIC. The 10^{-6} BER threshold of -63 dBm for 4QAM indicates that these early transmitter and receiver modules add a penalty of more than 8 dB to the receiver sensitivity. These results emphasize the need for careful control of how the module is designed and built.

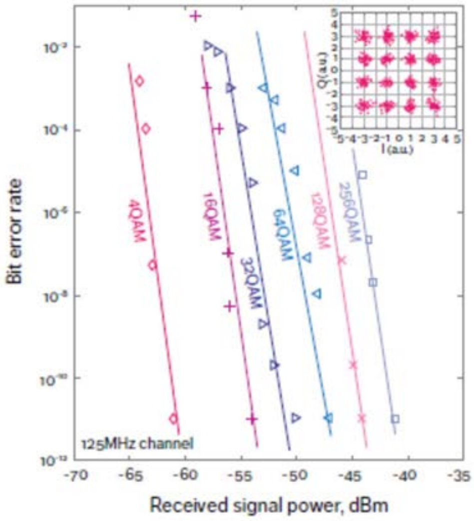


Figure 25: Measured bit-error-rate in a single 125 MHz, using prototype D-band modules. Inset shows the constellation diagram at 4Gbaud and 16 Gbps throughput (Source: Ericsson Sweden)

Figure 28 shows the assembled radio prototype in a weather proof mechanics. The antenna is 10 cm in diameter providing a gain of 40 dBi.

Figure 26: Assembled D-band radio prototype (Source: Ericsson Sweden)

9.3 NEC Europe Ltd (United Kingdom)

9.3.1 OAM technology description

Orbital Angular Momentum (OAM) of the electromagnetic (EM) waves has been known since the 1990s in the field of optics and physics [i.13]. It has a theoretical infinite number of modes that are mutually orthogonal. This trait can be exploited to convey large amount of information using multiple OAM modes. Experimental results on OAM mode-multiplexing transmission were reported in the field of optics [i.14]. Experimental results using OAM to multiplex several communication channels into one common radio channel was reported in [i.15]. Since then, the interest in OAM as a means of increasing capacity without utilizing additional spectrum resources has increased dramatically. However OAM has a practical limitation in achieving a link of several km at reasonable cost with antenna size similar to those used in conventional microwave radios. Until now, all experimental results reported for high-capacity radio utilizing multi modes OAM transmission have been for few meters. For the practical application of OAM in the mobile small cell backhaul a link distance in the order of 100 m is required. Achievement of practical link distance is a challenging subject which is currently being addressed and consideration are given for practical application of OAM.

What is OAM transmission?

AM is an abbreviation of Orbital Angular Momentum which is one of the physical mechanisms describing EM wave propagation. OAM has infinite independent modes (mode 0, +/-1, +/-2, ···). The OAM signal has a spiral equi-phase plane, and the shape is different between all of the modes as indicated in figure 29.

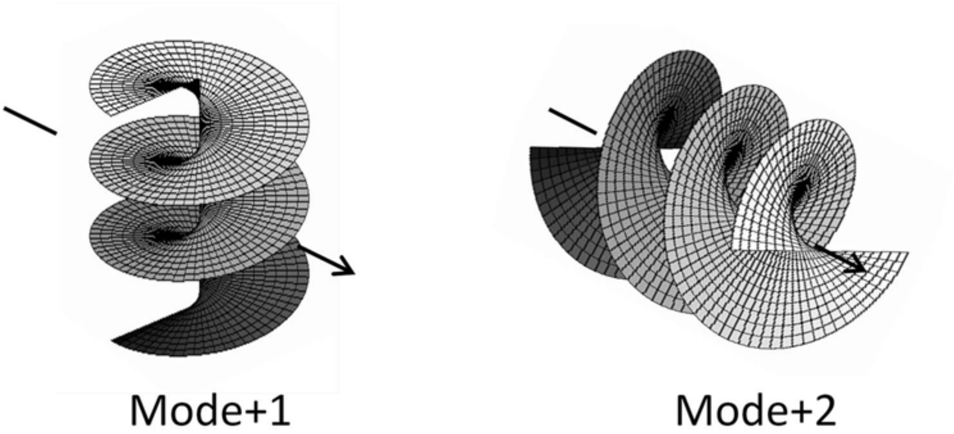


Figure 27: Equi-Phase Plane of OAM

Analysis also shows that OAM and polarization techniques are independent. This means the combination of OAM mode and polarization multiplexing has the potential of high-efficiency high-capacity radio.

However, OAM signal transmission has some issues and challenges for practical applications.

A theoretical analysis leads the following properties of OAM signal:

The power density distribution has a ring-shape, and its radius becomes larger with the increasing of mode-order and distance from the transmit antenna as illustrated in figure 30.

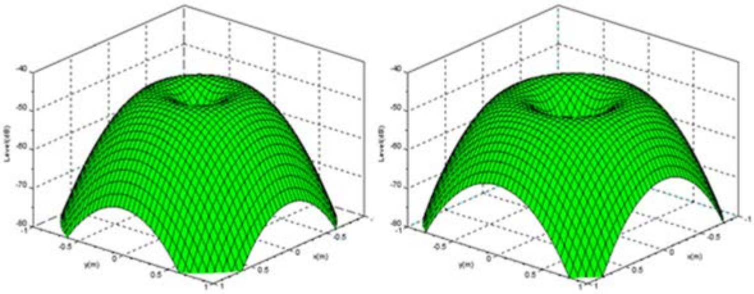


Figure 28: OAM power density distribution

These facts mean that the OAM signal transmission has an issue in the practical link distance for fixed antenna size at the receiver end as shown in figure 31.

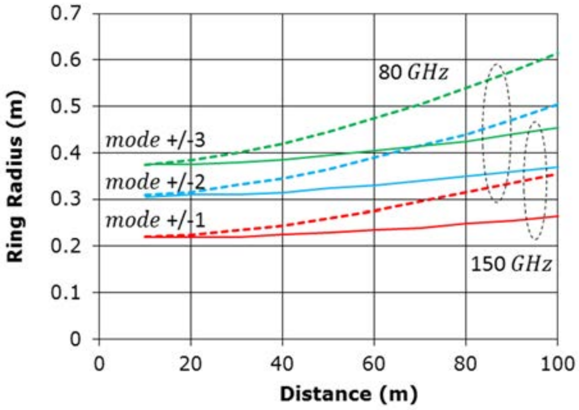


Figure 29: OAM power ring radius versus link length

In this figure, it is observed that the rate of increase in the ring radius becomes smaller with the increase of frequency. Therefore, higher frequency is better for the extension of the link distance.

Experimental Setup:

For 5G small cell backhaul and fronthaul applications, assume the required link distance is in the order of 100 m. Considering the required capacity, the candidate RF bands are limited to the millimetre-wave bands which have wider bandwidth than microwave bands. In particular, E-band (71 - 76/81 - 86 GHz) and D-band (141 - 174,8 GHz) are well suited for the target applications. Selection of 80 GHz as the carrier frequency for the E-band and 150 GHz for the D-band as the numerical model. The evaluation is a combination of an 8-element ring array antenna and 8x8 Butler matrix [i.16] at 5,2 GHz. The Butler matrix (a type of beam-forming network) is used as the OAM signal encoder and decoder and is connected with the antenna array, which transmits or receives the OAM signal having a helical equi-phase plane as indicated in figure 32. This also allows for generating multiple modes OAM signals simultaneously.

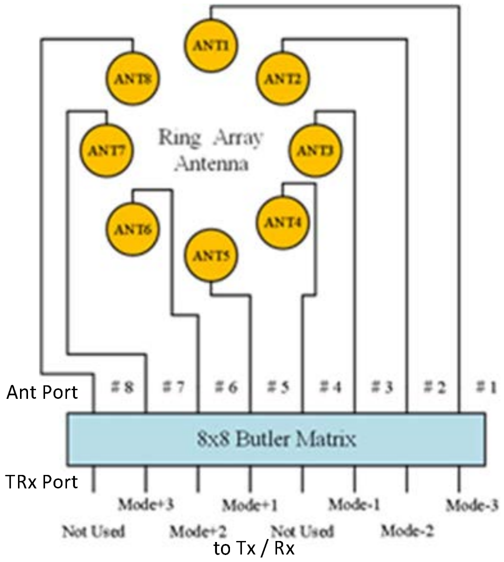


Figure 30: Connection between 8-element ring array antenna and Butler matrix

When each element of 8-elements ring array antenna samples the phase distribution of the associated Laguerre polynomial (i.e. solutions of the second-order linear differential equation) at 0 m, the phase at each element is same as the phase of the output of 8x8 Butler matrix. Figure 32 shows the connection between the 8-element ring array antenna and the 8x8 Butler matrix. The ring array antenna is excited by the rotational phase distribution. The amplitudes of the output signal are the same over all ports of the Butler matrix.

In order to verify the theoretical analysis, an experiment has been setup and conducted at 5,2 GHz with a link distance of 7 m.

The experiment setup and testing configuration is shown in figure 33.

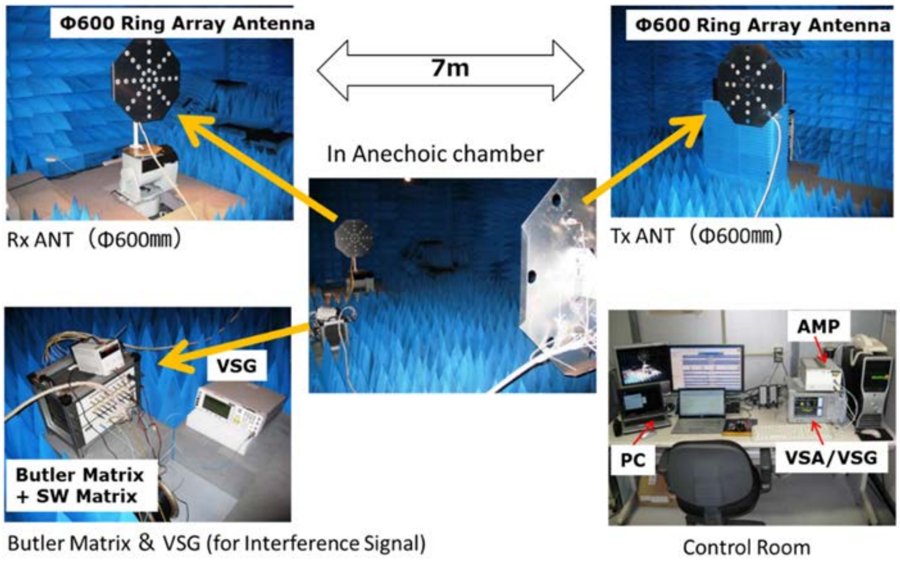


Figure 31: 7 m transmission measurement system setup and configuration

Experimental results:

The first experiment was conducted to verify the calculated EM field by comparing it with that of the measured as shown in figure 34 followed by the explanation of the experimental results of the OAM mode-multiplexing transmission with two 8-element ring array antennas with 8x8 Butler matrices. The second experiment was conducted to verify the effectiveness of OAM mode-multiplexing transmission with mode ±1 and mode ±2.

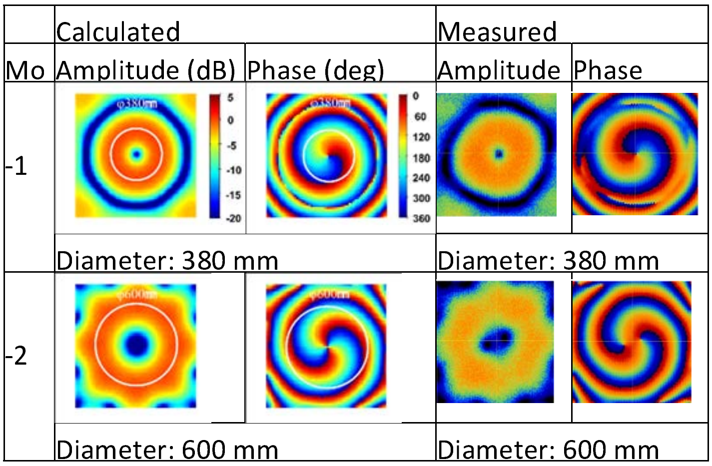


Figure 32: Calculated and measured electromagnetic field of 8-element ring array antenna with 8x8 Butler matrix on receiving plane at 1 m and 5,2 GHz

Figure 35 shows the performances of the mode-1 port of the Butler matrix when mode-1 and mode #n (#n=-1, +1, -2, +2) are multiplexed at the Tx antenna. When the two different modes are multiplexed, each mode is separated by more than a 20 dB SIR. The signal points are well identified in the measured constellation. When using an equalizer which is a well-established technology in microwave radios, the interference around the 20 dB SIR can be compensated and removed even for the 256QAM modulation scheme.

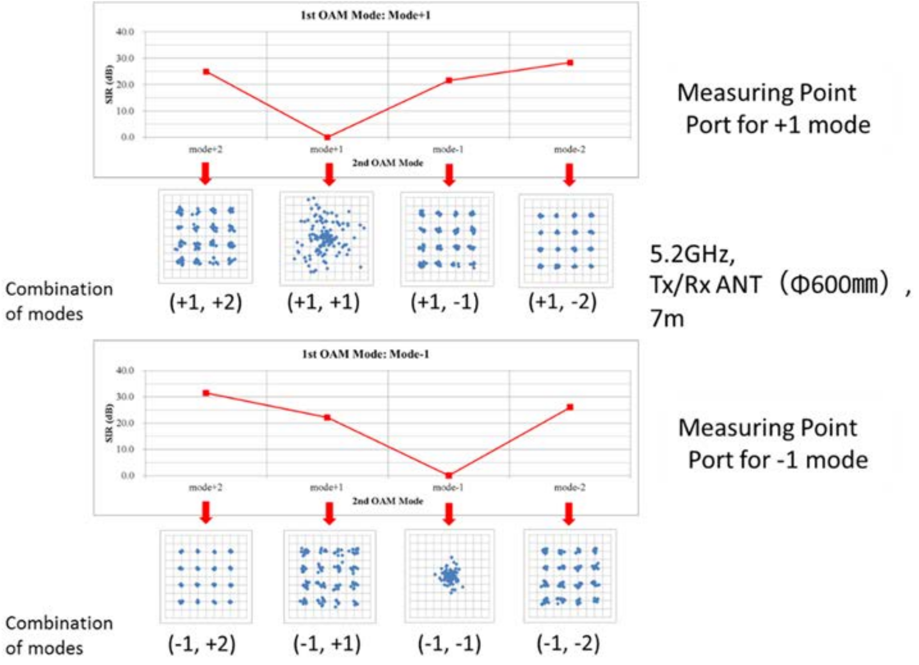


Figure 33: SIR and constellation of received signal at port of 8x8 Butler matrix when two OAM modes are multiplexed

Conclusion:

With the target application of the OAM transmission requiring link distance in the order of 100 m for 5G small cell backhaul and fronthaul, NEC conducted a theoretical analysis and validation experiments for a practical high-capacity OAM multi-modes with polarization multiplexing transmission system.

The numerical analysis of the OAM ring radius shows that in the D-band (150 GHz), at least modes 1 and 2 can be used for a link distance of 100 m with a pair of antennas of 0,3 m radius.

NEC also demonstrated that multiple OAM modes can be generated and separated by a combination of an antenna array and Butler matrix. NEC achieved a link distance of 7 m transmission for two-modes multiplexing with a prototype of a NEC system at 5,2 GHz. The experimental results are in alignment with the theoretical analysis, and estimation of 100 m transmission in the D-band can be realized.

The OAM mode-multiplexing transmission is suitable for practical link distance and can be a solution for meeting the demand of Ultra-high-capacity radios in the near future for 5G systems.

With conventional microwaves transmission systems, a channel bandwidth of 1 GHz - corresponding to a symbol rate of 0,8 Gbaud - can achieve 4,8 Gbps using 64QAM modulation. This value is not sufficient for the requirement of 5G systems. However, with four OAM modes multiplexing, the total capacity is 19,2 Gbps. Using four OAM modes dual polarization-multiplexing, the total capacity will be 38,4 Gbps in 1 GHz bandwidth.

9.4 Nokia

9.4.1 The DREAM project

NOKIA Bell Labs drives the research and innovation in the NOKIA group with a lot of different activities. In the specific field of radio, Bell Labs is researching in frequency bands up to 1THz covering different fields of applications. To focus on our specific interest here, figure 36 shows as an example a W-Band beam steering prototype.

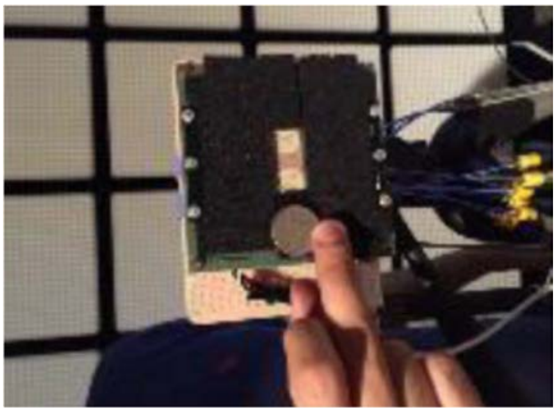


Figure 34: Example of a W-band steering prototype

Among such activities a new H2020 funding project, DREAM, has recently started. DREAM stands for D-band Radio solution Enabling up to 100 Gbps reconfigurable Approach for Meshed beyond 5G networks.

DREAM is researching mainly a D-band radio solution supporting data rates up to 100 Gbps covering distances of up to 300 m at ultra-high carriers, exploiting a channel bandwidth of few gigahertz. An important feature part of the solution is the beam steering functionality.

DREAM relies on a power efficient and silicon based BiCMOS transceiver analog front end to be integrated into an antenna array exploiting an intelligent low-cost packaging technology. A final prototype will be developed for the implementation of a proof of concept demonstrator

More details will be found in: http://www.h2020-dream.eu/.

10 State of the Art of Technology

10.1 Overview of Technological Maturity

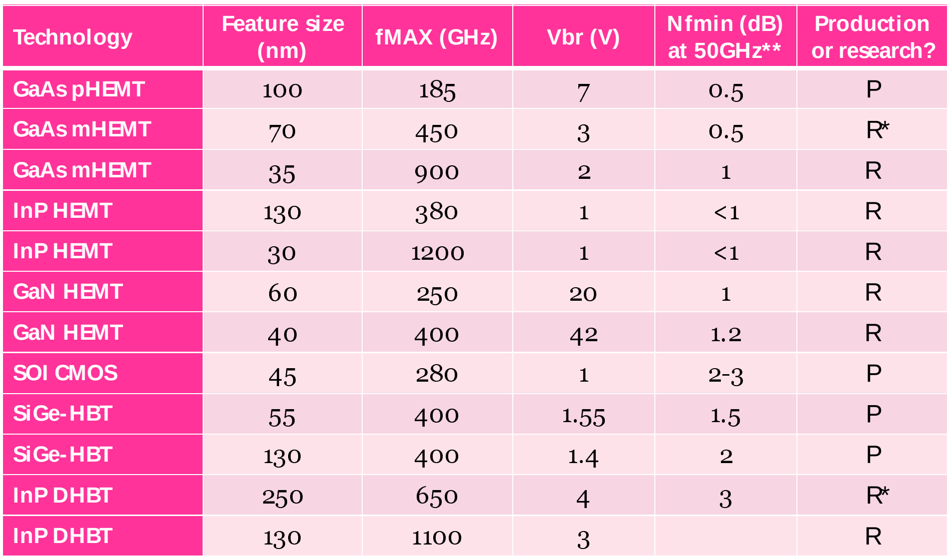
This clause provides an overview of technological maturity related to the W-band and the D-band (channel filters width, intelligent antenna availability, expected spectral efficiency, components frequency limitations, etc.).

The ISG mWT White paper [i.1], "mmWave Semiconductor Industry Technologies: Status and Evolution", provides further details on available technologies and trends.

10.2 Semiconductor technology for D-band: technological maturity and component frequency limitations

Semiconductor technologies for use beyond 100 GHz have undergone a tremendous evolution in the past few decades, driven largely by the space, defence and imaging industries. There are at least six compound semiconductor fabrics (III-V) and five silicon based fabrics capable of producing ICs for W & 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: [i.1])



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 costs. 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 right column in table 8 indicates the commercial maturity of the technology, where additional aspects are the development and production cost.

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. InGaAs mHEMT and InP pHEMT & DHBT technologies support very high frequencies, albeit at a higher material cost. 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, development of the processes for commercial applications is possible if a sufficient a market opportunity emerges.

Silicon technologies such as SOI CMOS and SiGe-HBT are today feasible up to W-band (92 - 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 - 400 GHz, further increase in fMAX above 400 GHz is under investigation, however as figure 38 shows, nMOS (SOI CMOS) seems to have an optimum of fMAX at 28 nm so may not catch-up with SiGe (BiCMOS).

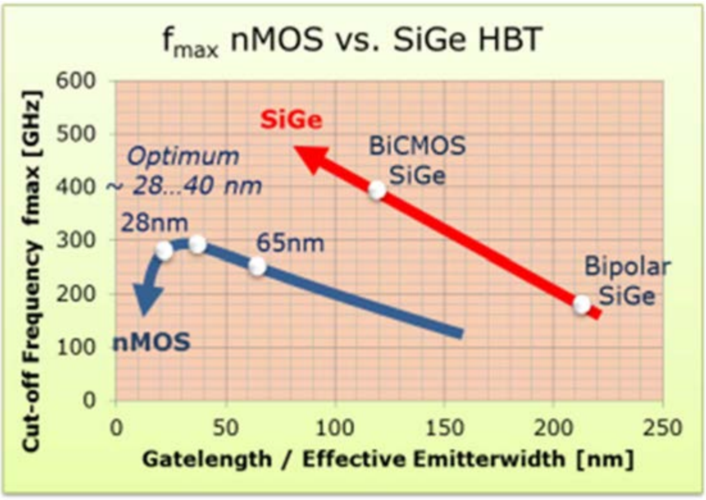


Figure 35: Overview of fMAX for SiGe (BiCMOS/HBT) and nMOS technologies (Source: [i.1])

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 39 shows examples of the performance demonstrated in D-band of power amplifiers and low noise amplifiers manufactured on III-V and Si technologies [i.19].

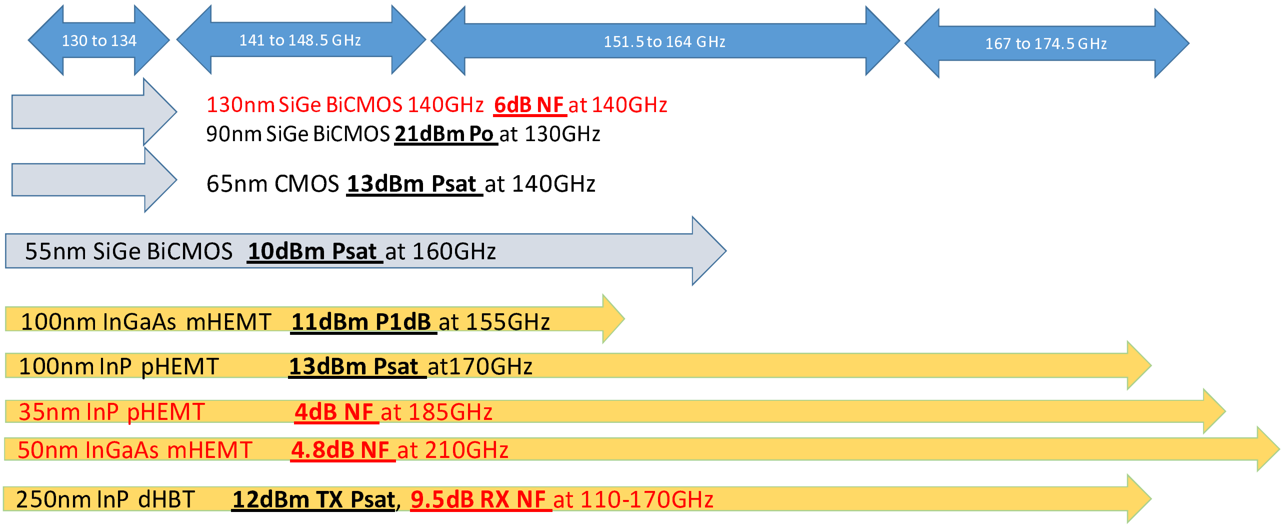


Figure 36: Performance for LNAs (red) and PAs (black) described in the literature (Source: [i.1])

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.

10.3 Challenges for volume manufacture of diplexers at D-band frequencies

Filtronic has performed 3D simulations to predict the RF performance that could be expected from diplexers created under manufacturing conditions used for E-band parts and operated over the temperature range required of a backhaul link. It is found that conventional machining will not be adequate to produce D-band diplexers with adequate RF performance and an acceptable manufacturing yield. Proposals are suggested how performance could be restored.

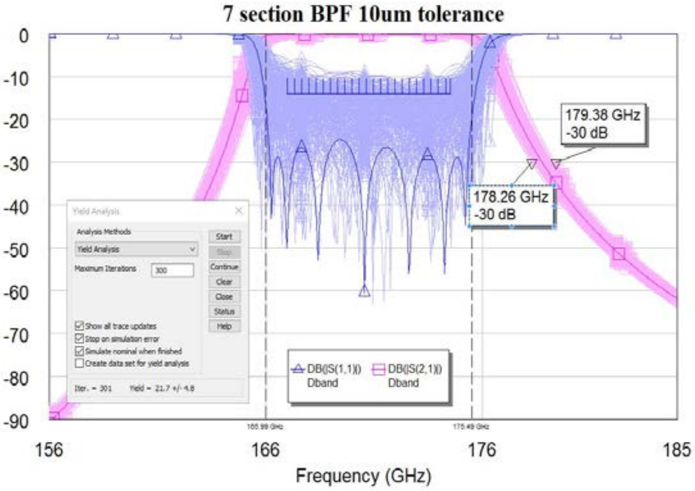
The frequency bands over which the diplexers are considered are:

- Band 1: 130 - 134 GHz and 151,5 - 155,5 GHz
- Band 2: 141 - 148,5 GHz and 155,25 - 162,75 GHz
- Band 3: 142,25 - 148,5 GHz and 156,5 - 162,75 GHz
- Band 4: 156,5 - 164 GHz and 167 - 174,5 GHz

The temperature range over which the diplexers are required to operate is -40 °C to +80 °C

The waveguide size is WR7 (1,651 x 0,826 mm)

In order to maintain low loss in the designated band, the actual bandwidth should be extended to tolerate the dimensional variation expected from machining and plating. High volume production of aluminium E-band diplexers is made with ±5 µm tolerances. However, when this variation is applied to D-band diplexers, the MonteCarlo analysis shows that only 20 % of parts would meet the return loss requirement of < -14 dB. Frequency drift up to 1,12 GHz can be expected which reduces isolation between transmitter and receiver. This is worst in band 4 and a simulation of loss is shown in figure 40.



Yield Analysis

Maximum Iterations 300

☑ Show all trace updates
☑ Stop on simulation error
☑ Simulate nominal when finished
☐ Create data set for yield analysis

Iter. = 301 Yield = 21.7 +/- 4.8

Figure 37: MonteCarlo simulation of D-band diplexer using prevailing manufacturing conditions for E-band diplexers

In addition, to ensure low loss is maintained across the designated bandwidth, the actual bandwidth should be extended further to cater for expansion and contraction arising from temperature variation. In band 4 it would be necessary to extend the bandwidth by a further 484 MHz which reduces the isolation between transmitter and receiver.

Performance could be improved in several ways:

- Reducing machining and plating tolerance from ±5 µm to ±2 µm would improve the yield to 97 %. Frequency drift would reduce from 1,12 GHz to 550 MHz
- Removing plating would reduce the variation but could degrade RF performance

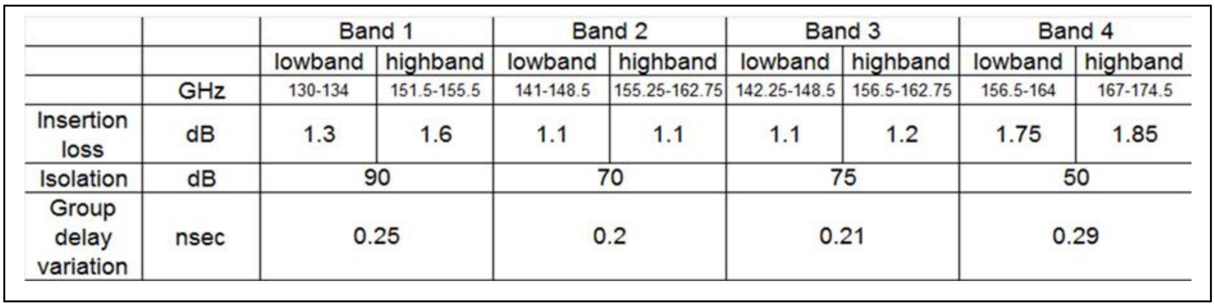
- Using alternative materials which have a lower Thermal Coefficient of Expansion would reduce variation over temperature. Alternatives to aluminium (TCE~22 x 10^{-6}/K) which are machinable are brass (TCE~18 x 10^{-6}/K) and copper (TCE~16 x 10^{-6}/K). Invar (TCE~1 x 10^{-6}/K) has a very low TCE but is expensive, hard to machine and heavy. Other materials with lower TCE have been considered in the simulations including alumina (TCE~8 x 10^{-6}/K) and quartz (TCE~0,5 x 10^{-6}/K). These could be formed into diplexers by micromachining and plating. Table 9 summarizes the necessary extensions (in band 4) as a result of such temperature variation to always achieve low loss in the designated band

Table 9: Effect of temperature variation for various materials on bandwidth extension

	BW extension (MHz)	
	Lowband	**Highband**
Aluminium	452	484
Brass	374	400
Copper	334	358
Alumina	162	172
Glass	65	70
Quartz	15	16

For a D-band diplexer manufactured using aluminium with ±2 µm machining and plating tolerances and temperature variation of -40 °C to +80 °C, simulated losses, isolation and group delay variation is given in table 10. It is seen that losses up to 2 dB can be expected which is intolerable.

Table 10: Simulated performance of aluminium diplexers made with ±2 µm machining and plating tolerances operating over -40 °C to +80 °C



		Band 1		Band 2		Band 3		Band 4	
		lowband	highband	lowband	highband	lowband	highband	lowband	highband
	GHz	130-134	151.5-155.5	141-148.5	155.25-162.75	142.25-148.5	156.5-162.75	156.5-164	167-174.5
Insertion loss	dB	1.3	1.6	1.1	1.1	1.1	1.2	1.75	1.85
Isolation	dB	90		70		75		50	
Group delay variation	nsec	0.25		0.2		0.21		0.29	

In summary:

- Conventional machining will not be adequate to produce D-band diplexers with an acceptable manufacturing yield. Manufacturing tolerances better than ±2 µm are needed to guarantee good yield. Manufacturing processes are under development which aim to achieve the required tolerances.

- Insertion loss up to 2 dB should be expected.

- Transmit to receive isolation > 70 dB could be achievable for the lower proposed bands. Isolation of > 50 dB may be difficult to achieve with 10,5 GHz DS in the highest bands.

11 Basic Considerations on Channel Arrangements

The ITU Radio Regulation 2016 [i.5] shows the bands allocated to fixed service (FS).

Table 11: ITU Table of Frequency Allocation (Radio Regulation 2016) [i.5]

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
123-130	
130-134	FIXED
134-141	
141-148,5	FIXED
148,5-151,5	
151,5-155,5 & 155,5-158,5 & 158,5-164	FIXED
164-167	
167-174,5 & 174,5-174,8	FIXED
174,8-191,8	
191,8-200	FIXED

1) Within CEPT ECC SE19 Work Item 37 [i.3] on the D-band, agreement has been reached on the following points:channelization based on 250 MHz basic channels and multiples according to the following:

   - Centre frequency of channels can be obtained as follows:

      - Fn = 130+ N×0,250 GHz N: 1 to 15 Sub-band "a"
      - Fn = 141+ N×0,250 GHz N: 1 to 29 Sub-band "b"
      - Fn = 151,5+ N×0,250 GHz N: 1 to 49 Sub-band "c"
      - Fn = 167+ N×0,250 GHz N: 1 to 30 Sub-band "d"

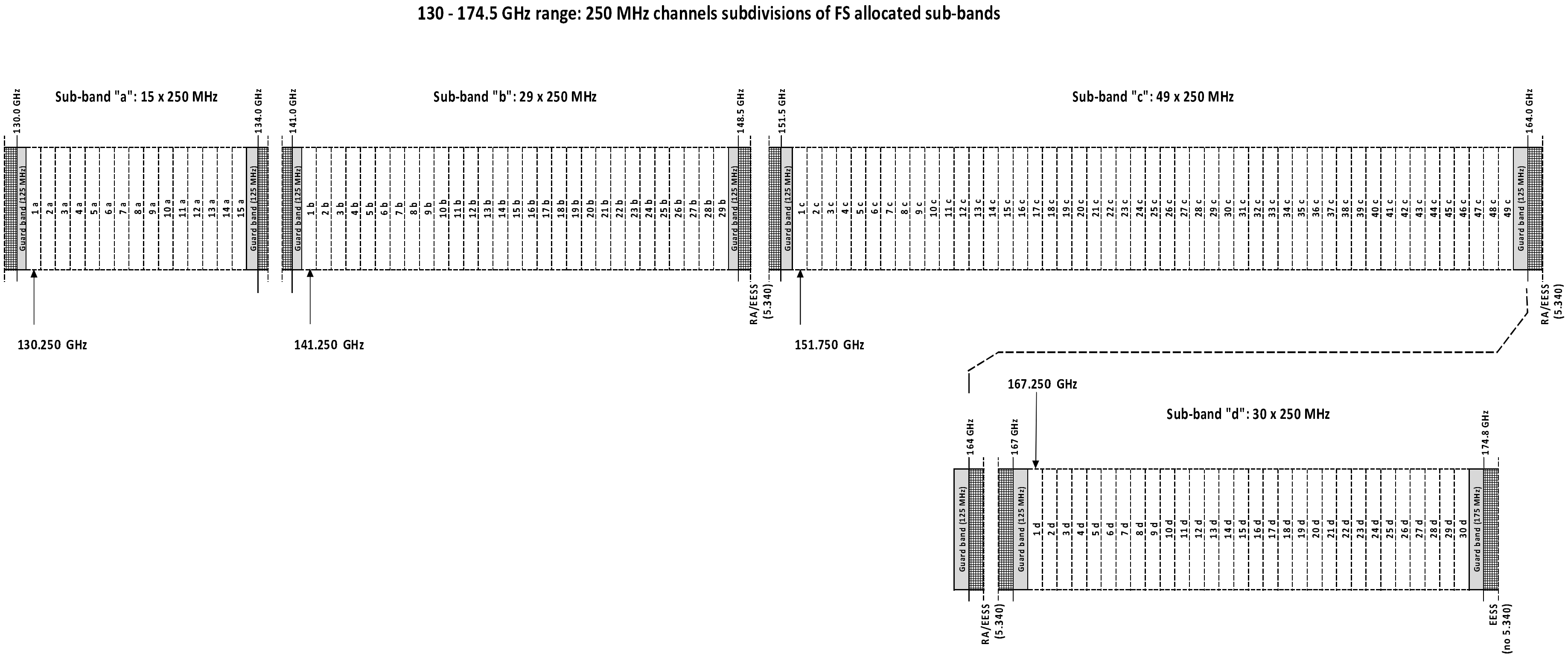


Figure 38: Basic channel ras

2) Two main uses of channel raster have been indicated:

   a) block based use of channels with "flexible duplexing" or duplexer-free architecture;

   b) use of equipment with traditional fixed duplexer schemes.

The related Recommendation ECC REC (18)01 [i.20] has been published in May 2018.

12 Summary and Conclusions

New abundant spectrum in millimetre-wave pushes to focus investments, identifying the most suitable bands for future transmission networks within 5G scenarios. Moreover, the 5G requirements imply big 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 30 GHz of spectrum are available in the D-band. The gas attenuation in the D-band is almost flat and, at about 140 GHz, the rain attenuation is confirmed flattened.

The significant advantages offered by the propagation characteristics in terms of frequency re-usability together with the large channel bandwidths available make D-band suitable for transmitting multi-Gbps in dense urban scenarios using very compact antennas and extreme low power.

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.

The results in field have shown that the link's behaviour remained stable for the trial duration and, given the short distances involved in dense urban deployments, the link performance remained error-free also in presence of significant rainfall events.

The experience with the D-band prototype and related measurements represent an important and promising step forward in the deployment and significant use of frequency bands above 100 GHz for very high throughputs in 5G transmission networks.

Annex A:
Further considerations on technology

A.1 SiGe:C BiCMOS

According to the paper "A Low Power Multichannel Receiver for D-Band Sensing Applications in a 0,13 µm SiGe BiCMOS Technology" [i.2], where D-band is here defined up to 132 GHz, presents a low power D-band (up to 132 GHz) multichannel receiver front-end implemented in a 0,13 µm SiGe/BiCMOS technology featuring HBTs with fT of 250 GHz and fmax of 360 GHz. The receivers are driven by a V to D-Band frequency doubler. Measurements on a breakout chip of the frequency doubler shows a maximum conversion gain and output power of 5 dB and -1 dBm respectively. The maximum suppression of the V-band signal at the output is better than 25 dBc. A minimum single sideband noise figure of 11,5 dB, a conversion gain greater than 18 dB and an input-referred 1-dB compression point of -7 dBm at an IF of 10 MHz for input signals between 120 and 132 GHz is obtained for the receivers. The channel-channel gain and noise variation remains below 1 dB and the IF channel-to-channel isolation was better than 40 dB. The circuit consumes 90 mA from a 3,3 V power supply.

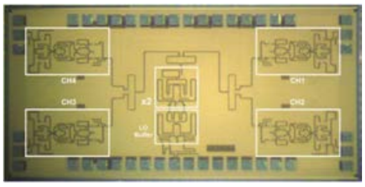


Figure A.1: Micrograph of the fabricated chip (Chip size is 3 x 1,4 mm^2)

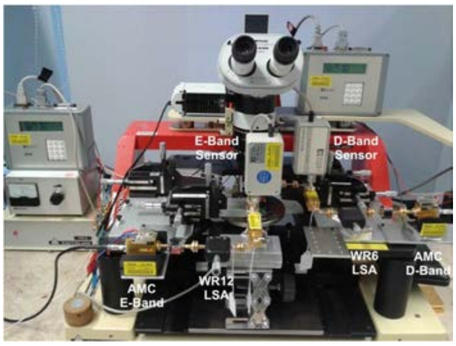


Figure A.2: Photograph of the measurement setup

In conclusion, a low noise, low power W-band multichannel receiver for sensing applications designed in advanced SiGe BiCMOS process is presented. A frequency doubler with conversion gain of 5 dB is presented. Receive channels showed a single sideband noise figure less than 12 dB with an IF channel-to-channel isolation greater than 40 dB. The entire chip consumes less than 300 mW. The measured results give a first overview using SiGe/BiCMOS technology for low-power applications beyond 100 GHz up to 132 GHz.

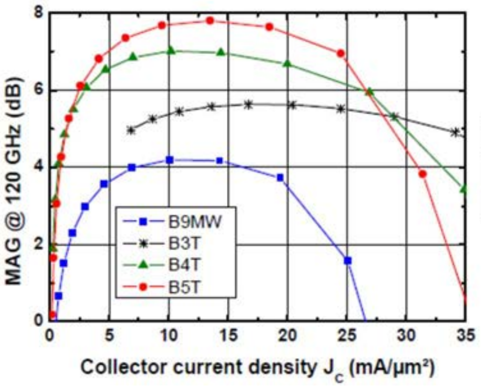
A.2 SiGe:C BiCMOS - Technology Features

Silicon Germanium (SiGe) BiCMOS technologies in production today address applications such as 77 GHz automotive radar or 100 Gb/s optical communications. The next generation of silicon-germanium (SiGe) heterojunction bipolar transistors (HBTs), with f_t/f_{max} around 300/400 GHz and thick metal back-end, makes it possible to design highly integrated, low-power and improved (in terms of larger gain and lower noise figure) transceivers for new low-cost applications above 100 GHz, such as wireline and wireless communications at higher data rates. While the high speed SiGe Heterojunction Bipolar Transistor (HBT) allows designing RF transceiver front end operating both in W and D bands, the need for always increasing digital processing in many applications asks for CMOS node with larger gate densities than those available in BiCMOS technologies today.

The BiCMOS055 also called B55 technology, developed on a 300 mm wafer line in ST, features low power and general purpose 55 nm gate length CMOS devices, high speed SiGe:C HBT exhibiting 320 GHz of f_T and 370 GHz of f_{MAX}. Transmission lines, capacitors, high-Q varactors and inductors dedicated to millimetre-wave applications are also available exploiting the 3 µm thick copper top metal layer of a back-end of line featuring eight copper metal layers and the aluminium capping layer. This combines the advantages of being fully compatible with the existing 55 nm CMOS libraries and to provide enhanced performance for millimetre-wave passives.

A.3 SiGe HBT performance in the W and D bands

While f_T and f_{MAX} are key figures of merit (FoM), other important parameters such as Maximum Available Gain (MAG), minimum noise figure (NFmin) and large signal measurements are of prime interest for RFIC designers. Figure A.3 shows the SiGe HBT MAG at 120 GHz versus the collector current density with the HBT f_t and f_{max} as parameters.



Parameter	B9MW	B3T	B4T	B5T
f_T (GHz)	220	260	270	300
f_{MAX} (GHz)	280	330	370	400

Figure A.3: MAG@120 GHz comparison between SiGe HBT having different performance in term of f_t and f_{max}

A.4 Low Noise Amplifier design

Direct measurement of NF_{min} and related noise parameters require the use of a tuner to generate the multiple impedances to be presented to the transistor. Such a measurement is difficult, especially at millimetre wave frequencies. Fortunately, extraction of the bipolar transistor NF_{min} from Y parameters is accurate, even in the D band.

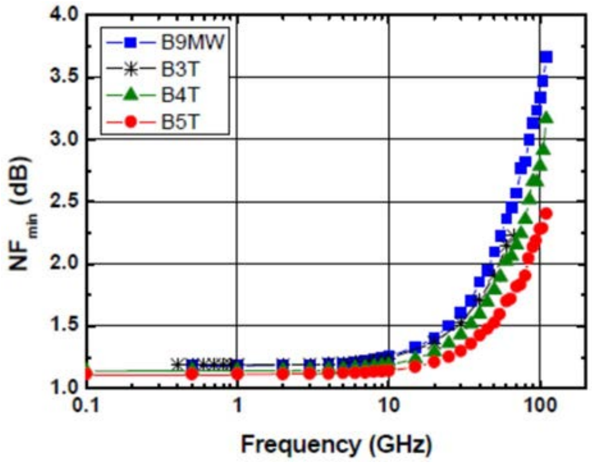
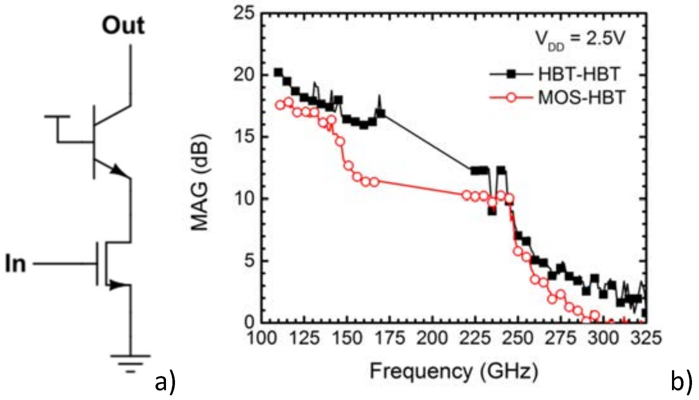


Figure A.4: Minimum noise figure NF_{min}, extracted from Y parameter measurements of B9MW, B3T, B4T and B5T high speed HBTs (L = 5 µm, VCB = 0,5 V, VBE for peak fT)

Figure A.4 shows the improvement in NF_{min} (extracted from Y parameters) brought by the latest SiGe:C HBT generation featuring the largest f_T. The B5T transistor exhibits ~1 dB less noise than the B9MW HBT one at 100 GHz to reach ~2,3 dB. This value is consistent with the state of the art where NFmin < 2 dB has been measured at 70 GHz with an in-situ tuner.



a) b)

Figure A.5: a) MOS-HBT cascode circuit, b) Measured max available gain for MOS-HBT & HBT-HBT cascodes (MOS: gate size 20 x 55 nm x 720 nm, HBT: emitter size 100 nm x 4,5 mm)

With the availability of both a high f_{MAX} 55 nm n-MOSFET and a SiGe:C HBT, the MOS-HBT cascode structure, shown in figure A.5 a), becomes the ideal topology for implementing a distributed amplifier. The gate of the MOSFET has higher Q impedance than the HBT and can be DC-coupled to the input line. Additionally the gate resistance can be minimized through layout techniques, while the common-base HBT provides high Q output impedance and superior isolation. The MOS-HBT cascode also exhibits higher linearity and better stability than the HBT-HBT cascode at the same bias current, with comparable maximum available gain and bandwidth, as shown in figure A.5 b).

A 5-stage distributed amplifier in 55 nm SiGe BiCMOS process has been designed and implemented. The design, which employs a MOS-HBT cascode, was optimized for low-noise, 135 GHz bandwidth and an input 1 dB compression point of 3,3 dBm, as needed in 200 GS/sec ADCs.

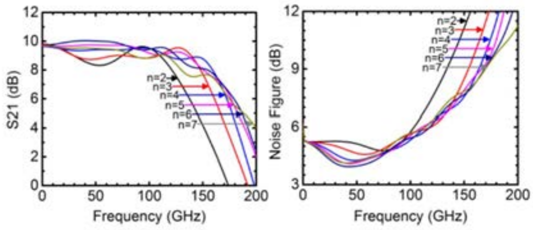
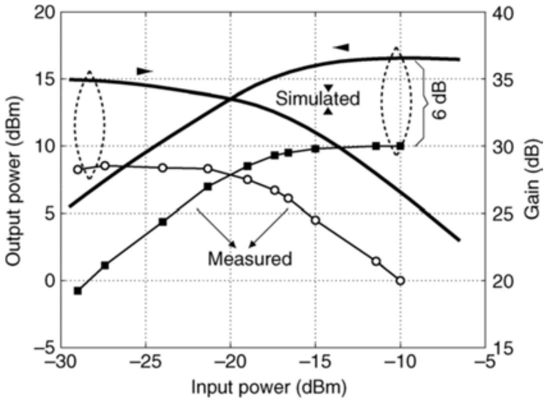


Figure A.6: Schematic simulations for W and D band S21 and noise figure for different numbers of stages at a fixed total current and output swing

The number of stages, N=5, has been optimized while fixing the total MOSFET gate width, the total HBT emitter length and the MOSFET and HBT current densities to maximize bandwidth, as shown in figure A.6.

A.5 D-band Power Amplifier design

Power amplifier (PA) design for 160 GHz applications in an advanced ST's SiGe heterojunction bipolar transistor (HBT) technology with saturated output power in excess of 10 dBm has been designed, implemented and reported. The architecture is based on a three-stage pseudo-differential configuration that was implemented in SiGe:C HBT technology with f_{max} of 400 GHz. At saturation, the PA circuit delivers 10 dBm with 20 dB gain. From 150 - 170 GHz, the small-signal gain is within 20 - 32 dB and the output referred 1 dB compression point is 8,5 dBm at 160 GHz. High output power was possible due to optimum device sizing, efficient layout, and accurate EM modeling.



NOTE: For simulation results, the effects of input and output baluns have been included.

Figure A.7*: Output power and large signal gain versus input power at 160 GHz*

Figure A.7 shows the comparison between the simulated and measured large-signal characteristic of the PA. To measure the large-signal characteristic, mm-wave source modules were first calibrated to account for their nonlinear behaviour. The measured P_{sat} at 160 GHz is 10 dBm with 20 dB gain at saturation and P_1 dB of about 8,5 dBm. In the frequency range 154 - 163 GHz, the saturated output power varies from 7 - 10 dBm, while the P_1 dB is between 4 - 7 dBm. The discrepancy for the large signal measurements is about 6 dB.

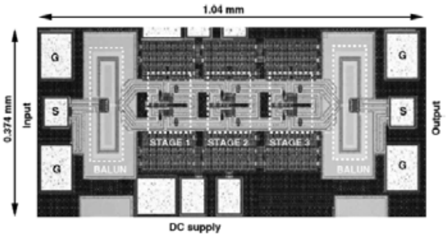


Figure A.8: Chip micrograph of the three-stage PA

The chip micrograph is shown in figure A.8 Marchand baluns have been added at the input and output for on-wafer measurement using single-ended ground-signal-ground probes.

A.6 150 GHz VCO and prescaler

A fundamental Colpitts-Clapp VCO and a divide-by-16 prescaler was fabricated as the most critical blocks required in the phase-locked loop of future fundamental 150 or 300 GHz harmonic transceivers.

At the input of the prescaler is a dynamic divider followed by three static divider stages, all operating from a nominal supply voltage of 1,5 V. The VCO-prescaler operates from 138 - 148 GHz, limited by the tuning range of the VCO. Its phase noise was measured throughout the band, at the divider output, and was found to vary from 80 - 81 dBc/Hz, at 1 MHz offset when accounting for the divider ratio (24 dB). The output power of the standalone VCO breakout varies from 5 - 11 dBm in the 138 - 148 GHz tuning range. The prescaler was verified to divide correctly by 16, when the supply voltage was varied between 1,4 - 1,8 V. Similarly, the VCO oscillates for values ranging from 1 - 2 V. The VCO core consumes 35 mW from 1,5 V, and the divider chain, without output buffers, draws 42,5 mA from 1,5 V. The VCO, prescaler, and buffers consume a total of 120 mW from a 1,5 V supply. Figure A.10 illustrates the measured and simulated tuning characteristics of the standalone VCO at two supply voltages of 1,5 and 2 V, respectively. The agreement is better than 8 %. The tuning characteristics are insensitive to the supply voltage, whereas the simulation results show some VCO pulling.

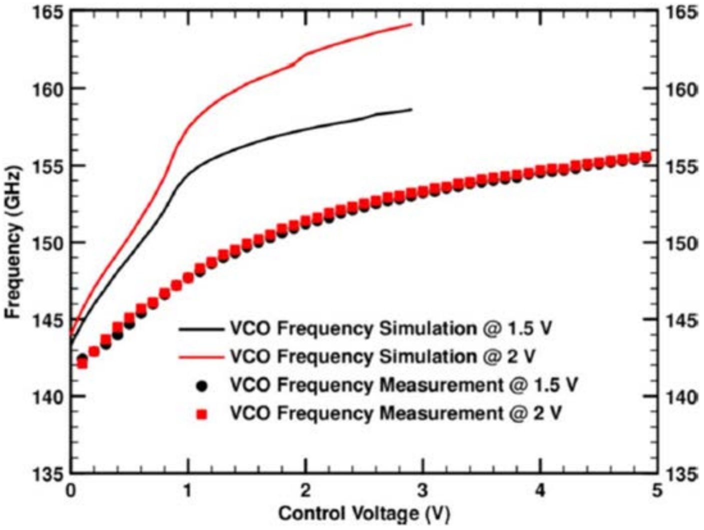


Figure A.9: Measured versus simulated VCO tuning range

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