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5G mmWave

26 GHz mmWave Unwanted Emissions Study

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1 Executive Summary

The ITU is currently performing compatibility studies for use of mmWave IMT equipment in the 26 GHz band (24.25 GHz to 27.50 GHz) in advance of a potential identification of the 26 GHz band for IMT at WRC-19. Users of the nearby spectrum at 23.6 – 24.0 GHz have raised concerns regarding potentially high levels of unwanted emissions interfering with the 23.6 – 24.0 GHz Earth Exploration Satellite Service (EESS) band which is extensively used for very sensitive passive sensing applications.

This study revisits the current unwanted emission (UWE) levels for the 23.6 – 24.0 GHz EESS band as defined by the various stake holders (3GPP, ITU, EC, ESA/EUMETSAT, and WMO) as can be seen below in Table 1-1.

These requirements may be met in many cases through care in the design of the RF chain, and in particular the power amplifier design, without the need for additional filtering. In fact, in the case of the user equipment (UE) the current 3GPP standard has implemented message NS_201 between the base station (BS) and the UE which tells the UE to adjust its output such that any unwanted emissions (UWE) comply with EC limits of -38 dBW/200 MHz (TRP), or any lesser limit that may be adopted.

To the extent not otherwise satisfied by RF chain and power amplifier design alone, this report discusses the use of miniature RF filters as one possible way, i.e. design choice, to fulfil the different unwanted emission levels while maximizing the useable bandwidth. Examples of existing technology in miniature RF filters in the mmWave band are highlighted to show the feasibility of developing cost and size effective solutions. A short overview of possible antenna architectures is given to derive size requirements for these filters for both base station array antennas and handset, UE, configurations.

The study seeks to evaluate the additional achievable performance with currently available filter technology with respect to unwanted emission requirements and determine whether any Guard Band might be required beyond the current 250 MHz band between 24.00 and 24.25 GHz (which is outside the 26 GHz band).

The current definitions of the different required unwanted emission level limits for 5G services in the 26 GHz mmWave band (US: 24.25 GHz – 27.50 GHz) vary quite heavily. Table 1-1 summarizes the different required unwanted emission level limits. As can be seen they range between -20 dBW/200 MHz for 3GPP standards and -55 dBW/200 MHz which is proposed by the World Meteorological Organization (WMO). The European Commission recently published the decision 2019/784 [13] to define the harmonization in exactly this band for terrestrial systems in Europe.

Throughout this study, a baseline is used of the 5G NR FR2 base stations which meets the 3GPP 5G Category A stated requirements of unwanted emission levels below -20 dBW/200MHz through the power amplifier design and the defined guard band contained within the 5G NR Channel Bandwidth without additional filtering on the power amplifier output(s). To the extent that equipment providers' power amplifier implementations have actual emissions below this limit, that will reduce the rejection needed to be achieved by any additional filtering (a power amplifier with UWE below the 3GPP 5G requirement may be the result of good design practices for the transmitter).

Table 1-1: Summary of unwanted emission level requirements as proposed from the different institutions

	ITU-R SM.329 Category A / B[1] levels [dBW/200 MHz]	**3GPP 5G unwanted (out-of-band & spurious) emission levels, worst case [dBW/200MHz]**	**IMT unwanted emission into the passive band (reference level) based on 5G parameter [dBW/200 MHz]**	**EC Decision 2019/784 [dBW/200 MHz TRP]**	**ESA/EUMETSAT/ EUMETNET study result [dBW/200 MHz]**	**WMO Decision [dBW/200 MHz]**
BS	-20.0 -37.0[2]	-20.0	-23.8	-42.0	-54.2	-55.0
UE	-20.0 -37.0	-20.0 -38.0[3] (NS_201)	-20.0	-38.0	-50.4	-51.0

ESA/EUMETSAT has stated that levels higher than -54.2 dBW/200 MHz for the BS and higher than -50.4 dBW/200 MHz for UEs cause problems to their systems [8]. The World Meteorological Organization (WMO) has also stated levels in the same range -55 dBW/200 MHz and -51 dBW/200 MHz respectively.

In order to be able to achieve these ESA and WMO unwanted emissions levels, filters could be added.

To derive possible filter solutions, where applicable, first principal antenna architectures which may be used by IMT are introduced to get an estimate of the available space for filters. For calculating the needed filter rejection levels, the currently defined unwanted emission levels as specified by 3GPP (IMT) of -20 dBW/200 MHz for Category A are used as a starting point, and then compared with selected unwanted emission levels as proposed by other organizations.

Many current base station antenna solutions are based on flat panel arrays with a 8x8 architecture to achieve the minimum required performance. It is worth noting that filtering at each antenna element places certain physical

[1] Category A is the umbrella definition, Category B limits are based on limits defined and adopted in Europe (an exact definition can be found in *Table 11-14*.

[2] Category B levels are derived from that specification and are applicable in Europe.

[3] This lower limit has to be met when NS_201 is signaled within the cell [10].

limitations on the used filter technology. Other design choices (especially on architectural and amplifier levels) are available to the equipment manufacturer which may help to overcome size limits. For example, driving the power amplifiers within a more linear portion of their characteristic curve to avoid spectral regrowth reduces the requirements on the filtering itself and filters may even be placed between the amplifier and the modem. Additionally, optimized antenna architectures with a lower number of amplifiers (with possible reductions in steering angle ranges) can be further studied as means for possible reductions in unwanted emissions.

As mentioned above, in its latest User Equipment requirements document [10], 3GPP has introduced an UWE requirement based on the European Commission UWE level stated in decision 2019/784. Compliance with this level is ensured by signaling from the base station using the message NS_201 (see Table 1-1). Therefore, UEs may either reduce their transmit power based on that messaging or otherwise may implement a design that meets this value when the UE operates at full power. With this provision implemented, the UE will have to meet the EC recommendation of -38 dBW/200 MHz (TRP) and thus can be in compliance with the EC standard, as well as any lesser UWE requirements that may be adopted, and can do so without the need for the additional filtering discussed in this report. Even if the most stringent UWE level (as proposed by WMO) is adopted and must be complied with, a filter of maximum size of 3 x 3 x 1.5 mm³ is possible for the UE. For completeness, an evaluation of a possible antenna architecture, its mounting possibility within handsets and one promising filter technology for use in mobile UE devices are included in this report.

To the extent that equipment designs must incorporate filtering technologies, this document presents multiple miniature filter technologies and explains that there are already viable solutions on the market, which at scale will be at affordable prices. The most promising solutions are based on SMT Microstrip or PolyStrata® technologies. The PolyStrata® filter examined in this report was designed as is described below to meet a 20 dB filter rejection. It could be modified to provide greater levels of rejection. These technologies also offer small filter sizes that can be implemented in the base station and the user equipment at a reasonable cost.

The performance requirements for the filters are high, especially the desire for minimal insertion loss (i.e., loss of signal power occurring in the transmission band of a device (e.g., filter)). Achieving the minimal insertion loss within the passband while at the same time achieving the desired level of attenuation or filter rejection at the lower edge of the 26 GHz band leads to a few possible filter approaches.

The cost of such filters can be in the order of $1.00 to $2.00 and therefore are already quite inexpensive.

A summary of the salient parameters for the most promising filter technologies is provided in the following table:

Table 1-2: Summary of filter parameters for base-stations

Technology	SMT microstrip	PolyStrata®
Insertion loss	3dB	1 dB
Guard band to achieve proposed UWE levels		
IMT [-20 dBW/200 MHz]	0 MHz (No filter required)	0 MHz (No filter required)
EC [-42 dBW/200 MHz TRP]	500 MHz	0 MHz (Note 1)
WMO [-55 dBW/200 MHz]	1000 MHz	Under study (Note 2)
Required Lower Edge of Operating Band Edge		
IMT [-20 dBW/200 MHz]	24.25 GHz	24.25 GHz
EC [-42 dBW/200 MHz TRP]	24.75 GHz	24.25 GHz, (Note 1)
WMO [-55 dBW/200 MHz]	25.25 GHz	Under study, (Note 2)
Available Bandwidth for IMT		
IMT [-20 dBW/200 MHz]	3.25 GHz	3.25 GHz
EC [-42 dBW/200 MHz TRP]	2.75 GHz	3.25 GHz, (Note 1)
WMO [-55 dBW/200 MHz]	2.25 GHz	Under study, (Note 2)
Size [mm³]	4 x 1,6 x 1,6	3 x 5 x 1, (Note 3)
Technology maturity	High	High[4]
Manufacturing stability	High	High
Estimated cost	1-2 $	1-2 $

Note 1: As detailed in Chapter 11, the 3GPP 5G specification provides for three different IMT BS types, with medium range and local area BS producing 7 dB lower nominal levels of unwanted emissions into 23.6 – 24.0 GHz than wide area BS. The Guard-Band under the EC standard is 0 MHz for the case of medium range BS and local BS. For wide range BS, the Guard Band under the EC standard using the specific PolyStrata® filter examined is about 200 MHz, but this can also be as low as 0 MHz with PolyStrata® filters designed to satisfy the EC standard – See Note 2.

Note 2: The example PolyStrata® filter examined in this analysis was designed to provide 20 dB of rejection in the stop band at 24.0 GHz. With small adjustments, a PolyStrata® filter could be designed for greater stop band rejection, reducing, or possibly eliminating any additional guard band required to meet the WMO unwanted emission limit.

Note 3: The UE has somewhat less stringent requirements leading to a likely filter size of 3 x 3 x 1.5 mm³.

[4] Not yet being mass produced

CONCLUSION

UWE requirements with respect to mmWave IMT base station equipment operating in the 26 GHz band may be met in many cases through care in the design of the RF chain, and in particular the power amplifier design, without the need for additional filtering. In the case of the user equipment (UE) the current 3GPP standard has implemented message NS_201 between the base station (BS) and the UE which tells the UE to adjust its output such that any unwanted emissions (UWE) comply with the EC limits on UWE, and any less stringent limits that may adopted.

As can be seen in previous Table 1-2 to the extent that IMT equipment designs incorporate filtering technologies as a design choice, or to achieve more stringent UWE levels than the EC limit that may be adopted, possible filter technologies are already available on the market for a reasonable price.

In the case of base stations, with these filters in combination with appropriate designs for the antenna architecture and the related amplifiers all unwanted emission levels can be met.

The 3GPP/IMT proposed unwanted emission protection levels of -20 dBW/200 MHz does not require any additional filtering which allows the entire band of 3.25 GHz from 24.25 – 27.5 GHz to be used for IMT.

The SMT microstrip filter can be used to decrease the additional guard band requirements for the requirements beyond the 3GPP/IMT but it cannot eliminate the need for some additional guard band.

The PolyStrata® filter examined can achieve the EC proposed 5G unwanted emission TRP limit of -42 dBW/200 MHz in the 23.6 – 24.0 GHz band while allowing the entire band of 3.25 GHz from 24.25-27.5 GHz to be used for IMT for medium range BS and local area BS. In addition, with small design adjustments to this PolyStrata® filter design, the same EC unwanted emission can be achieved while allowing the entire band of 3.25 GHz from 24.25-27.5 GHz to be used for IMT for all 5G BS types.

The PolyStrata® filter examined also achieves any unwanted emission levels less stringent than -42 dBW/200 MHz while also allowing the entire band of 3.25 GHz from 24.25-27.5 GHz to be used for IMT for all 5G BS types. Other commercially viable filters may be designed and manufactured to achieve different proposed unwanted emission protection levels similarly.

For the UEs, the implementation of the NS_201 signaling built into the 3GPP standards allows UEs to meet the UWE limit recommended by the EC, as well as any less stringent limits without the need for the additional filtering discussed in this report. In those cases where filtering may be needed to achieve a more strict limit than the EC limit (such as the WMO proposed limit), it bears note that the UE requirements are less stringent than the BS requirement, with at least 8 dB more power permitted at the band edge. In the case where UE filtering is needed to achieve more strict limits than the EC limit, the most challenging parameter is the size of the filters. With an implementation in the PolyStrata® technology we believe that a filter size of 3 x 3 x 1.5 mm^3 is possible.

2 Table of Content

3 Introduction

3.1 Scope of Study

This study analyses ways to mitigate potential interference between proposed 5G IMT networks operating in the 24.25 -27.50 GHz frequency band and currently in use satellite frequencies for passive earth exploration satellite service (EESS) meteorological earth observations in the mmWave-band at 23.6 – 24.0 GHz.

3.2 Acronyms

3GPP	3rd Generation Partnership Project
5G	5th Generation
AAS	Active Antenna Systems
ACLR	Adjacent Channel Leakage power Ratio
BPF	Band Pass Filter
BS	Base Station
BWP	Bandwidth Part
CA	Carrier Aggregation
CEPT	European Conference of Postal and Telecommunications Administrations
CPW	Coplanar Waveguide
CR	Change Request
CSRR	Coupled Split Ring Resonator
ECC	Electronic Communications Committee
EESS	Earth Exploration Satellite Service
EIRP	Equivalent Isotropic Radiated Power
ERC	European Radiocommunications Committee
ESA	European Space Agency

EVM	Error Vector Magnitude
FR	Frequency Range
FSL	Free Space Loss
IC	Integrated Circuit
IIS	Institut für Integrierte Schaltungen
IMT	International Mobile Telecommunications
ISS	Inter-Satellite Service
ITU	International Telecommunication Union
LRTC	Least Restrictive Technical Conditions
LS	Liaison Statement
LTCC	Low Temperature Cofired Ceramics
MFCN	Mobile/Fixed Communications Networks
NR	New Radio
OBUE	Operating Band Unwanted Emissions
OOB	Out of band
OTA	Over The Air
PBCH	Physical Broadcast Channel
PCB	Printed Circuit Board
PRB	Physical Resource Block
RAN	Radio Access Network
RAS	Radio Astronomy Service
RB	Resource Block
RF	Radio Frequency
RX	Receiver
SCS	Subcarrier Spacing
SIW	Substrate-Integrated-Waveguides
SRS	Space Research Service
SS	Synchronization Signal
TDD	Time Division Multiplex
TRP	Total Radiated Power
TS	Technical Specification
TX	Transmitter
UAV	Unmanned Aircraft Vehicle
UE	User Equipment
UWE	Unwanted Emission
US	United States
WMO	World Meteorological Organization
WP	Work Package
WP5D	Working Party 5D

3.3 Definitions

Guard Band: Any required operating offset from lower/upper end of 26 GHz band to achieve UWE limits

Unwanted Emission: Combination of out-of-band and spurious emissions

3.4 Applicable and Referenced Documents

[1] ID1.1: ITU-R Recommendation ITU-R RS.515-5 (08/2012), "Frequency bands and bandwidths used for satellite passive remote sensing"

[2] ID1.2: R15-WP5D-C-0784!!MSW-E (1).docx

[3] ID1.3: 3GPP TSG-RAN WG4 Meeting #84, R4-1714048

[4] ID1.3: 3GPP TSG-RAN WG4 Meeting #85, R4-1712718

[5] ID1.3: 3GPP TSG-RAN WG4 Meeting #85, R4-1713636

[6] ID1.4: ECC PT1(18)023A21_ECC-ESA-EUM_PC Decision18FF and Report 68 (final).docx and ECC PT1(18)049_UK EESS passive study 26 GHz.docx

[7] CEPT ECC Decision (18)06, "Harmonised technical conditions for Mobile/Fixed Communications Networks (MFCN) in the band 24.25-27.5 GHz", approved 06 July 2018 and corrected 26 October 2018.

[8] ESA-EUMETSAT-EUMETNET, "Comments to Public Consultations on draft ECC Decision (18)FF and draft CEPT Report 68", 6 April 2018, ECC PT1(18)023A21_ECC-ESA-EUM_PC Decision18FF and Report 68 (final).docx

[9] 3GPP TS 38.101-2 V15.4.0 (2018-12): 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone (Release 15)

[10] 3GPP TS 38.101-2 V16.0.0 (2019-06): 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone (Release 16)

[11] 3GPP TS 38.104 V15.4.0 (2018-12): 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; Base Station (BS) radio transmission and reception (Release 15)

[12] ITU-R SM.329

[13] European Commission Decision (EU) 2019/784 of 14 May 2019 on harmonisation of the 24,25-27,5 GHz frequency band for terrestrial systems capable of providing wireless broadband electronic communications services in the Union, published May 16th, 2019

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[15] SAGE datasheet SCF-26301370-SFSF-B3, SCF-26301370-SFSF-B3.pdf

[16] MiniCircuits datasheet: BFCN-1262+.pdf

[17] Knowles Dielectric Labs datasheet: B274MB1S_Datasheet.pdf

[18] Knowles Dielectric Labs datasheet: B280LB0S_Datasheet.pdf

[19] Corry Micronics datasheet: CMIBPF-23G-2G

[20] Liam Devlin, Graham Pearson, Jonathan Pittock, "RF and Microwave Component Development in LTCC", Plextek Ltd, London Road, Great Chesterford Essex, CB10, online: https://www.plextekrfi.com/publications/white-papers/LTCC_technology_overview.pdf

[21] Ming Dong ; Dongya Shen ; Chaojun Ma ; Xiupu Zhang, "A cascaded six order bandpass siw filter using electric and magnetic couplings technology", 2017 Sixth Asia-Pacific Conference on Antennas and Propagation (APCAP), 2017

[22] Qing Liu ; Dong-Fang Zhou ; De-Wei Zhang ; Yi Zhang, „A Miniaturized Quasi-Elliptic BPF with High Selectivity Based on Combining CPWs and CSRR in a Single Dual-Mode SIW Cavity", 2018 International Conference on Microwave and Millimeter Wave Technology (ICMMT), 2018

[23] Peter Matthews, "Approaching the 5G mmWave Filter Challenge - Key specifications for mmWave filtering and available options", in Microwave Journal, Vol. 62, No.5, pp. 56-66, Norwood, USA, May, 2019

[24] US patent, number US 9,312,589 B2, "Coaxial waveguide microstructure having center and outer conductors configured in a rectangular cross-section", granted Apr. 12, 2016

[25] Nuvotronics Presentation, 2019_05_20_Nuvotronics_Presentation.pdf

[26] Nuvotronics filter addendum to 3GPP TSG-RAN WG4 #79, Tdoc R4-164226, PolyStrata filter implementation example_rev2.doc

[27] RP-191240: RAN4 CRs to New Radio Access Technology, part 5; Newport Beach California, UNITED STATES; 3rd Jun 2019 - 6th Jun 2019

[28] 3GPP TR 38.815 V15.0.0 (2018-06): 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; New frequency range for NR (24.25-29.5 GHz) (Release 15)

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[38] https://www.everythingrf.com/news/details/7681-Qualcomm-Introduces-2nd-Gen-5G-RF-Front-End-Solutions-for-Sleeker-5G-Multimode-Mobile-Devices

[39] https://www.techinsights.com/blog/samsung-galaxy-s10-5g-teardown

[40] https://www.everythingrf.com/News/details/7070-Qualcomm-Unveils-the-Smallest-5G-NR-mmWave-Antenna-Module

4 Summary of Regulatory Documents

The following table shows the summary of all required unwanted emission levels as proposed by the different institutions. As can be seen, there is a large variety between -20.0 dBW/200 MHz and -55.0 dBW/200 MHz. These values will later be used to determine any filter and Guard Band requirements. A detailed explanation for these required unwanted emission levels can be found in chapter 11.

Table 4-1: Summary of emission levels as proposed from the different institutions

	ITU-R SM.329 Category A / B[5] levels [dBW/200 MHz]	3GPP 5G unwanted (out-of-band & spurious) emission levels [dBW/200MHz]	IMT unwanted emission into the passive band (reference level) based on 5G parameter [dBW/200 MHz]	EC Decision 2019/784 [dBW/200 MHz TRP]	ESA/EUMETSAT/ EUMETNET study result [dBW/200 MHz]	WMO Decision [dBW/200 MHz]
BS	-20.0 -37.0	-20.0	-23.8	-42.0	-54.2	-55.0
UE	-20.0 -37.0	-20.0 -38.0[6] (NS_201)	-20.0	-38.0	-50.4	-51.0

[5] Category A is the umbrella definition, Category B limits are based on limits defined and adopted in Europe (an exact definition can be found in *Table 11-14*.

[6] This lower limit has to be met when NS_201 is signaled within the cell [10].

5 Signal Properties of 5G IMT mmWave Communications

5.1 Operation bands

The frequency range of FR2 is divided into the following 4 operating bands:

Table 5-1: Operating bands in FR2

Operating Band	Uplink (UL) operating band BS receive UE transmit	Downlink (DL) operating band BS transmit UE receive	Duplex Mode
n257	26500 MHz - 29500 MHz	26500 MHz – 29500 MHz	TDD
n258	24250 MHz – 27500 MHz	24250 MHz – 27500 MHz	TDD
n260	37000 MHz – 40000 MHz	37000 MHz – 40000 MHz	TDD
n261	27500 MHz – 28350 MHz	27500 MHz – 28350 MHz	TDD

However, as listed in the table above, all operating bands use the same frequency range for uplink and downlink.

In this study only the operating band n258 is analyzed. An analysis of unwanted emissions in other FR2 bands and potential interference with other services may be studied in a future report.

5.2 Channel bandwidth

The UE channel bandwidth supports a single NR RF carrier in the uplink or downlink at the UE. From a BS perspective, different UE channel bandwidths may be supported within the same spectrum for transmitting to and receiving from UEs connected to the BS. Transmission of multiple carriers to the same UE (CA) or multiple carriers to different UEs within the BS channel bandwidth can be supported.

From a UE perspective, the UE is configured with one or more BWP / carriers, each with its own UE channel bandwidth. The UE does not need to be aware of the BS channel bandwidth or how the BS allocates bandwidth to different UEs.

The placement of the UE channel bandwidth for each UE carrier is flexible but can only be completely within the BS channel bandwidth.

The relationship between the channel bandwidth, the Guard Band and the transmission bandwidth configuration is shown in Figure 5-1

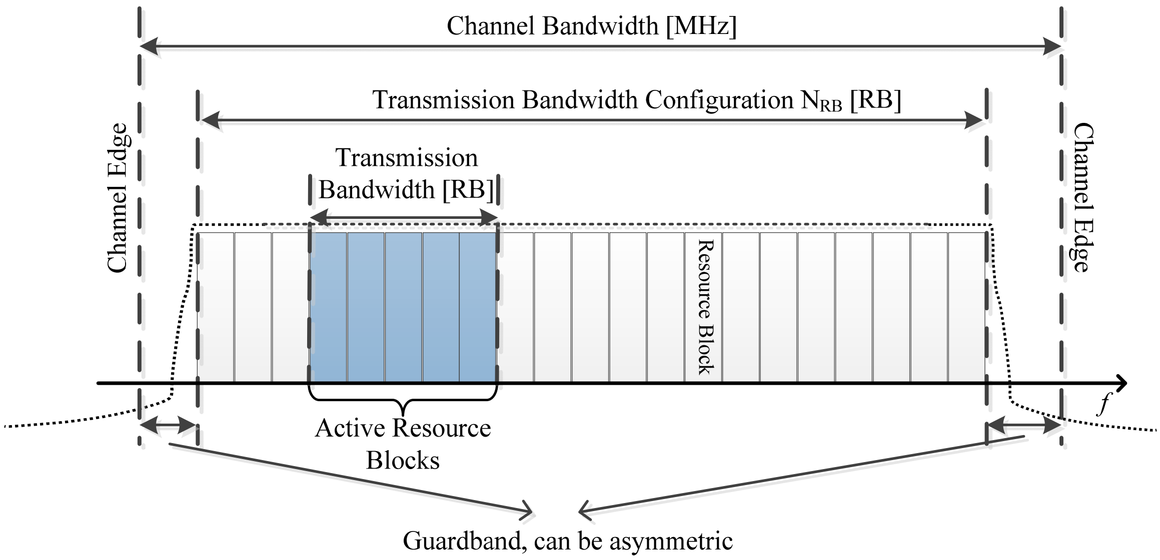

Figure 5-1: Definition of channel bandwidth and transmission bandwidth configuration for one NR channel

The maximum transmission bandwidth configuration N_RB for each UE channel bandwidth and subcarrier spacing (SCS) is specified in Table 5-2.

Table 5-2: Maximum transmission bandwidth configuration

SCS (kHz)	50 MHz N_RB	100 MHz N_RB	200 MHZ N_RB	400 MHz N_RB
60	66	132	264	N.A.
120	32	66	132	264

The minimum Guard Band for each UE channel bandwidth and SCS is specified in Table 5-3.

Table 5-3: Minimum Guard Band (kHz) and transmission bandwidth configuration

SCS (kHz)	50 MHz	100 MHz	200 MHZ	400 MHz
60	1210	2450	4930	N.A.
120	1900	2420	4900	9860

However, in FR2 an additional SCS of 240 kHz exists.

The minimum Guard Band of receiving BS SCS 240 kHz SS/PBCH block for each UE channel bandwidth is specified in Table 5-4.

Table 5-4: Minimum Guard Band (kHz) of SCS 240 kHz SS/PBCH block

SCS (kHz)	100 MHz	200 MHz	400 MHZ
240	3800	7720	15560

The number of RBs configured in any channel bandwidth shall ensure that the minimum Guard Band specified in this clause is met.

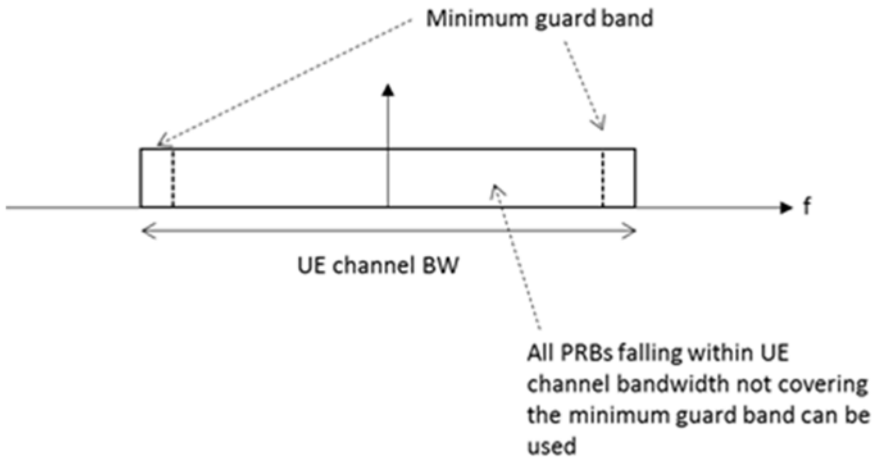

Figure 5-2: UE PRB utilization

5.3 Channel arrangements

Table 5-5: Channel raster to resource element mapping

	N_RB mod 2 = 0	N_RB mod 2 = 1
Resource element index k	0	6
Physical resource block number N_PRB	$n_{\mathrm{PRB}} = \left\lfloor \frac{N_{\mathrm{RB}}}{2} \right\rfloor$	$n_{\mathrm{PRB}} = \left\lfloor \frac{N_{\mathrm{RB}}}{2} \right\rfloor$

5.4 Summary of Relevant Requirements

The Guard Bands as defined within 3GPP depend on the different bandwidths as defined. If higher bandwidths like 200 MHz are used an additional Guard Band of 7.7 MHz can be added to the filter Guard Band. This does not have too much of an impact on the filters needed as proposed later. Therefore, we ignore these additional 7.7 MHz as they only relax the filter performance by a small portion.

6 Considerations on Antenna Design

6.1 Base Stations

The following chapter will give a short description how a base station antenna may be implemented. It assumes that full beamforming is mandatory and dedicated phase-shifting front-end chips will be used.

Antenna Layout

To maximize the coverage area we assume that full beam-steering in the elevation plane of the antenna is necessary. Additionally, we assume that no polarization tracking is implemented to minimize the number of components. To cover the complete hemisphere of such an antenna a distance between the elements of no more than λ/2 at the highest frequency is needed.

– λ/2(@27.5 GHz) = 5.45 mm

The following Figure 6-1 shows a principal layout of such an antenna for a base station. The dimensions are calculated for an element distance of 5.5 mm.

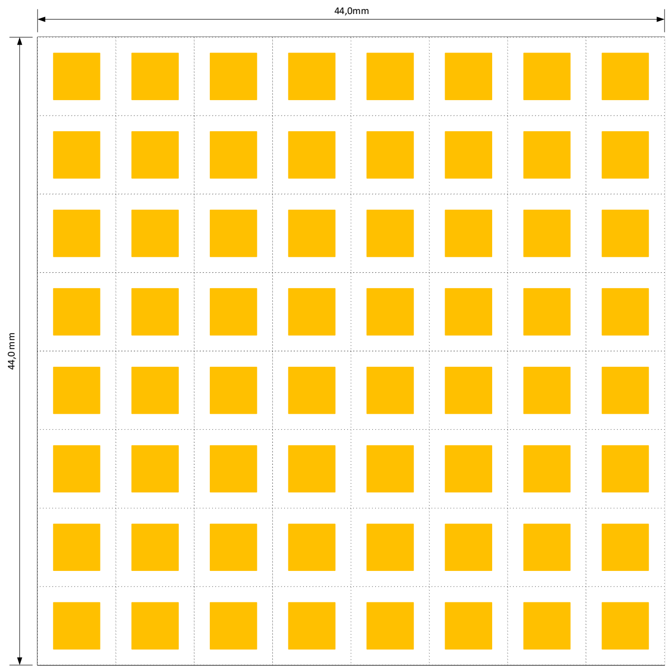

Figure 6-1: Layout and dimensions of 8x8 array antenna

To drive the individual antenna elements integrated phase shifter / amplifier solutions are needed. E.g., Anokiwave provides such solutions and shall serve as an example.

A suitable chip is the Anokiwave 24/26 GHz Silicon 5G Tx/Rx Quad Core IC AWMF-0139. It is a chipset serving 4 antenna elements with a maximum output power of 14 dBmW, a noise figure of 5.5 dB, 6 bit phase and 5 bit amplitude control. We assume that the 14 dBmW are per output, so a total output power of 20 dBmW is achieved. Power consumption is 1.3 W for the receivers and between 1.8 W and 2.5 W for the transmitters. So, the total power consumption of such an antenna will be about 21 W for the receiving stages and between 29 W and 40 W for the transmitters, added up between 50 W and 61 W. The total transmitted power without integrating the antenna gain will then be 32 dBmW.

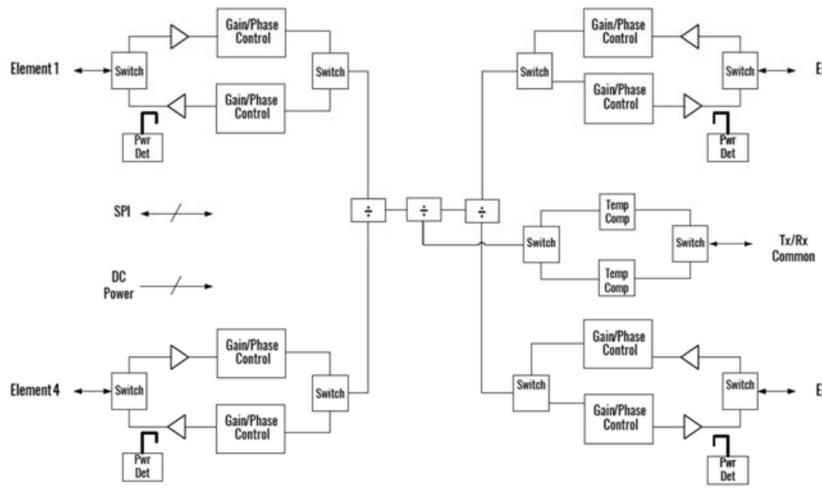

Figure 6-2: Block diagram of 4-channel phase-shifter / amplifier chip Anokiwave AWMF-0139

To implement these kinds of chips together with a filter, the following figure shall serve as a principal approach. It does not consider additional peripheral elements. It also assumes that the chip together with the filter can be implemented on the same PCB-side.

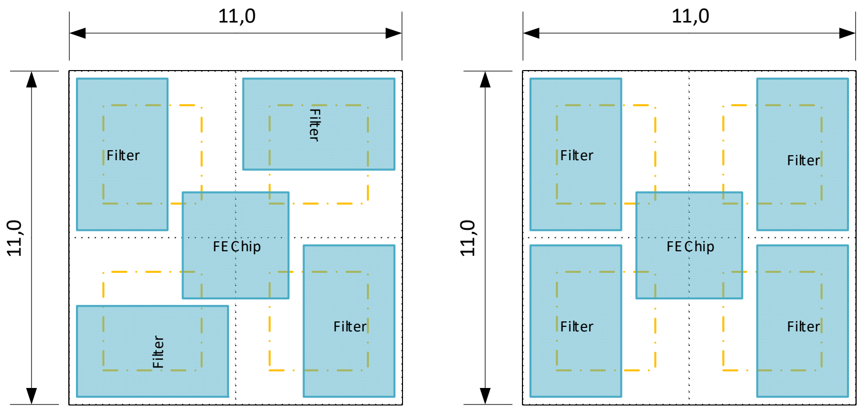

Figure 6-3: Placement of quad phase shifter / amplifier chip together with filters within a 2x2 antenna subelement

Such a 2x2 sub-element will have a dimension of 11 x 11 mm². The chip has a size of 3.6 x 3.6 mm². For an easy implementation a PCB-mountable filter of a maximum size of 3 x 5 mm² is mandatory.

For the array integration all supply voltages, the command lines and the feed network need to be implemented in additional layers in the PCB. We assume that for such an antenna at least 10 layers. A first stack-up is shown in Figure

6-4. If additional functions need to be implemented the number of layers may increase.

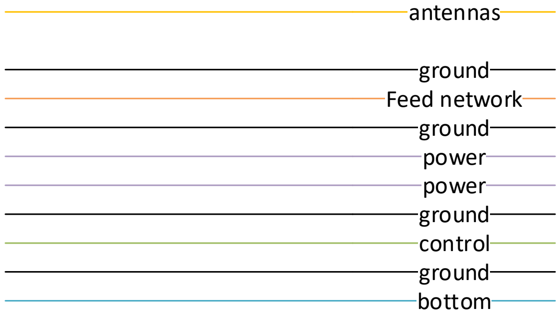

Figure 6-4: Stack-up of an example PCB covering the following functions: antenna layer, ground layers, feed network layer, power layers, control line layer and assembly layer

The constraints as pointed out before are based on the most dense implementation of the antenna. There may also be additional solutions where the number of amplifiers is reduced as one amplifier may feed a number (say four) of antenna elements. Then, either external phase-shifters and attenuators or a sub-grouping of antenna elements has to be implemented. The first approach leads to more external components and a lower integration level of the phase shifting circuitry. The latter leads to reduced scanning properties of the antenna array. Both approaches lead to a reduction of the number of filters by a factor of four and increased available area for the filters.

6.2 User Equipment

While we noted that UE meeting the requirements for NS_201 will not need further filtering to meet the EC decision recommendations, we have included a short survey of UE filter possibilities for completeness. For determining antenna approaches for the user equipment, a short survey on different technologies has been conducted. In the following we summarize the findings. We focus on handset/smart-phone antennas as these are most challenging ones. For other user equipment like laptops, tablets, etc. the challenge of integrating the antenna is much lower.

6.2.1 Antenna Structures as Discussed in Literature

Literature is currently discussing a lot of antenna approaches for enabling adaptive and flexible antennas in 5G mmWave. Aqeel Hussain Naqvi and Sungjoon Lim performed a meta-study named "Review of Recent Phased Arrays for Millimeter-Wave Wireless Communication" [29] summarizing antenna approaches for user equipment and for base-stations. Here, we will focus on the user equipment.

A special focus in the design of UE antennas has to be drawn to the effect of their location inside the handset and the human body. This will affect the performance of the antenna on the connection side as the impedance will change and on the radiation side as the patterns will be deteriorated and the radiation efficiency most probably will decrease. Modern handset are densely packed with PCBs, metal, battery and a large liquid-crystal display (LCD). The authors present antenna arrays with single- and multilayer printed circuit board (PCB) technologies, polarization diversity, and a wide scanning range.

The authors refer to Hong et al. [30] who presented a concept design for antennas for 5G mmWave at 28 GHz. There, 2 1 × 16 element phased arrays at the top and bottom positions of cellular phones have been realized (see Figure 6-5d)). The mesh-grid patch antennas are shown in Figure 6-5b). With this kind of antenna measured peak gain of more than 10.5 dBi was achieved. It can scan within a range of ±70° and has 10 dB bandwidth of more than 1 GHz. Transferring this to the 26 GHz shows that a significant bandwidth increase has to be achieved.

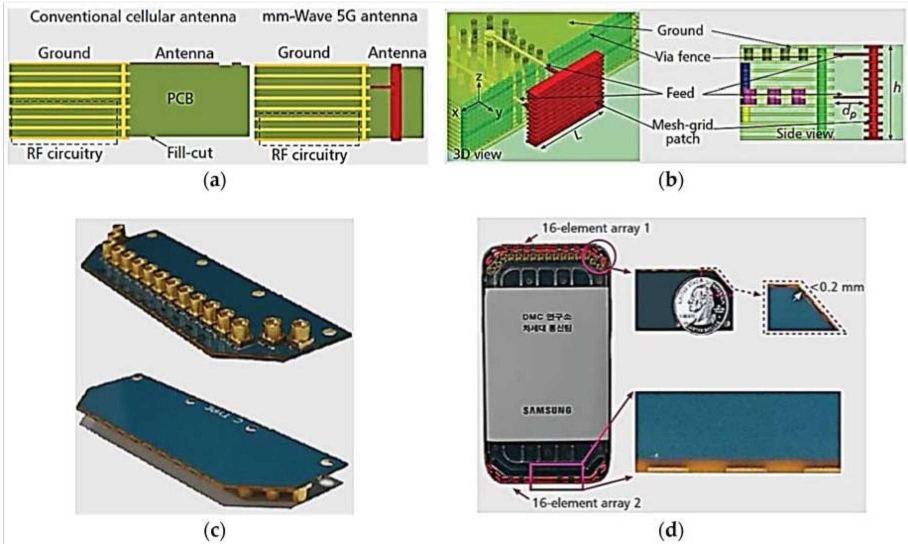

Figure 6-5: a) Comparative illustration of the standard cellular antenna and mm-wave 5G antenna. (b) Proposed antenna. (c) Prototype photograph of the standalone mm-wave antenna array with coaxial connectors. (d) Photograph of mm-wave 5G cellular antenna array integrated inside a Samsung handset and zoomed-in views of 5G mm-wave antenna array (taken from [29]).

In another publication [31] cited in the report, a planar quad-mode wideband phased array for a 5G mobile terminal device was reported. The phased array design consists of eight antenna elements. They are placed within a multilayer design consisting of two substrate layers. Dipoles are used on both bottom and top layers. As a matter of this fact the antenna achieves significant bandwidth of more than 4 GHz. The antenna is fed by a differential stripline feed. The dimensions of this antenna are 45 mm x 1.2 mm x 0.2 mm which is a suitable design. It has been measured at 25, 27, 29, and 31 GHz and shows good scanning behavior with a peak gain of between 12 dBi and 14 dBi.

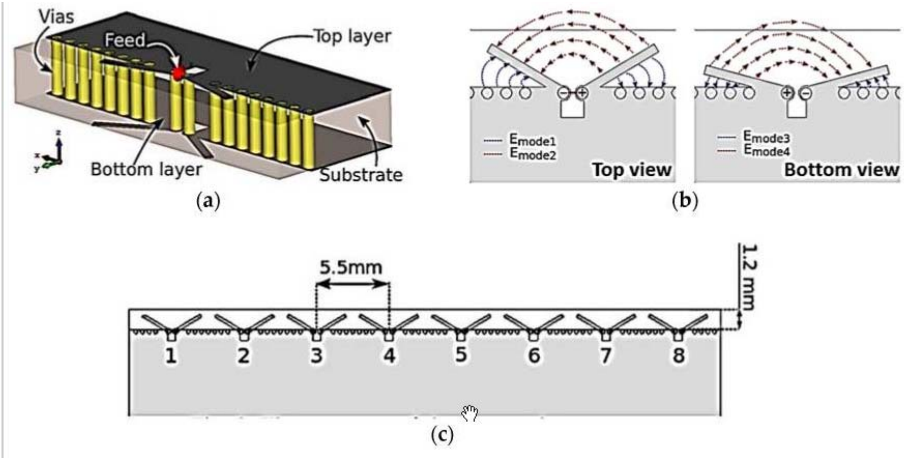

Figure 6-6: (a) Three-dimensional (3D) illustration of proposed antenna element. (b) Electric fields of proposed antenna's modes: top view (left) and bottom view (right). (c) Geometry of proposed eight-element phased-array antenna, taken from [29]

Another approach discussed [32] are phased-array antennas using patch elements. These may also be arranged in 3D-manner for a switchable three-dimensional (3D) scanning. Each subarray consists of eight microstrip patch antenna elements (MPAs) and has a beam-scanning capability of ±90° in the θ plane. The antenna was designed for a frequency range from 21 to 22 GHz, so certain bandwidth improvements would have to made. With a beam-scanning range of −90° to +90° with a gain of more than 12.5 dBi, the antenna acts as the ones before.

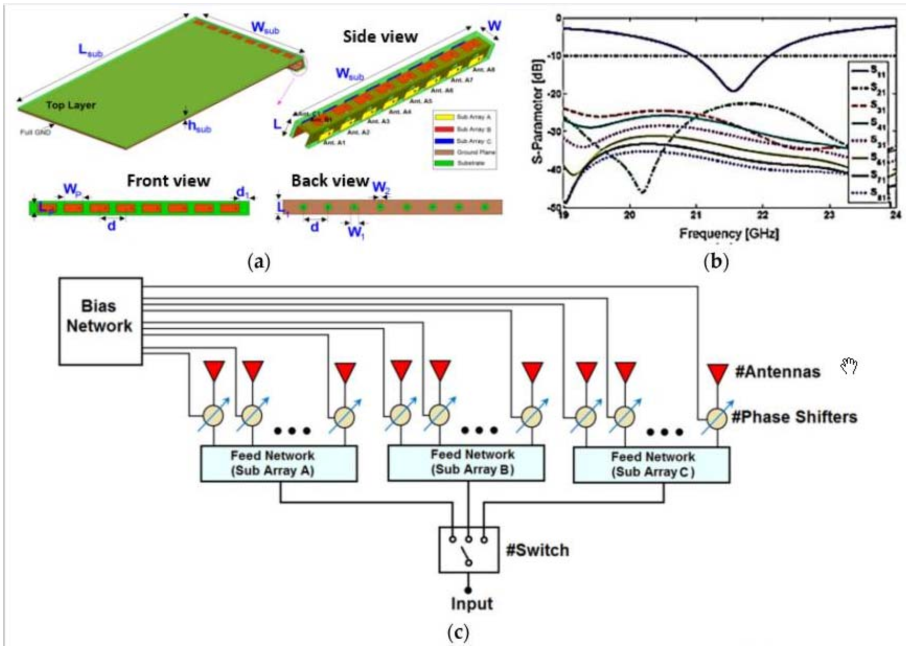

Figure 6-7: (a) Proposed view of 5G phased-array antenna with full ground plane. (b) S-parameters of proposed phased-array antenna with eight elements. (c) Proposed phased-array architecture, taken from [32]

Next to the above mentioned antenna types also Yagi-Uda, Vivaldi and multi-plate antennas are discussed. All of them offer the ability to scan the beam in a certain range and to provide the electrical performance needed. From an area consumption viewpoint these antenna types suffer from the larger space they need.

Another paper by Jonhu Park et al. [33] discusses an optically invisible antenna to be implemented on the display. They use a patch antenna approach which is mounted at the edge of the display as illustrated in Figure 6-8. With that approach the authors achieve a significant bandwidth at around 28 GHz. The efficiency of the antenna is below 30% thus achieving with an 1x8 array configuration an overall gain of almost 7 dBi with a directivity of almost 13 dBi. The large difference is caused by significant feeding network losses which could be avoided by directly feeding the antenna elements with individual amplifier and phase-shifter stages.

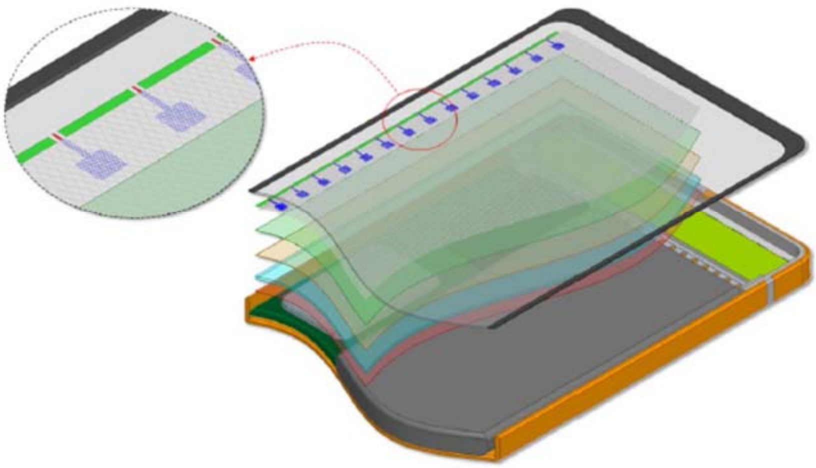

Figure 6-8: Illustration of the antenna on display concept, taken from [33]

In summary it can be said that a number of different implementations are available with different approaches and also achieving low volume consumption to be implemented in handsets.

All of these antenna implementation have to consider that the spacing between the elements has to be less than λ/2 at the highest frequency (λ/2(@27.5 GHz) = 5.45 mm).

6.2.2 Antenna Structures as Proposed by Qualcomm

Qualcomm announced in July 2018 the QTM052 antenna module for 5G mmWave applications. It is designed to work together with their Snapdragon X50 5G modem. Three months later, they came up with a 25% smaller version. It is suitable for operating in three 5G bands, handling up to 800 MHz aggregated carrier bandwidth in the 26.5 to 29.5 GHz band (n257) and covering the entire 27.5 to 28.35 GHz band (n261) and the entire 37 to 40 GHz band (n260). Functionally, it combines a phased array antenna, a radio transceiver and the power management. Beamforming and beam steering is done using the X50 modem.

Figure 6-9: QTM052 versions, the smaller one measuring app. 5.1 mm x 19 mm [37]

In 2019 Qualcomm announced the QTM525 which extends the usable frequency range also to n258 making it usable also in Europe.

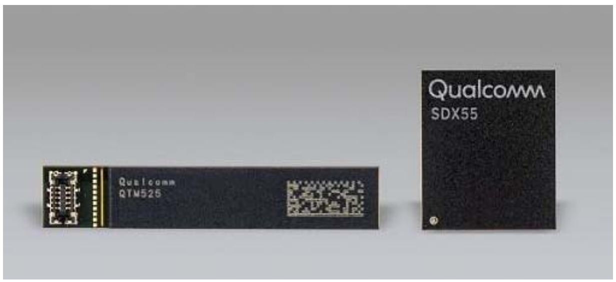

Figure 6-10: QTM525, measuring app. 4.4 mm x 24 mm, next to its modem companion SnapDragon X55 (taken from [38])

Both QTM052 and QTM525 have an integrated RF transceiver consisting of an Up-/downconverter, a LO frequency generation, phase shifters as well as low noise and power amplifiers. A sketch of such a device is depicted in Figure 6-11 showing a huge number of antenna terminals. Considering 4 patch elements providing 2 polarizations and the 6 dipoles we end up with 14 antenna elements. Each of the power amplifiers may provide about 10 – 15 dBmW of power. To achieve the significantly low Error Vector Magnitude (EVM) of -25 dB the amplifier has to be backed off to 6 – 8 dBmW.

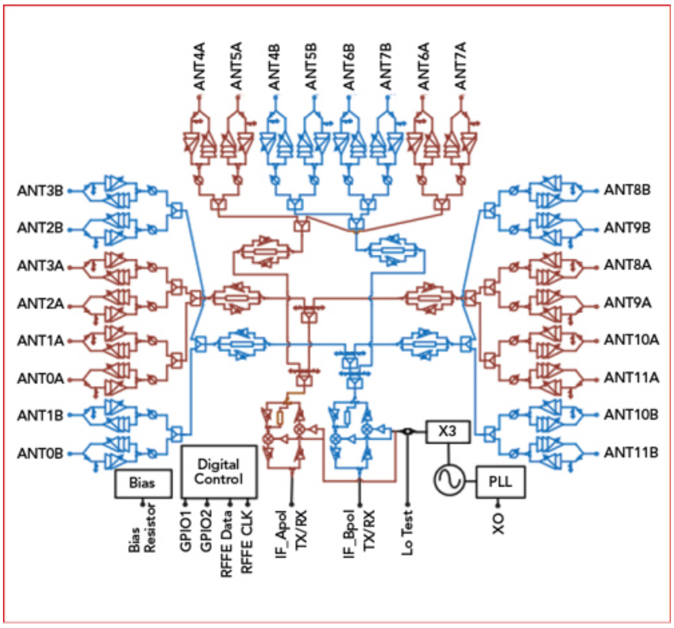

Figure 6-11: Notional block diagram of mmWave frontend IC [34]

Considering a 1x4 antenna array and assuming a reasonable implementation we may end up with an EIRP of about 23 – 26 dBmW. Still, TRP will be lowered by the antenna gain to about 14 dBmW.

The following Figure 6-12 shows the connectivity between antennas and amplifier modules. With the more compact implementation of the QTM525 only one module could be sufficient as it can provide 12 antenna ports. We can also assume that the width of the antenna module is then mainly driven by the RFIC size.

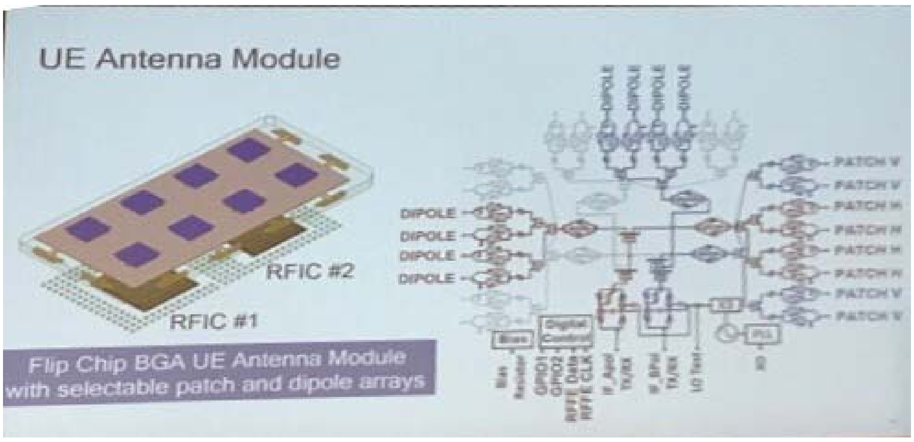

Figure 6-12: Connection diagram of QTM052 antenna module[7]

6.2.3 Short discussion on linearity requirements

Most of the antenna modules will be active. So, also the amplifier performance has to be taken into account. A well designed amplifier (having a certain linearity) will help in reducing the UWE levels.

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[7] Picture reference: https://www.microwavejournal.com/ext/resources/blogs/Pat/Brooklyn5G-2018/Qualcomm.jpg

Within [10] also a number of signal properties are defined. The main figures to be mentioned are the Error Vector Magnitude (EVM) and the Adjacent Channel Leakage Ratio (ACLR). Both figures are related to the linearity of the power amplifier but there is no direct transition calculation between both figures available. In essence it can be said that the better the EVM the lower the ACLR will be.

For different modulation schemes different EVMs are defined in [10]. The most stringent is applicable for a 64-QAM with a EVM of 8% or -22 dB.

Independent of the modulation scheme there is also a value for the ACLR defined as can be found in chapter 6.5.2.3 of [10]. This value is set to -17 dBc.

Taking into consideration some amplifier effects as discussed in chapter 0 we can deduce the following.

Using an array of 1x4 elements 4 amplifiers are implemented. Current designs are able to deliver about 10 dBmW per element with significant linearity. This leads to a TRP of 10 dBmW + 6 dB = 16 dBmW.

With the considered ACLR of -20 dBc, which is achieved by fulfilling the EVM requirements, we arrive at an UWE level of -4 dBmW.

The European Commission level of -8 dBmW/200 MHz is therefore almost reached and a filter with 4 dB rejection would be sufficient. This may help equipment manufacturers as with a proper amplifier design they are able to use less performant filter technologies or even may be able to omit the filter completely.

Still, to achieve the levels in all implementations we have to consider that a output power (TRP) of 23 dBmW is reached and that the amplifiers simply follow the requirement of -17 dBc ACLR as set by 3GPP.

6.2.4 Possible Mounting Locations in Handsets

All antenna implementations have to consider that the spacing between the elements has to be less than λ/2 at the highest frequency (λ/2(@27.5 GHz) = 5.45 mm).

We therefore sketch a similar antenna approach as in the base-station discussion above but reducing the array to a 1x4 array.

The following assumptions have been made:

- PCB-size: 27.5 x 5.5 x 1.5 mm³
- Filter-size: 3.0 x 3.0 x 1.5 mm³
- Front-End Chip: 4.0 x 4.0 x 1.0 mm³

In the following Figure 6-13 a sketch of such an antenna construction is given. It is based on what is possible from an antenna implementation point of view and a set of assumptions on the different components. The filters as displayed there have been sized to 3.0 x 3.0 x 1.5 mm³ expecting an implementation which can have to filters within one package. With that, we still achieve the usage of both polarizations within the overall system.

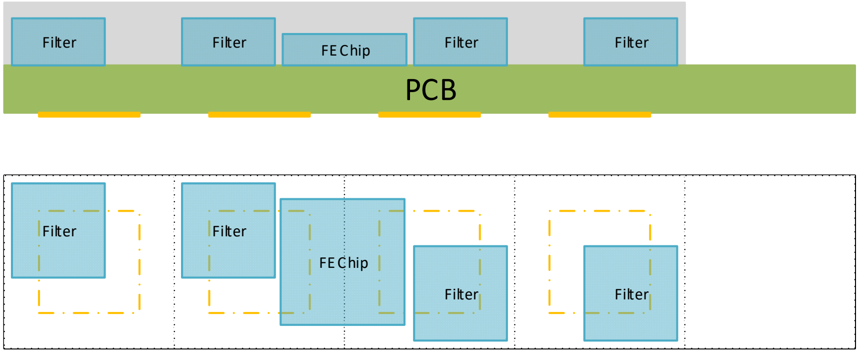

Figure 6-13: Sketch of a 1x4 array. Top: side view; bottom: top view

This approach leads to an overall size of 27.5 x 5.5 x 3.5 mm³. With that size we try to incorporate that structure in some of the current handset designs.

6.2.4.1 Qualcomm Reference Design

Qualcomm uses reference designs to promote their chipset and additional solutions. Such a reference design is used to show possible locations of the QTM052 antenna module. This is shown in the following Figure 6-14. The QTM052 still is of a certain width, therefore handsets tend to be thicker than 9 mm. The newer module QTM525 may overcome this problem leading to reasonable handset thicknesses.

Figure 6-14: Possible locations of QTM052 antenna module in a smart phone (taken from [40])

The height of the modules is not stated, pictures of the reference design demonstrate it is not a significant size driver. Considering the approach as displayed above, an implementation using additional filters for some of the elements seems feasible. With that approach one can achieve the additional requirements as proposed by 3GPP and the European Commission.

6.2.4.2 Samsung S10 5G

The design as proposed before was tried to place inside a Samsung Galaxy S10 5G. The preferred positions to achieve a good coverage and reasonable connection performance were taken from the Qualcomm reference design.

As from the teardown picture it cannot be fully determined if there really is space for such an antenna approach. An increase of width and length of the handset has to be considered. This may introduce some additional 2 mm in length and some 3 mm in width if some thinning of the cover can be arranged at the antenna locations. This would also help to overcome mismatch for the antenna and an occasional reduction in antenna efficiency. The current dimensions of this smart phone are 162.6 x 77.1 x 8 mm³.

Figure 6-15: Possible mounting locations of antenna module in a Samsung Galaxy S10 5G, picture taken from [39]. The red rectangle shows the RF-board.

7 Determination of Filter Requirements

Based on the emission levels as defined in Table 4-1 we calculate the corresponding filter rejection levels to fulfil the different requirements. This is assuming that the 5G unwanted emission levels are anyway achieved by design of the active hardware used in 5G mmWave technologies. Therefore, we also do not take into account all the calculations regarding EIRP, TRP etc. as the proposed emission levels already include some statistical modelling of the unwanted emissions. In essence, all the UWE levels are based on TRP[8].

For clarification, the definitions of EIRP and TRP shall be shortly described.

Totally Radiated Power – TRP is a measure for the integrated power in a volume around the transmitter. It sums up all the power on a sphere's surface around the transmitting device. The following formula displays this:

$$TRP = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} P(\vartheta, \varphi) \sin(\vartheta) \; d\vartheta d\varphi$$

Where

$$P(\vartheta, \varphi) = P_{Tx} G(\vartheta, \varphi)$$

In essence TRP should be the product of Transmit Power P_{Tx} and the efficiency η of the antenna:

$$TRP = \eta P_{Tx}$$

Equivalent Isotropically Radiated Power EIRP is a calculative measure to determine the radiated power of an antenna in a certain direction (main-beam) direction and therefore displays the space-filtering properties of an antenna.

$$EIRP = P_{Tx} G_{max}$$

As gain and directivity are also connected via the efficiency, we can say:

$$EIRP = TRP \; D_{max}$$

The required filter rejection is a simple difference between the 5G requirements and the individual requirements from the other institutions.

$$\begin{aligned} a_{filter}(23.6 - 24GHz) \\ &= unwanted\ emission\ level\ (5G) \\ &- required\ unwanted\ emission\ level\ (other\ institutions) \end{aligned}$$

As can be seen in the following Table 7-1 the filter rejection required to achieve the most stringent proposed EESS protection levels can be as high as 31 – 35 dB at a distance of 250 MHz from 26 GHz band edges. This clearly leads to a very sharp filter performance which is challenging to achieve in order to meet the most stringent proposed EESS protection levels.

[8] It is based on TRP as it assumed that the BS points below horizon and that in a worst case scenario all the power transmitted is somehow scattered and contributing to interference (but not being directed towards a certain direction).

As for the base-station no upper limits are given, the UWE limits as defined have to be achieved. Therefore, it is considered that the BS will reach the 3GPP requirement and needs additional filtering for the other UWE levels.

Considering the UEs this is slightly different as maximum power levels are given for the UEs and additionally an ACLR of -17 dBc is defined.

For the default UE Class 3 a TRP of 23 dBmW is defined. With the above mentioned ACLR the ACLP will be 23 dBmW – 17 dBc = 6 dBmW.

To achieve the European Commission limit of -38 dBW (= -8 dBmW) a 14 dB filter rejection is needed as can be found in the Table 7-1 below. All the other filter rejection values are also based on that ACLP of 6 dBmW.

This filter rejection may also be less if we assume that a lower ACLR of the amplifier is achieved. A short discussion on ACLR can be found in chapter 0. There, most of the implementations achieve ACLRs better than -20 dBc or even -25 dBc. This would relax the filter performance by another 3 dB to 8 dB.

Table 7-1: Required filter rejection levels in 24 GHz EESS bands based on different required unwanted emission levels in these bands

	ITU-R SM.329 Category A / B levels [dBW/200MHz]	**3GPP 5G unwanted (out-of-band & spurious) emission levels [dBW/200MHz]**	**IMT unwanted emission into the passive band (reference level) based on 5G parameter [dBW/200 MHz]**	**EC Decision 2019/784 [dBW/200 MHz TRP]**	**ESA/EUMETSAT/ EUMETNET study result [dBW/200 MHz]**	**WMO Decision [dBW/200 MHz]**
BS	-20.0 -37.0	-20.0	-23.8	-42.0	-54.2	-55.0
Required filter rejection @ EESS bands (See Note):	0.0 17.0	0.0	3.8	22.0	34.2	35.0
UE	-20.0 -37.0	-20.0 -38.0 (NS_201)	-20.0	-38.0	-50.4	-51.0
Required additional rejection @ EESS bands	0.0 13.0	0.0 14.0	0.0	14.0	26.4	27.0

Note: In estimating the required filtering levels for BSs, there are 3 classes of BSs to be considered under the 3GPP standard, wide area BS, medium area BS and local area BS. The required filter rejection estimated in the above table is for the wide area BS case which represents the worst case, since these BSs operate with the highest transmit power. Given their lower output power, the required filter rejection for the medium area BS and local area BS is 7 dB lower than for the wide area BS case and therefore the filter rejection is relaxed by the same number.

For estimating the required filtering level for UEs the required ACLR performance has to be considered. This leads to an UWE level of 6 dBmW. There is a new requirement for UEs in band n258 where a special signaling (NS_201) can be applied leading to lower UWE levels in 23.6 – 24.0 GHz frequency range. This level corresponds to the level in the EC Decision 2019/784.

7.1 Filter Requirements for use in Base Stations

In total, this leads to following main parameters for the filters:

- Pass band: 24.25 - 27.50 GHz (relative bandwidth: 12.56%)
- Pass band loss: as minimum as possible
- Stop bands: ≤ 24.00 GHz, ≥ 27.50 GHz
- Stop band attenuation (filter rejection) below pass-band loss: 0dB, 3.8 dB, >22 dB, >35 dB
- Maximum size: 3 mm x 5 mm for planar arrays
- PCB mountable or PCB structure

7.2 Filter Requirements for use in UE

In total, this leads to following main parameters for the filters:

- Pass band: 24.25 - 27.50 GHz (relative bandwidth: 12.56%)
- Pass band loss: as minimum as possible
- Stop bands: ≤ 24.00 GHz, ≥ 27.50 GHz
- Stop band attenuation (filter rejection) below pass-band loss: 0dB, 3.8 dB, >22 dB, >35 dB
- Maximum size: 3 mm x 3 mm x 1.5 mm
- PCB mountable or PCB structure

8 Filter Technologies in mmWave Bands

8.1 Theoretical Design of Filter

Taking the requirements as derived in the former chapters and based on the evaluation of the discussed regulations an ideal filter would have the following main parameters:

– Pass band: 24.25 - 27.50 GHz
– Stop bands: <24.00 GHz, >28.00 GHz
– Stop band attenuation (filter rejection): at least 20 dB
– Size: 3 mm x 5 mm

Taking some theoretical calculations to achieve this kind of filter performance this leads to the following architectures based on different topologies. Various filter technologies exist to achieve multiple goals, including signal roll off. A Butterworth topology is not promising as it would need an order of 19 which is not possible to realize.

In addition, one of the most challenging tasks is to provide a technology which can be manufactured with a high yield.

If a Guard Band has to be introduced, this will add to the lower pass-band edge (24.25 GHz + Guard Band) and therefore reduces the usable bandwidth for 5G/IMT.

8.1.1 Cauer or Elliptical Filter

Using an elliptical or Cauer filter one would need a filter of fifth order. This could be realized in microstrip technology.

The following Figure 8-1 shows the topology of the filter. It has been simulated using lumped elements which are not available for this frequency range, especially values of some pH. Nonetheless, this architecture would have to be translated to a microstrip filter approach.

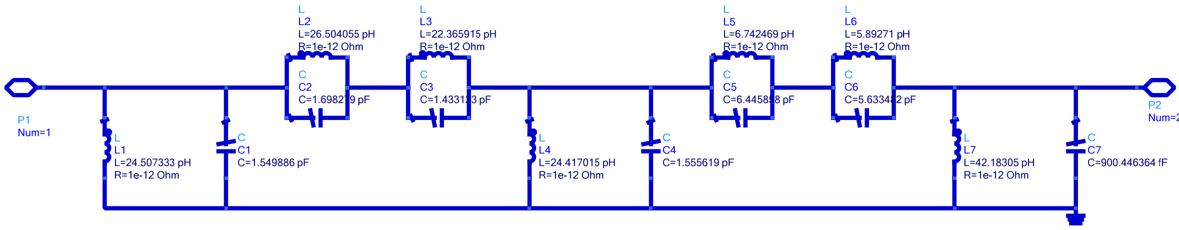

Figure 8-1: Topology of 5th order Cauer filter

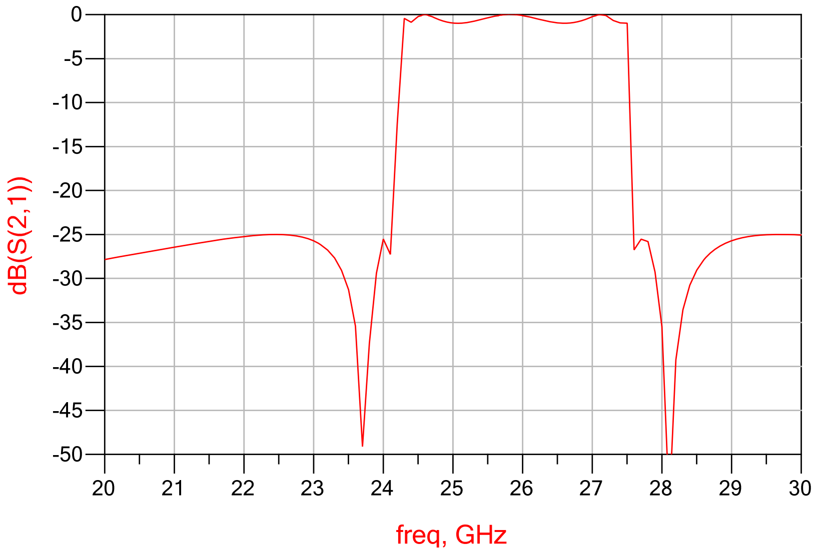

Figure 8-2: Filter performance of 5th order Cauer filter using ideal elements

As can be seen in Figure 8-2 the Cauer filter approach may be used to fulfil the different filter requirements. It could also achieve the 35 dB filter rejection with some additional Guard Band to protect EESS.

8.1.2 Chebyshev Filter

To implement this requirements a Chebyshev filter of 9th order would be needed. This may also be realised in microstrip technology.

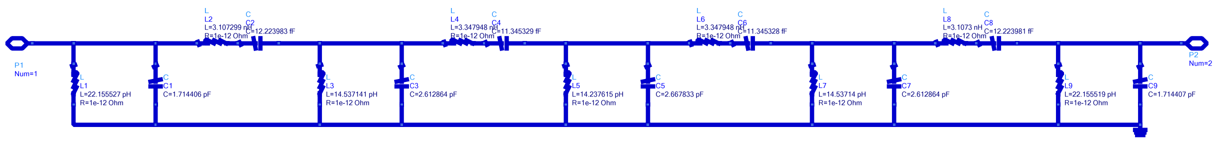

Figure 8-3: Filter topology of 9th order Chebyshev filter

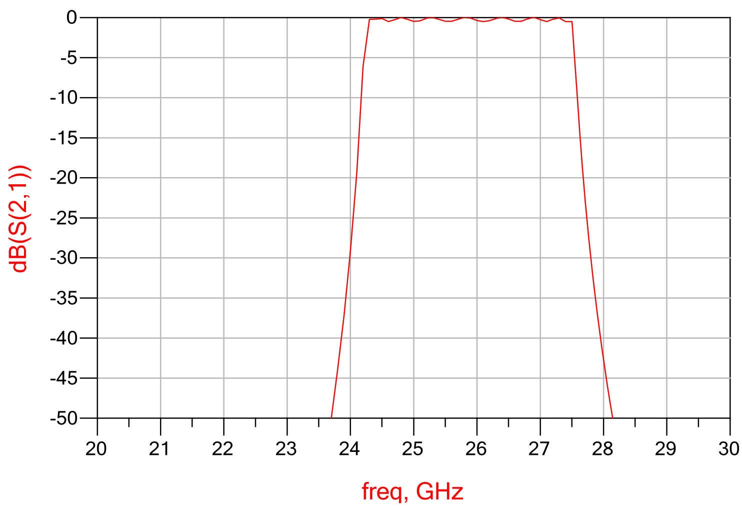

Figure 8-4: Filter performance of Chebyshev filter

As can be seen from Figure 8-4 also a Chebyshev type of filter can used to achieve the needed requirements.

8.1.3 Microstrip and Stripline Filter Topologies

The following Figure 8-5 shows a short summary of different filter topologies.

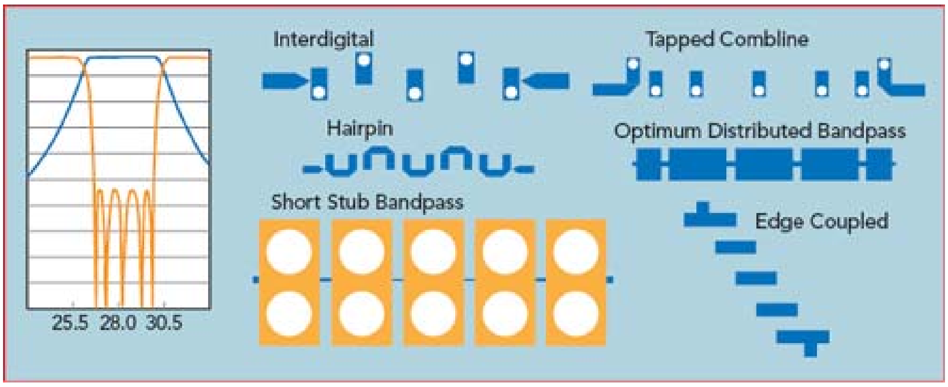

Figure 8-5: Types of filters for usage on microstrip or stripline technology [ref]

The design of such filters uses filter synthesis design tools which allow to design distributed designs such as edge coupled, hairpin, interdigital and combline, based on ideal distributed microstrip and stripline models. Incorporating manufacturing limits and tolerances can be very difficult and can last very long.

- Interdigital band pass structures consist of a number of coupled shortened quarter-wavelength resonators
- Tapped combline filters are of the same structure as interdigital filters, just adding a capacitive load at the open ended side
- Hairpin filters consist of folded half-wavelength resonators with edge coupling
- A optimum distributed bandpass structure uses a stepped impedance approach to achieve the filter properties
- A short stub bandpass filter consists of a transmission line symmetrically loaded with a number of short circuited stubs
- Edge coupled microstrip line filters consist of a number of half-wavelength filters coupled at the edge by defining the distance and the coupling length

8.1.4 Currently Available Filters on the Market

The following Table 8-1gives an overview of different available filters on the market.

Table 8-1: Overview of available filters

Manufacturer	Device	Passband (GHz)	Size (mm)	Technology
Mini-Circuits	BFCN-1262+	12.1 – 13.2	3.2 x 1.6	LTCC
Knowles Dielectric Labs	B274MB1S	26.5 – 29.5	11.4 x 2.7	Microstrip
Knowles Dielectric Labs	B260MB2S	24.25 – 27.5	TBD	TBD
SAGE Millimeter Inc.	SCF-26301370-SFSF-B3	25 – 26	47.5 x 15.0 x 9.0	Coaxial Bandpass Filter (SMA)
SAGE Millimeter	SWF-24323340-42-H1	> 24.1	88.9 x 22.3 x 11.4	Waveguide Highpass Filter
Pasternack	PE8747	27.5 – 31	40.6 x 9.7	Coaxial Bandpass Filter (SMA)
Corry Micronics	CMIBPF-23G-2G	22 – 24	12.7 x 5.0 x 3.0	Strip Line
ATLANTA micro	AM3066	12 – 26.5	6.0 x 6.0	Digitally Tunable Bandpass Filter

Mini-Circuits provides a filter for Ku-Band [16] and does currently not provide filters for K-Band. We believe that they are working on this kind of filters as a large demand is expected. The current implementation at Ku-Band has a passband insertion loss of 5 dB and a lower stop band filter rejection of about 20 dB starting at 600 MHz distance from the pass-band. Translating this performance to K-Band would lead to even higher insertion losses which seem to be not acceptable. The cost of such a filter is $ 3.85 when ordering 500 pc. It is expected to drop to about $ 2.00 or lower when ordering high volumes.

Knowles Dielectric Labs has a filter on stock (B274MB1S, [17]) and is currently developing a filter (B260MB2S, [18]) which is targeting the application discussed here. With a length of about 12 mm these filters are still a little too large so that 3D approach to reduce the size would be necessary. Unfortunately, we do not have insight in their technology, so we cannot predict if they are able to reduce the size accordingly. The current available filter has an insertion loss of 3.5 dB and a stop band filter rejection of 20 dB at 25.8 GHz with pass-band starting at 26.5 GHz. We except a similar behavior for the 26 GHz approach.

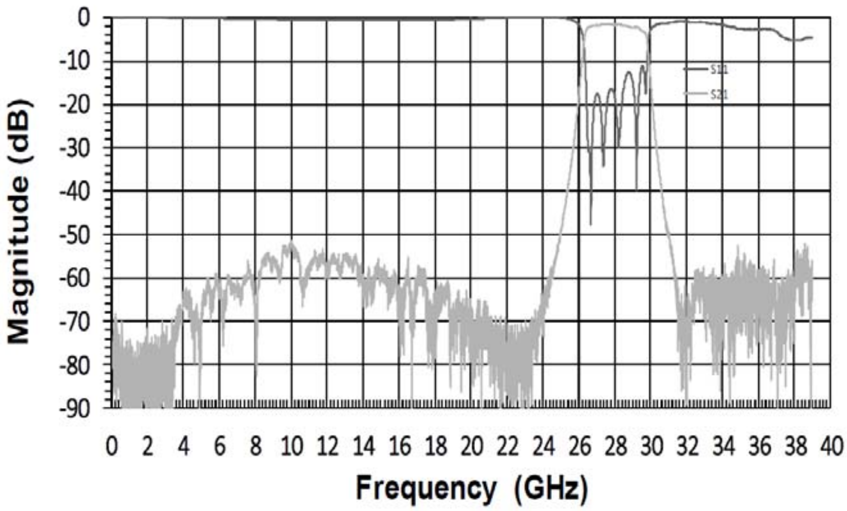

Table 8-2: Performance of B274MB1S [17]

To implement this kind of filter one would have to go for a multi-layer approach on the antenna PCB. This would increase the complexity of the stack-up. Additionally, the antenna element distances would have to be increased to 6 mm (see Figure 8-6), leading to a slightly reduced steering capability of the antenna. Still, most applications could be addressed with this kind of antenna.

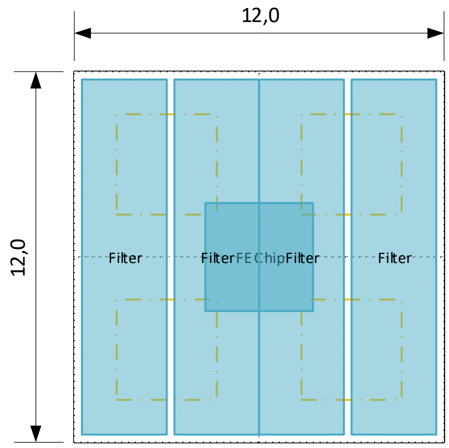

Figure 8-6: Sketch of implementation of Knowles Dielectric Labs filter in antenna sub-element

The cost of these filters is not stated and we were not able to get any information.

The filters from SAGE Millimeter Inc. [15] and Pasternack are based on classical coaxial or waveguide concepts and are way too large for this application.

Corry Micronics with its CMIBPF-23G-2G [19] provides a filter for 23 GHz which can easily be adjusted to the required 26 GHz range. They claim to have a pass-band insertion loss of 2.0 dB but do not tell the stop-band rejection close to the lower edge of the pass-band.

8.2 Short List of Filter Technologies as discussed in Current Literature

8.2.1 LTCC Filters

The paper "RF and Microwave Component Development in LTCC" discusses the usage of LTCC technologies at mm-wave frequency bands. As an example, an edge coupled four section 28 GHz version has been designed and manufactured. This was not designed for an optimum low edge performance as required for the application of this study. Figure 8-7 shows the implementation of such a filter with a size of 3 x 6 mm². The minimum dimensions used were 160 µm for line widths and spacing. Currently LTCC provides as minimum dimensions 100 µm for widths and spacing with an accuracy of about 5% which leads to variations of about 5 to 10 µm. The most problematic property is that this accuracy mostly relates to the line widths and not the gaps. So, for specific designs these deviations add up in the design.

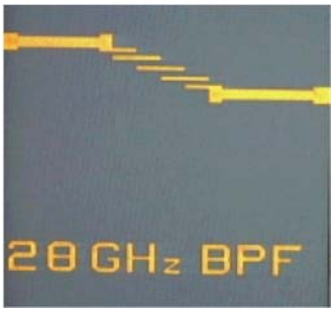

Figure 8-7: Example implementation of 28 GHz bandpass filter, total size of tile 15 x 15 mm² [16]

The measured results are shown in Figure 8-8. What can be seen is a slight frequency deviation and an insertion loss of about 2 dB down to 1.5 dB. It was realized on a Dupont 951 substrate.

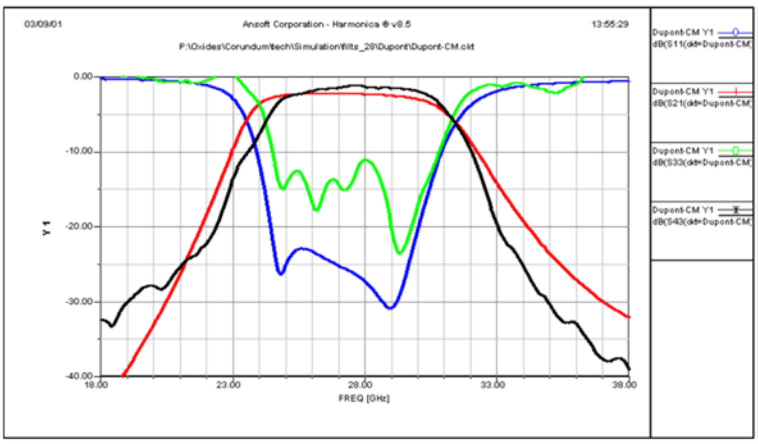

Figure 8-8: Simulated and measured performance of LTCC band pass filter [16]

This shows that also LTCC can be used to design such filters. One possible issue is the manufacturing accuracy which could lead to a low yield and would imply a measurement of each and every device at the end of the manufacturing process.

8.2.2 SIW Filters

Substrate-Integrated-Waveguides (SIW) show one of the most promising technologies to be used in the future for implementing filters in K- and Ka-Bands. In most implementations the usage of high performance substrates based on PTFE is used. The following section will summarize some of the latest papers using this technology.

The paper "A Cascaded Six Order Bandpass SIW Filter Using Electric and Magnetic Coupling Technology" [16] describes a filter based on an "ordinary" Rogers RO4003 substrate with a thickness of 0.304 mm. It has been optimized for a passband at around 15 GHz. The following Figure 8-9 shows a photo of the realized filter together with the main size. Due to the relatively low dielectric constant of RO4003 the size of the filter is around 40 mm in length and 15 mm in width.

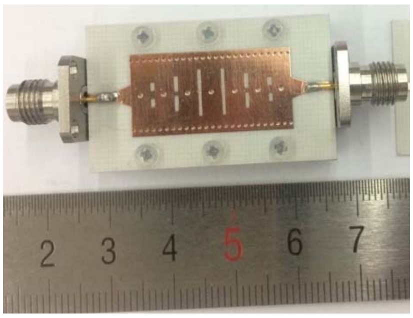

Figure 8-9: Photo of 6th order band pass [16]

The filter has a bandwidth of about 2 GHz with a pass band insertion loss of about 5 dB in this implementation (Figure 8-10). The simulated values were significantly better which the authors trace back to their implementation and some insufficient ground contacts.

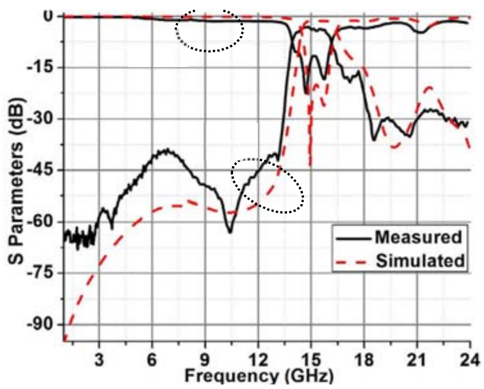

Figure 8-10: Simulated and measured performance of the proposed filter [16]

This concept can be reduced in size by using thin-film technology on a Al_2O_3 substrate with a possible size reduction factor of 1.7 and an additional size reduction of 1.7 by moving to 26 GHz, leading to a total size reduction of a factor of 3 and therefore 13 mm.

The paper "A miniaturized quasi-elliptic BPF with high selectivity based on combining CPWs (Coplanar Waveguides) and CSRR in a single dual-mode SIW cavity" [16] describes a SIW filter with an additional coupled split ring resonator (CSRR) optimized for operation at 5.8 GHz with a bandwidth of a little more than 500 MHz. It is implemented on a RO5880 substrate of height 0.508 mm with a dielectric constant of 2.2. The size of this implementation is 37.4 mm x 37.4 mm. The following Figure 8-11 shows a photo of this filter.

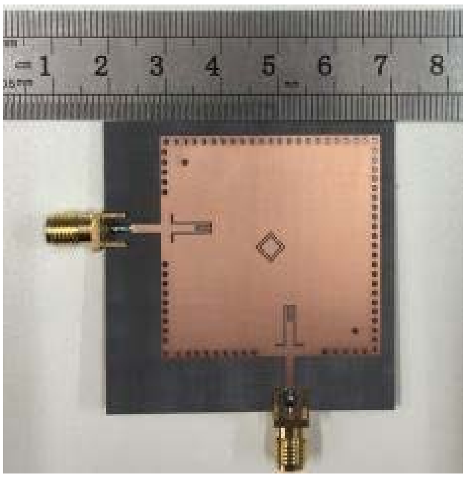

Figure 8-11: Photo of implemented filter [16]

The performance of the filter in pass- and stop-bands is shown in the following Figure 8-12. It can be seen that a quite low passband insertion loss is achieved with about 1.5 dB and quite steep drop at the lower frequency end with a filter rejection of 20 dB at about 5.4 GHz. Scaling this behavior to the 26 GHz region we would expect a size reduction of 70% also leading to higher accuracy demands for manufacturing this kind of filter. This would lead to a filter size of 11 x 11 mm². The main point to be seen here is the proper choice of transmission zeros which should also be applied to the requested filters.

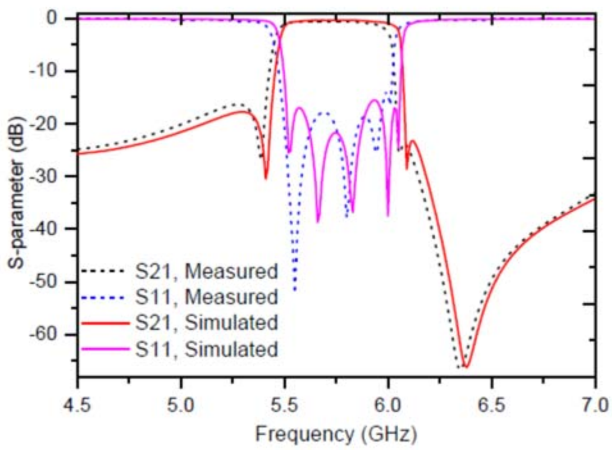

Figure 8-12: S-parameters of measured vs. simulated filter [16]

8.3 Outlook to New Filter Implementations

8.3.1 SMT Filters based on Microstrip Technology

Knowles Precision Devices recently published a comparison of different filter technologies in Microwave Journal of May 2019 [23]. There, they discuss different approaches for filtering in the 5G mmWave bands. As shown before, a filter placed directly at the antenna element is the preferred solution.

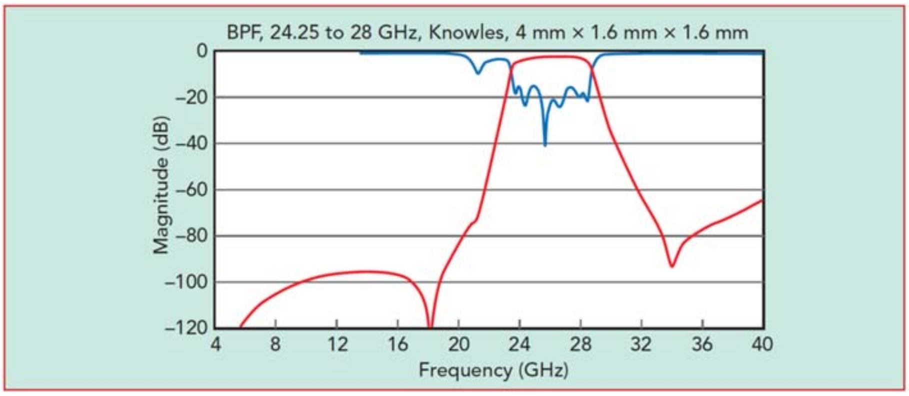

Figure 8-13: Performance of a Knowles Precision Devices 26 GHz microstrip band-pass filter on a single-layer [23]

The filter has a very small footprint of 4 x 1.6 x 1.6 mm³ based on a proper choice of the filter structure and the substrate it is built on. As can be seen in Figure 8-13 the pass-band insertion loss is about 3 dB, whereas stop-band filter rejection is below 60 dB for a wide frequency range. As we here focus on the close-by filter rejection especially between 23.6 GHz and 24 GHz we have to zoom in to find an indication of the performance. Currently, this frequency band is in the pass band. So, we have to consider Guard Bands to fulfil the performance and consider an improvement of 500 MHz to achieve the correct passband performance.

Then, we end up with an additional Guard Band ranging from zero to approximately 500 MHz or 1 GHz, depending on the type of 5G BS used and depending on the required emission suppression level.

Any such Guard Band would reduce the usable bandwidth for 5G services provided by wide area BSs by the same amount (24.25 GHz to 24.75 GHz or 25.25 GHz as lower edge of the band resulting in 3.25 GHz, 2.75 GHz or 2.25 GHz of available bandwidth for 5G within the band up to 27.5 GHz).

8.3.2 Coaxial Line Filters based on PolyStrata® Technology

Cubic Nuvotronics has implemented a manufacturing technology based on chip technology. It is using lithography to generate metallic layers on a substrate based on former chip manufacturing technologies. It operates with a resolution of about 1 µm. Therefore, small structures can be built up and manufactured. The main building blocks of this technology are based on coaxial lines which can operate up to 200 GHz. With this technology very compact structures can be achieved for a reasonable price, even at high frequencies.

It is patented by (among others) US 9,312,589 B2 [16], which is the base patent of this technology. The structures will be built up in a multi-layered approach as shown in Figure 8-14 and Figure 8-15. With this kind of layered approach and the small sizes of the coaxial lines different structures of RF devices can be built.

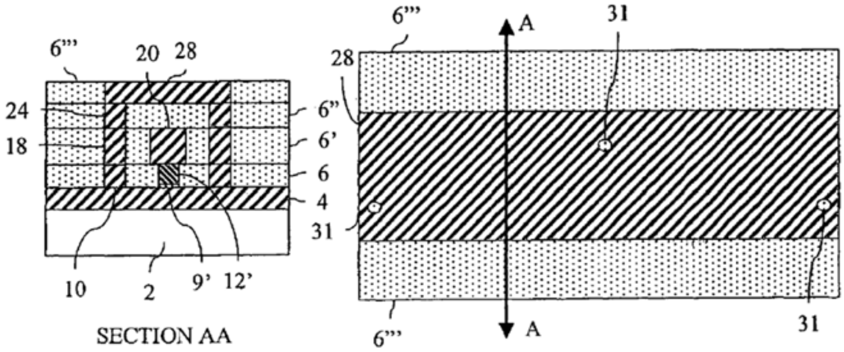

Figure 8-14: Layered approach of manufacturing method of Nuvotronics [16]

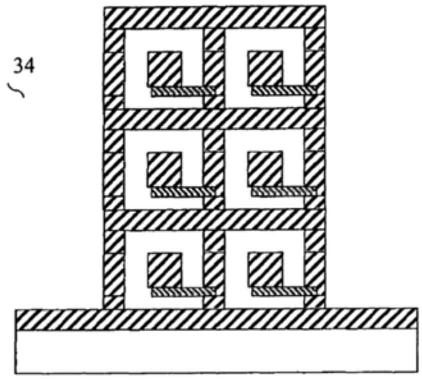

Figure 8-15: Stacked approach to build up space-efficient devices [16]

Currently, the height of these structures is limited to about 3 coaxial devices on top of each other. Additional structures can be glued together with properly defined interfaces. This technology offers a good alternative to classical PCB- or hybrid-based approaches. Filters using this technology have been built and operated at frequencies as high as 60 GHz.

Nuvotronics has already implemented an antenna structure for mmWave 5G operations. It offers a phased array beam forming solution to cover over ±45° steerability and can lower the power consumption by implementing a low-loss feeding network.

Figure 8-16: Artist view of Nuvotronics antenna (taken from their website)

Nuvotronics has started developing filters for 5G mm-wave base stations. For one particular filter designed to provide 20 dB of insertion loss at 24 GHz, Nuvotronics are stating a filter performance as shown in Figure 8-18 and Figure 8-19. The implementation is based on PolyStrata® technology intended for surface mount assembly. The following Figure 8-17 shows such filters with a size of 3 x 4 x 1 mm³. It was designed for a pass-band of 24.25 – 27.5 GHz with 20 dB suppression at 24.0 GHz (EESS band).

Figure 8-17: Example array of prototype of 24.25-27.5 GHz PolyStrata® filters [26].

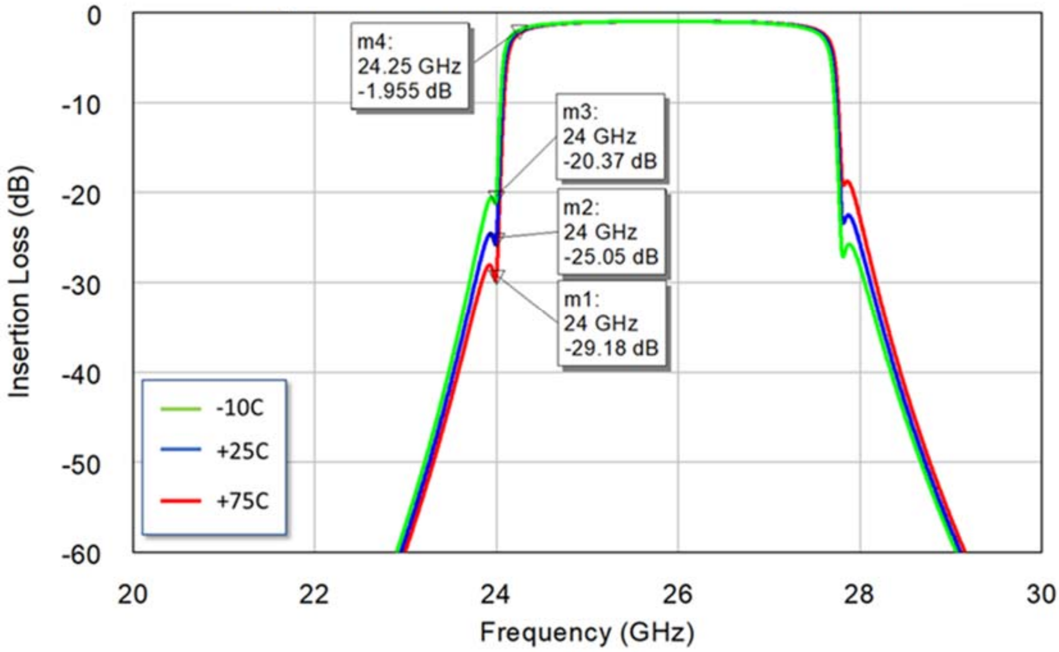

Figure 8-18: Simulated performance of a PolyStrata® 24.25-27.5 GHz filter designed for -20 dB filter rejection over temperature, [26]

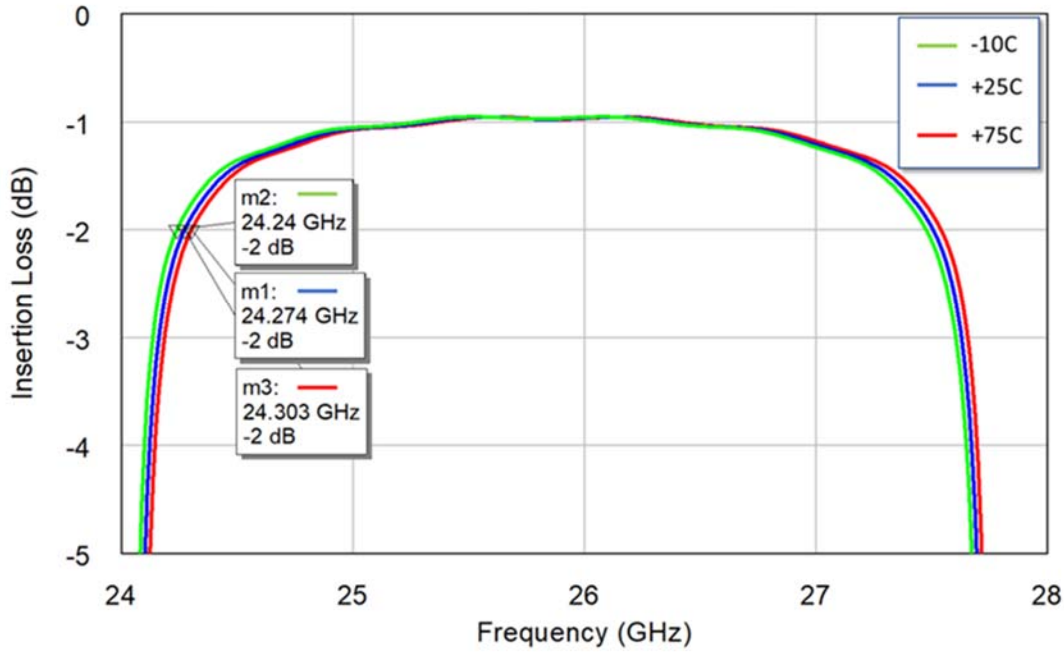

Figure 8-19: Simulated insertion loss of a PolyStrata® 24.25-27.5 GHz filter designed for -20 dB filter rejection over temperature, [26]

This would fully satisfy the requested filter performance of 20 dB filter rejection with reasonable insertion loss (approximately 1 dB) in the passband. The size of such a filter would be in the range of 3 x 5 x 1 mm³.

- As noted above, based on the 3GPP specifications, no additional filtering is necessary to achieve the -20 dBW/200 MHz unwanted emission level.

- This example PolyStrata® filter meets the -42 dBW/200 MHz requirements as defined by the EC in the case of 5G medium range and local area BS, and would nearly meet the same requirement in the case of wide area BS.

- The above PolyStrata® filter example with some design adjustments could fully satisfy that EC requirement for wide area BS.

The following Figure 8-20 shows an implementation example of such a filter in a 2 x 2 antenna sub-element. It can be seen that with this kind of filters such antennas will be feasible.

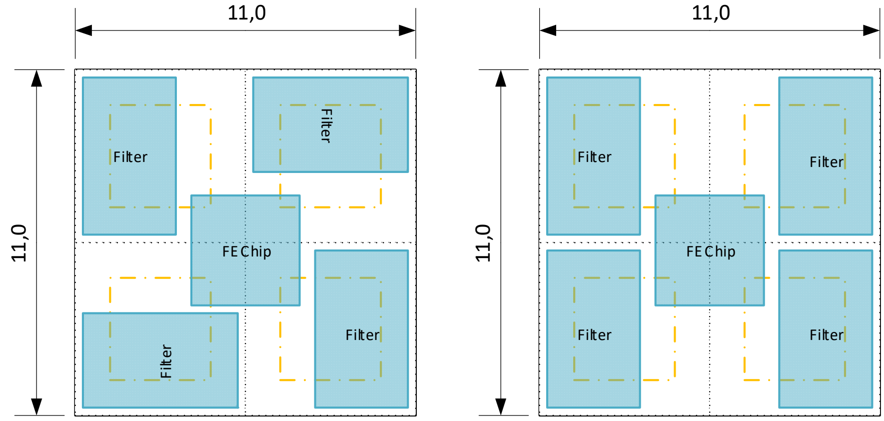

Figure 8-20: Layout of 2 x 2 antenna subelement with filters

The manufacturing technology was developed under different NASA and DoD contracts. It seems to be stable and working as already some examples and components have been produced. As the technology is based on chip manufacturing technology it should be capable of mass manufacturing.

To have a first assessment, we consider the following:

- 8" substrate: 203,20 mm diameter
- Wafer area: 32429,28 mm²
- area efficiency: 95%
- effective wafer area: 30807,81 mm²
- filter area (including cutting): 19.25 mm²
- possible number of filters: 1600
- yield: 98%
- effective number of filters: 1568

In essence, on processed wafer can contain about 1568 working filters. With increased area efficiency and yield one could get up to 1650 working filters.

Depending on the array structure of 5G mmWave base stations, 16 – 64 filters may be used. So, one wafer can serve best case 103, worst case 25 base station antennas.

The main question will then be how many wafers can be processed in a certain time-frame. As the technology is based on chip manufacturing it should be possible to use other foundries to increase volumes.

The above example PolyStrata® filter permits use of the full 3.25 GHz passband in the 26 GHz IMT band at 24.25 – 27.5 GHz under the EC protection level (-42 dBW/200 MHz)for medium range and local area BS types.

Since the PolyStratra® filter in this report was designed specifically for 20 dB out of band filter rejection, the resulting response can not be interpreted as providing the minimum possible Guard Band necessary for achieving higher levels of rejection.

As noted above, with a small design change this example PolyStrata® filter can meet the stricter required unwanted emission level of -42 dBW/200 MHz of the EC for wide-area BS types with similar level of insertion loss (approximately 1 dB to 1.5 dB).

Other PolyStrata® designs with greater stop band filter rejection (e.g. > 30 dB) to meet or nearly meet the requirements of the WMO should be possible. Trade-offs would need to be made on these other designs in size, cost, insertion loss etc.

Cubic Nuvotronic is currently manufacturing samples of these devices which should be available for testing during the fall of 2019. These filters may be available in significant numbers by beginning of 2020.

More generally, millimeter wave filter technology is advancing rapidly and new technologies that improve the rejection without compromising other parameters are likely to emerge given the high level of interest and investment.

8.4 Summary of Filter Technologies

Table 8-3 shows a summary of the characteristics of the filter technologies discussed above. As can be seen technologies based on SMT microstrip and PolyStrata® are the most promising for using them in 5G mmWave applications.

Table 8-3: Summary of filter characteristics for the different technologies

Technology	Microstrip on Alumina	SMT microstrip	Coaxial	LTCC	SIW on LTCC	PolyStrata ® (Note 1)
Insertion loss	3.5 dB	3 dB	3 dB	2 dB	2 dB	1 dB
Guard Band to achieve proposed UWE levels[9]						(see Notes)
IMT [-20 dBW/ 200 MHz] (Note 2)	0 MHz	0 MHz	0 MHz	0 MHz	0 MHz	0 MHz
EC [-42 dBW/ 200 MHz]	1500 MHz	500 MHz	400 MHz	1500 MHz	750 MHz	0 MHz (Note 3)
WMO [-55 dBW/ 200 MHz]	Not possible	1000 MHz	800 MHz	Not possible	1500 MHz	Under study (Note 4)
Size [mm³]	11 x 3 x 2	4 x 1,6 x 1,6	50 x 15 x 3	3 x 4 x 1[10]	3 x 4 x 1[11]	3 x 5 x 1
Technology maturity	high	high	high	high	medium	high[12]
Manufacturing stability	high	high	high	medium	medium	high
Estimated cost	10 $	1-2$	50 $	2-4 $	2-4 $	1-2 $
Note 1: The evaluation of the PolyStrata® filter examined used the values as displayed in the above figures at the worst case temperature curve and added 50 MHz to compensate for manufacturing tolerances.						
Note 2: For the IMT required unwanted emission level of -20 dBW/200 MHz, no additional filter is required , since the unwanted emission level under the 3GPP specification is also -20 dBW/200 MHz.						

9 Any required Guard Band would be added to the lower edge of the 26 GHz bandwidth for 5G, therefore reducing the usable bandwidth by that amount.

10 Estimated size

11 Estimated size

12 Not yet being mass produced

Note 3: The EC Guard Band value for the PolyStrata® filter examined is 0 MHz for the case of medium range BS and local area BS. For the wide area BS, the Guard Band for the PolyStrata® filter examined would be 200 MHz, but this Guard Band value can be reduced to 0 MHz when the PolyStrata® example filter discussed above is adjusted slightly to add additional rejection (of about 2 dB) in the stop band.

Note 4: The WMO Guard Band is presently under study using an adapted filter design.

PolyStrata® would be a very promising technology to provide the needed performance at reasonable cost and with the lowest impact on Guard Bands for all the different requirements imposed by IMT, EC or WMO.

If one takes the EC required unwanted emission levels for BSs, the use of PolyStrata® filters in 5G BSs should allow for development of 5G services using the entire 24.25 – 27.5 GHz band.

If the high requirements on the insertion loss as requested by WMO are to be implemented it even seems to be a possible short term solution.

9 Table of Figures

10 Table of Tables

11 Discussion of Regulatory Documents

11.1 ITU requirements for adjacent band protection (ID1.1)

ID1.1 (ITU-R RS.515-5, "Frequency bands and bandwidths used for satellite passive remote sensing") describes the measurement methods for passive sensing of atmospheric parameters like temperature and water vapor as well as surface parameters like roughness and vegetation covers, ice thickness and moisture content.

No specific requirements for adjacent band protection are given in this ITU-R document. However, the referenced ITU-R RS.2017 ("Performance and interference criteria for satellite passive remote sensing") gives more insight and maximum allowed interference levels, see below. A level of -166 dBW in 200 MHz bandwidth is reported within the band of 23.6 to 24.0 GHz. Only 0.01% time share is allowed where this value may be exceeded.

Since the interference will be created by a multitude of uncorrelated FR2 base stations and UEs within the sensing coverage area, the specified time share seems to be more or less irrelevant. Even in case of a completely synchronous network, the different slant range to the satellite will lead to an averaging of the unwanted emissions over time at the satellite receiver.

It is assumed that the total sum power of the out-of-band emissions from all FR2 base stations and UEs arriving at the satellite receiver have to be always below the maximum interference level, as stated below.

A very rough estimation of the total received interference power on the satellite with the expected interference levels from 3GPP (see next chapter). A detailed study of interference levels is in ECC document (ID1.4):

P_{total} =
-20 dBW / 200 MHz -20 dB (out of band emissions towards sky, conservatively estimated; assuming that beam forming with multi antenna elements is no more calibrated and working properly outside the specified frequency range)
+ 30 dB (~1000 terrestrial transmission points in urban and suburban areas; footprint in ID1.4 is >= 201 km^2)
– 180 dB (free space loss, FSL, for a medium 1000 km distance)
+ G_{rx} (Receiver antenna gain) = -190 dBW + G_{rx} = -160 … -148 dBW, which is >> -166 dBW, so indeed the interference level from 3GPP is too high.

EIRP per TP to sky = -20 dBW – 20 dB = -40 dBW

FSL = (4*PI*d^2) * lambda^2 / (4*PI) = 183 dB, assuming d=1000 km and lambda = 1.2 cm

G_{rx} (Beam gain) is between 30.4 and 52 dBi according to ID1.4 "ECC PT1(18)049_UK EESS passive study 26 GHz.docx"

Rec. ITU-R RS.2017-0 5

TABLE 2

Interference criteria for satellite passive remote sensing up to 1 000 GHz

Frequency band(s) (GHz)	Reference bandwidth (MHz)	Maximum interference level (dBW)	Percentage of area or time permissible interference level may be exceeded(1) (%)	Scan mode (N, C, L)(2)
1.370-1.427	27	−174	0.1	N, C
2.64-2.70	10	−176	0.1	N
4.2-4.4	200	−166	0.1	N, C
6.425-7.25	200	−166	0.1	N, C
10.6-10.7	100	−166	0.1	N, C
15.2-15.4	50	−169	0.1	N, C
18.6-18.8	200	−163	0.1	N, C
21.2-21.4	100	−169	0.1	N
22.21-22.5	100	−169	0.1	N
23.6-24	200	−166	0.01	N, C
31.3-31.8	200	−166	0.01	N, C
36-37	100	−166	0.1	N, C

Figure 11-1: Maximum interference levels as specified in ITU-R RS.2017-0

11.2 ITU WP5D liaison statement with ITU IMT characteristics (ID1.2)

Mainly three documents are relevant here from ID1.2. However some more Liaison Statements (LS) have been exchanged between WP5D and 3GPP:

1 [R4-1707004] LS from ITU-R WP5D to RAN4 "Unwanted emission for IMT-2020"
"ITU-R WP 5D notes that 3GPP is studying the feasibility of more stringent spurious domain emission limits than the -13 dBmW/MHz limit (Category A) for base stations. WP 5D would like to know the feasibility of achieving - 30 dBmW/MHz spurious limits (Category B) in a practical design for base stations and user terminals. If achieving this limit is not feasible, WP 5D would like to know what is achievable and under which conditions or circumstances"

2 [R4-1710084] 1st LS from 3GPP RAN4 to WP5D (September 2017)
"…Considering the complexity of reaching a stricter spurious emission level, and taking into account state-of-the-art mm-wave technologies on transmitters and filtering, integration and power efficiency aspects, further investigations are needed. RAN4 will continue to study the possibilities and will update ITU-R WP 5D when further progress is achieved."

3 [R4-1714090] 2nd LS from 3GPP RAN4 to WP5D (December 2017)
"An additional requirement to protect specific sensitive services (e.g. passive services) is under discussion in RAN4 and several observations were already given in the previous LS from 3GPP (R4-1710084). In addition to

those preliminary observations made, the following can be said… RAN4 will continue to study the possibilities and will update ITU-R WP 5D when further progress is achieved."

4 [R4-1809643] LS from WP5D to RAN4, "Definition of and test methods for OTA unwanted emissions of IMT radio equipment", (RAN4#88 June 2018)
"Therefore, ITU-R is not planning to update Recommendation ITU-R SM.329 until additional information is received.
Furthermore, ITU-R WP 5D is aware of regional activities (e.g. work in CEPT SE21 to finalize the revision of ERC Recommendation 74-01) as well as in 3GPP RAN4 to try to address this issue.
In order to progress the work within ITU-R, WP 5D would like to request further information on the definition and test methods of unwanted emissions for AAS for IMT radio equipment above and below 6 GHz. WP 5D is particularly interested in information on the definition and test methods for OTA (over the-air) unwanted emissions."

5 [R4-1900024] LS on Definition of test methods for Over-The-Air unwanted emissions of IMT radio equipment: Responses from RAN4 and RAN5,
"The test cases are defined in 3GPP TS 38.521-2 and 3GPP TS 38.521-3. The test cases are now expected to be complete by March 2019 after final definition of measurement uncertainty and test tolerances. RAN WG5 will continue to work closely with RAN WG4 and the test and measurement industry concerning maintenance of test procedures for additional permitted OTA test methods"

6 [R4-1902824] WP5D REPLY LIAISON STATEMENT TO ITU-R WP 1A, WP 1C, COPY TO 3GPP RAN4/RAN5,
TEST METHODS FOR OVER-THE-AIR TRP MEASUREMENTS OF IMT RADIO EQUIPMENT UTILIZING ACTIVE ANTENNAS,
"As stated in these materials, the work within 3GPP RAN is ongoing on this topic. However, the task of 3GPP RAN and its expertise are within the area of measuring TRP in a controlled environment such as an anechoic chamber.
WP 5D has reviewed and analyzed this material and further discussed possible test methods for field measurement of Over-The-Air (OTA) unwanted emissions of IMT radio equipment (BS & UE) with active antennas, which administrations may use as a guide when monitoring IMT transmitters.
As this topic of field measurements is one important element within regulatory compliance, WP 5D will communicate its findings and further development of the field measurement procedures with WP 1A and WP 1C in due time."

Conclusion for ITU-R WP5D until 05/2019:

- Final 3GPP specification is in TS 38.104 (BS) and TS 38.101-2/-3 (UE for Standalone / non-standalone), specifying -20 dBW / 200 MHz. This means, 3GPP did not implement the reduced emissions as requested by WP5D.
- It seems that after the response from RAN4 (R4-1714090, Dec 2017), WP5D did not insist on the lower interference levels in 3GPP any more.

Also 3GPP did not give any update specifically on out-of-band emissions to WP5D.

Update for June 3GPP RAN plenary 2019:

- The Category B requirements were adopted in the Change Requests for the TS 38.104 in the version of 2019-06 to have more stringent requirements for Base stations in FR2, for Europe.

3GPP differentiates between spurious emission requirements (-13 dBmW / MHz) and unwanted emission limits (tables, see below in next chapter on 3GPP).

11.3 Relevant 3GPP documents (ID1.3)

11.3.1 3GPP TS 38.101-2 NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone

For user equipment's (UEs) in FR2, the over the air (OTA) requirements of the technical specification TS 38.101-2[9] are applicable.

The occupied bandwidth is defined as the bandwidth containing 99% of the total integrated mean power of the transmitted spectrum on the assigned channel. In total 4 different channel bandwidths are defined: 50 MHz, 100 MHz, 200 MHz, and 400 MHz.

The out of band (OOB) emissions are unwanted emissions immediately outside the assigned channel bandwidth resulting from the modulation process and non-linearity in the transmitter but excluding spurious emissions. This OOB emission limits of FR2 are specified in the tables below.

11.3.1.1 UE Power Classes and EVM levels

The maximum output power for UEs will be displayed in the following. UEs are split in 4 classes as shown in the following Table 1-1.

Table 11-1: UE power classes as defined in [10]

UE Power class	UE type
1	Fixed wireless access (FWA) UE
2	Vehicular UE
3	Handheld UE
4	High power non-handheld UE

For these different UE classes the following maximum output power limits are defined for band n258 as shown in Table 11-2. These figures apply for any of the transmission bandwidths. Power class 3 is the default power class.

Table 11-2: Output power limits for the different UE classes

UE class	Max. TRP	Max EIRP
Class 1 (FWA)	35 dBmW	55 dBmW
Class 2 (Vehicular)	23 dBmW	43 dBmW
Class 3 (Handheld UE)	23 dBmW	43 dBmW
Class 4 (HP non- handheld UE)	23 dBmW	43 dBmW

For the EVM the following is defined.

Table 11-3: EVM levels for the different modulations

Parameter	Unit	Average EVM level	Reference signal EVM level
Pi/2 BPSK	%	30.0	30.0
QPSK	%	17.5	17.5
16 QAM	%	12.5	12.5
64 QAM	%	8.0	8.0

11.3.1.2 General spectrum emission mask

Table 11-4: General NR spectrum emission mask for frequency range 2: Spectrum limit (dBmW)/Channel bandwidth

Δf_OOB (MHz)	50 MHz	100 MHz	200 MHz	400 MHz	Measurement bandwidth
± 0-5	-5	-5	-5	-5	1 MHz
± 5-10	-13	-5	-5	-5	1 MHz
± 10-20	-13	-13	-5	-5	1 MHz
± 20-40	-13	-13	-13	-5	1 MHz
± 40-100	-13	-13	-13	-13	1 MHz
± 100-200		-13	-13	-13	1 MHz
± 200-400			-13	-13	1 MHz
± 400-800				-13	1 MHz

The spurious emissions are emissions which are caused by unwanted transmitter effects such as harmonics emission, parasitic emissions, intermodulation products and frequency conversion products, but exclude out of band emissions. The spurious emissions are apply for frequency ranges that are more than f_OOB (MHz) of Table 11-4. The boundary between NR out of band and spurious emissions equals two times the regular channel bandwidth (e.g. 100 MHz for 50 MHz channel).

The spurious emission limits for FR2 is defined as follows: "12.75 GHz ≤ f < 2nd harmonic of the upper frequency edge of the UL operating band in GHz" and is set to a maximum level of -13 dBmW at a measurement bandwidth of 1 MHz.

11.3.1.3 Adjacent channel leakage ratio

TS 38.101-2 [10] states: "Adjacent Channel Leakage power Ratio (ACLR) is the ratio of the filtered mean power centered on the assigned channel frequency to the filtered mean power centered on an adjacent channel frequency. ACLR requirement is specified for a scenario in which adjacent carrier is another NR channel.

NR Adjacent Channel Leakage power Ratio (NR_{ACLR}) is the ratio of the filtered mean power centered on the assigned channel frequency to the filtered mean power centered on an adjacent channel frequency at nominal channel spacing. The assigned NR channel power and adjacent NR channel power are measured with rectangular filters with measurement bandwidths specified in" Table 11-5.

Table 11-5: General requirements for NR_{ACLR}

	Channel bandwidth / NR_{ACLR} / Measurement bandwidth			
	50 MHz	**100 MHz**	**200 MHz**	**400 MHz**
NR_{ACLR} for band n257, n258, n261	17 dB	17 dB	17 dB	17 dB
NR_{ACLR} for band n260	16 dB	16 dB	16 dB	16 dB
NR channel measurement bandwidth	47.52 MHz	95.04 MHz	190.08 MHz	380.16 MHz
Adjacent channel centre frequency offset (MHz)	+50/ -50	+100.0/ -100.0	+200/ -200	+400/ -400

11.3.1.4 Additional spurious emission requirements for NS_201

A new requirement has been introduced in the latest version of the UE requirements document TS 38.101-2 [10]. There, it is stated: "When "NS_201" is indicated in the cell, the power of any UE emission shall not exceed the levels specified in" Table 11-6. This is a new requirement and also applies for the frequency ranges that are less than F_{OOB} (MHz) from the edge of the channel bandwidth. It therefore addresses additional OOB emission requirements for a wider frequency range. The level introduced corresponds to the levels as specified in the European Commission Decision [13].

Table 11-6: Additional requirements (NS_201)

Frequency band (GHz)	**Channel bandwidth / Spectrum emission limit (dBm)**				**Measurement bandwidth**	**NOTE**
	50 MHz	**100 MHz**	**200 MHz**	**400 MHz**		
$23.6 \leq f \leq 24$	-8	-8	-8	-8	200 MHz	1
NOTE 1: The protection of frequency range 23600 - 24000 MHz is meant for protection of satellite passive services.						

11.3.2 3GPP TS 38.104: NR; Base Station (BS) radio transmission and reception

For base stations (BS) in FR2, the OTA requirements are applicable in TS 38.104[11].

In general the following different types of base station are defined:

- BS type 1-C: NR base station operating at FR1 with requirements set consisting only of conducted requirements defined at individual antenna connectors
- BS type 1-H: NR base station operating at FR1 with a requirement set consisting of conducted requirements defined at individual TAB connectors and OTA requirements defined at RIB
- BS type 1-O: NR base station operating at FR1 with a requirement set consisting only of OTA requirements defined at the RIB
- BS type 2-O: NR base station operating at FR2 with a requirement set consisting only of OTA requirements defined at the RIB

However, in this study the focus is on FR2, so only BS type 2-O requirements are of interest.

Unwanted emissions consist of so-called out-of-band emissions and spurious emissions according to ITU definitions ITU-R SM.329. In ITU terminology, out of band emissions are unwanted emissions immediately outside the BS channel bandwidth resulting from the modulation process and non-linearity in the transmitter but excluding spurious emissions. Spurious emissions are emissions which are caused by unwanted transmitter effects such as harmonics emission, parasitic emission, intermodulation products and frequency conversion products, but exclude out of band emissions.

The OTA out-of-band emissions requirement for the BS type 1-O and BS type 2-O transmitter is specified both in terms of Adjacent Channel Leakage power Ratio (ACLR) and operating band unwanted emissions (OBUE). The OTA Operating band unwanted emissions define all unwanted emissions in each supported downlink operating band plus the frequency ranges Δf_OBUE above and Δf_OBUE below each band. OTA Unwanted emissions outside of this frequency range are limited by an OTA spurious emissions requirement.

The maximum offset of the operating band unwanted emissions mask from the operating band edge is Δf_OBUE. The value of Δf_OBUE is defined in Table 11-7 for BS type 2-O.

Table 11-7: Maximum offset Δf_OBUE outside the downlink operating band

BS type	Operating band characteristics	Δf_OBUE (MHz)
BS type 2-O	FDL,high – FDL,low ≤ 3250 MHz	1500

11.3.2.1 OTA Adjacent Channel Leakage Power Ratio (ACLR)

The OTA ACLR limit is specified in Table 11-8.

The OTA ACLR absolute limit is specified in Table 11-9.

The OTA ACLR (CACLR) absolute limit in Table 11-9 or Table 11-12 (unless stated differently in regional regulation) or the ACLR (CACLR) limit in Table 11-8, Table 11-10 or Table 11-11, whichever is less stringent, shall apply.

Table 11-8: BS type 2-O ACLR limit

BS channel bandwidth of lowest/highest NR carrier transmitted BW_Channel (MHz)	BS adjacent channel centre frequency offset below the lowest or above the highest carrier centre frequency transmitted	Assumed adjacent channel carrier	Filter on the adjacent channel frequency and corresponding filter bandwidth	ACLR limit (dB)
50, 100, 200, 400	BW_Channel	NR of same BW (Note 2)	Square (BWConfig)	28 (Note 3) 26 (Note 4)
NOTE 1: BW_Channel and BWConfig are the BS channel bandwidth and transmission bandwidth configuration of the lowest/highest NR carrier transmitted on the assigned channel frequency.				
NOTE 2: With SCS that provides largest transmission bandwidth configuration (BWConfig).				
NOTE 3: Applicable to bands defined within the frequency spectrum range of 24.25 – 33.4 GHz				
NOTE 4: Applicable to bands defined within the frequency spectrum range of 37 – 52.6 GHz				

Table 11-9: BS type 2-O ACLR absolute limit

BS class	ACLR absolute limit	Equivalent level
Wide area BS	-13 dBmW/MHz	-20 dBW/200 MHz
Medium range BS	-20 dBmW/MHz	-27 dBW/200 MHz
Local area BS	-20 dBmW/MHz	-27 dBW/200 MHz

Table 11-10: BS type 2-O ACLR limit in non-contiguous spectrum

BS channel bandwidth of lowest/highest NR carrier transmitted (MHz)	Sub-block gap size (Wgap) where the limit applies (MHz)	BS adjacent channel centre frequency offset below or above the sub-block edge (inside the gap)	Assumed adjacent channel carrier	Filter on the adjacent channel frequency and corresponding filter bandwidth	ACLR limit
50, 100	Wgap ≥ 100 (Note 5)	25 MHz	50 MHz NR (Note 2)	Square (BW_Config)	28 (Note 3)
	Wgap ≥ 250 (Note 6)				26 (Note 4)
200, 400	Wgap ≥ 400 (Note 6)	100 MHz	200 MHz NR (Note 2)	Square (BW_Config)	28 (Note 3)
	Wgap ≥ 250 (Note 5)				26 (Note 4)

NOTE 1: BW_Config is the transmission bandwidth configuration of the assumed adjacent channel carrier.
NOTE 2: With SCS that provides largest transmission bandwidth configuration (BW_Config).
NOTE 3: Applicable to bands defined within the frequency spectrum range of 24.25 – 33.4 GHz.
NOTE 4: Applicable to bands defined within the frequency spectrum range of 37 – 52.6 GHz.
NOTE 5: Applicable in case the BS channel bandwidth of the NR carrier transmitted at the other edge of the gap is 50 or 100 MHz.
NOTE 6: Applicable in case the BS channel bandwidth of the NR carrier transmitted at the other edge of the gap is 200 or 400 MHz.

Table 11-11: BS type 2-O CACLR limit in non-contiguous spectrum

BS channel bandwidth of lowest/highest NR carrier transmitted (MHz)	Sub-block gap size (Wgap) where the limit applies (MHz)	BS adjacent channel centre frequency offset below or above the sub-block edge (inside the gap)	Assumed adjacent channel carrier	Filter on the adjacent channel frequency and corresponding filter bandwidth	CACLR limit
50, 100	50 ≤ Wgap < 100 (Note 5) 50 ≤ Wgap < 250 (Note 6)	25 MHz	50 MHz NR (Note 2)	Square (BW_Config)	28 (Note 3) 26 (Note 4)
200, 400	200 ≤ Wgap < 400 (Note 6) 200 ≤ Wgap < 250 (Note 5)	100 MHz	200 MHz NR (Note 2)	Square (BW_Config)	28 (Note 3) 26 (Note 4)

NOTE 1: BW_Config is the transmission bandwidth configuration of the assumed adjacent channel carrier.
NOTE 2: With SCS that provides largest transmission bandwidth configuration (BW_Config).
NOTE 3: Applicable to bands defined within the frequency spectrum range of 24.25 – 33.4 GHz.
NOTE 4: Applicable to bands defined within the frequency spectrum range of 37 – 52.6 GHz.
NOTE 5: Applicable in case the BS channel bandwidth of the NR carrier transmitted at the other edge of the gap is 50 or 100 MHz.
NOTE 6: Applicable in case the BS channel bandwidth of the NR carrier transmitted at the other edge of the gap is 200 or 400 MHz.

Table 11-12: BS type 2-O CACLR absolute limit

BS class	CACLR absolute limit	Equivalent level
Wide area BS	-13 dBmW/MHz	-20 dBW/200 MHz
Medium range BS	-20 dBmW/MHz	-27 dBW/200 MHz
Local area BS	-20 dBmW/MHz	-27 dBW/200 MHz

11.3.2.2 OTA operating band unwanted emissions

Out-of-band emissions in FR2 are limited by OTA operating band unwanted emission limits. Unless otherwise stated, the OTA operating band unwanted emission limits in FR2 are defined from Δf_OBUE below the lowest frequency of each supported downlink operating band up to Δf_OBUE above the highest frequency of each supported downlink operating band. The values of Δf_OBUE are defined in Table 11-7 for the NR operating bands.

Table 11-13: OBUE limits applicable in the frequency range 24.25 – 33.4 GHz

Frequency offset of measurement filter -3B point, Δf	Frequency offset of measurement filter centre frequency, f_offset	Limit	Measurement bandwidth
0 MHz ≤ Δf < 0.1*BW_contiguous	0.5 MHz ≤ Δf_offset < 0.1* BW_contiguous +0.5 MHz	Min(-5 dBmW, Max(P_rated,t,TRP – 35 dB, -12 dBmW))	1 MHz
0.1*BW_contiguous ≤ Δf < Δfmax	0.1* BW_contiguous +0.5 MHz ≤ Δf_offset < f_ offsetmax	Min(-13 dBmW, Max(P_rated,t,TRP – 43 dB, -20 dBmW))	1 MHz
NOTE 1: For non-contiguous spectrum operation within any operating band the limit within sub-block gaps is calculated as a cumulative sum of contributions from adjacent sub blocks on each side of the sub block gap			

As a worst case assumption, the -13 dBmW per MHz result in +10 dBmW / 200 MHz (-20 dBW / 200 MHz).

11.3.3 Change Requests on 3GPP TS 38.104: NR; Base Station (BS) radio transmission and reception

During the 3GPP RAN#84 Plenary in Newport Beach, California between the 3rd and 6th of June 2019, change requests (CRs) for 3GPP TS 38.101-2 [9] and 3GPP TS 38.104 [11] have been introduced via 3GPP RP-191240: RAN4 CRs to New Radio Access Technology, part 5 [27]. One of this change requests introduces additional OBUE limits for the frequency range 24.25 – 33.4 GHz for the emission limits of "Category B".

The "Categories" are defined in ITU-R SM.329 [12], as follows:

Table 11-14: Category definition according to ITU-R SM.329:

Category	Description
Category A	Category A limits are the attenuation values used to calculate maximum permitted spurious domain emission power levels. RR Appendix 3 is derived from Category A limits. These limits are given in § 4.2.
Category B	Category B limits are an example of more stringent spurious domain emission limits than Category A limits. They are based on limits defined and adopted in Europe and used by some other countries. These limits are given in § 4.3.

Category C	Category C limits are an example of more stringent spurious domain emission limits than Category A limits. They are based on limits defined and adopted in the United States of America and Canada and used by some other countries. These limits are given in § 4.4.
Category D	Category D limits are an example of more stringent spurious domain emission limits than Category A limits. They are based on limits defined and adopted in Japan and used by some other countries. These limits are given in § 4.5.
Category Z	Radiation limits for ITE specified by the International Special Committee on Radio Interference (CISPR). These limits are given in § 4.6.

According the ITU in ITU-R SM.329 [12], "Category B" is foreseen for Europe and also other countries. In addition to the ITU-R SM.329 also 3GPP states in TR 38.815[28]: "3GPP Technical Specification Group Radio Access Network; New frequency range for NR (24.25-29.5 GHz)"that the more stringent rules of "Category B" shall apply for Europe.

According to the introduced CRs for 3GPP TS 38.104 [11], the following unwanted emission levels are defined for the frequency range 24.25 – 33.4 GHz:

Table 11-15: OBUE limits applicable in the frequency range 24.25 – 33.4 GHz

Frequency offset of measurement filter -3B point, Δf	Frequency offset of measurement filter centre frequency, f_offset	Limit	Measurement bandwidth
0 MHz ≤ Δf < 0.1*BW_contiguous	0.5 MHz ≤ Δf_offset < 0.1* BW_contiguous +0.5 MHz	Min(-5 dBmW, Max(P_rated,t,TRP – 35 dB, -12 dBmW))	1 MHz
0.1*BW_contiguous ≤ Δf < 2*BWcontiguous	0.1* BW_contiguous +0.5 MHz ≤ Δf_offset < 2*BWcontiguous +0.5 MHz	Min(-13 dBmW, Max(P_rated,t,TRP – 43 dB, -20 dBmW))	1 MHz
2*BWcontiguous ≤ Δf < Δfmax	2 BWcontiguous +5 MHz ≤ f_offset < f_ offsetmax	Min(-5 dBm, Max(Prated,t,TRP – 33 dB, -10 dBm))	10 MHz
NOTE 1: For non-contiguous spectrum operation within any operating band the limit within sub-block gaps is calculated as a cumulative sum of contributions from adjacent sub blocks on each side of the sub block gap.			

In addition to that, also the spurious emissions for "Category B" has been updated for the base stations according to the table below.

Table 11-16: BS radiated Tx spurious emission limits in FR2 (Category B)

Frequency range	Limit	Measurement Bandwidth	Note
21.00 – 22.75 GHz	-10 dBm	10 MHz	Note 1
29.00 – 30.75 GHz	-10 dBm	10 MHz	Note 1
NOTE 1:	Limit and bandwidth as in ERC Recommendation 74-01, Annex 2.		

The frequency range between 22.75 – 29.00 GHz is specified according to Table 11-15.

11.4 CEPT ECC Decision on 26 GHz IMT-2020 (ID1.4)

11.4.1 CEPT ECC Decision

In the following we will summarize the CEPT ECC Decision (18)06, "Harmonised technical conditions for Mobile/Fixed Communications Networks (MFCN) in the band 24.25-27.5 GHz", approved 06 July 2018 and corrected 26 October 2018. [7]

For this study the main statements are:

"d) that for a single MFCN network a contiguous block of 800-1000 MHz is desirable to enable the full capabilities of IMT-2020/5G systems;"

"e) that differences in the market demand for spectrum for MFCN and different authorisations regimes across CEPT countries is likely to lead to different timescales concerning the introduction of MFCN in the band 24.25-27.5 GHz; "

"g) that in many CEPT administrations the 26.5-27.5 GHz frequency range is less used by incumbent systems than the 24.5-26.5 GHz frequency range;"

"m) that the 26 GHz band will mainly be used for urban and suburban hotspot areas; however there may be a need for a limited number of hotspots in rural areas; it is not expected that the band will be used for contiguous wide/nationwide coverage of MFCN; "

"n) that a regular assessment of the evolution of MFCN system characteristics, including network deployments, in a timeline consistent with the 5 years review process of the Decision, or sooner if necessary, will provide additional confidence that these LRTC ensure adequate protection of other services, in particular space services;"

"o) that appropriate provisions are needed in the authorisation for MFCN to define precisely how to safeguard in a proportionate way the use of existing EESS/SRS receiving earth stations and the possibility for future earth station deployments in the 25.5-27 GHz frequency band;"

"p) that appropriate provisions are needed in the authorisation for MFCN to define precisely how to safeguard in a proportionate way the use of existing FSS transmitting earth stations and the possibility for future earth station deployments in the 24.65-25.25 GHz frequency band;"

"q) that methodologies will be developed to support coordination/coexistence between MFCN and earth stations in the 26 GHz band (receiving EESS/SRS and transmitting FSS earth stations) through the definition of suitable separation/coordination areas and/or any other solutions as part of appropriate provisions mentioned in considerings o)and p));"

"r) that most sharing studies have shown that Fixed-Satellite Service (FSS) and the Inter-Satellite Service (ISS) would be protected with a margin of more than 12 dB, based on agreed assumptions, and it will be necessary to ensure that these services remain protected (see considering n);"

"s) that the pointing elevation of the main beam (electrical and mechanical) should normally be below the horizon for outdoor base stations;"

"u) that the protection of the Earth Exploration-Satellite Service (EESS) (passive), requires the introduction of appropriate limits of unwanted emission power in the band 23.6-24 GHz, applying to MFCN operating in the band the 24.25-27.5 GHz; additionally the protection of RAS will require the implementation of suitable separation distances between RAS stations and MFCN transmitters on a case-by-case basis;"

"v) that the protection of the Earth Exploration-Satellite Service (EESS) (passive) in the band 50.2-50.4 GHz and 52.6-54.25 GHz is ensured by the existing generic spurious limits of -30 dBmW/MHz applying to base stations;"

"x) that CEPT is studying usage of MFCN for the command, control and payload link of unmanned aircraft systems (UAS) in MFCN bands, including in the 26 GHz band. However, due to its specific characteristics and usage, the 24.25-27.5 GHz MFCN band is not to be used for connectivity from base stations to terminals on board unmanned aircraft vehicles (UAV). In addition, the connectivity from terminals on board UAV to base stations may have a significant impact, e.g. on separation distance from EESS/SRS earth stations, which requires further study. These UAV operations should not be an obstacle to the deployment of future EESS/SRS earth stations;"

This leads to the following selected decisions:

"3. that CEPT administrations wishing to introduce MFCN in the band 24.25-27.5 GHz shall apply the frequency arrangement and technical conditions according to decides 4, 5 and 7;

4. that the MFCN frequency arrangement in the band 24.25 - 27.5 GHz is an unpaired Time Division Duplex (TDD) frequency arrangement as provided in Annex 1;

5. that the Least Restrictive Technical Conditions (LRTC) specified in Annex 2 shall apply to the MFCN systems;

7. that MFCN in the 24.25-27.5 GHz band shall not be used for connectivity from base stations to terminals on-board UAV and that only communications for connectivity from terminals on-board UAV to base stations is authorised taking into account considering x) ;"

Annex 1 of the decision describes the frequency arrangement for the band 24.25 – 27.5 GHz, using TDD with a block size of 200 MHz, which can be adjusted to narrower blocks (multiples of 50 MHz) adjacent to other users for full use of spectrum, with block offsets done in 10 MHz steps if needed.

Figure 11-2: Example of possible frequency arrangements for MFCN in the 24.25-27.5 GHz band [7]

Annex 2 describes the least restrictive technical conditions and especially the unwanted emission levels in the bands 23.6-24 GHz.

Base station MFCN BS additional baseline requirement: maximum emissions into the 23.6 - 24.0 GHz band (described in Table 4 of [ref])

– 23.6 – 24.0 GHz: -42 dBW (in 200 MHz bandwidth)

Note: This level requirement applies for BS for all foreseen modes of operation (i.e. maximum in-band power, electrical pointing, carrier configurations)

Table 5 in [7] states that the normal beam pointing of base stations shall be below horizon.

Terminal station MFCN terminal station maximum emissions into the 23.6 – 24.0 GHz band (described in Table 6 of [ref])

– 23.6 – 24.0 GHz: -38 dBW (in 200 MHz bandwidth)

Note: This level requirement applies for terminal station for all foreseen modes of operation (i.e. maximum in-band power, electrical pointing, carrier configurations)

11.4.2 ESA-EUMETSAT-EUMETNET Comment

An investigation performed by ESA-EUMETSAT-EUMETNET reflects the decision of CEPT ECC. There, a compilation of different approaches is given and compromise has been worked out. It is stated that the current limit of -20 dBW/200 MHz is harmful to the EESS (passive) sensors in the 23.6 - 24 GHz band [8].

The draft ECC Decision (18)FF proposes the following possible range of unwanted emission limits, based on a multi-country proposal presented at last ECC meeting (Document ECC(18)021):

- For BS : [-42/-44] dBW/200 MHz
- For UE : [-38/-40] dBW/200 MHz

These values are studied by ESA-EUMETSAT-EUMETNET.

The basic analysis states the a hard protection limit of EESS (passive) sensors in the 23.6 - 24 GHz band for IMT-2020 stations operated in the 24.25 – 27.5 GHz band:

- For BS : -54.2 dBW/200 MHz
- For UE : -50.4 dBW/200 MHz

These limits would ensure the protection of all current and planned EESS (passive) sensors.

Taking these limits the parties state that the above mentioned limits are somehow optimistic to ensure the operation of EESS (passive) sensors. The concerns are the following:

- First of all the concern about the "provisional" nature is stated:
  - It is the assumption that this proposal is only the first step and additional compromises with relaxed limits will be asked for in the future.
  - These levels are based on optimistic assumptions
- A second concern reflects the [90/99]th percentile that is used to balance the fact that the reference pattern underestimates the sidelobes.

There will be ongoing discussions on the used reference pattern, the antenna pointing and the number of base stations considered. These parameters highly affect the calculated levels.

Additionally, it is pointed out that the unwanted emissions are not really beamformed in space as these are a product of all the beam directions will be spatially flat (having the same value in all directions)[13]. This will also be applicable to frequencies further away from the carrier as the phase behavior will change dramatically leading to more equally distributed radiated energy. Here, it seems that additional studies have to be performed.

The study provides the following Table 11-17 with the different unwanted emission levels as proposed by 3GPP, the levels needed to fully protect the passive sensors and the compromise which would have to be made to conform with the draft ECC Decision (18)FF.

[13] Spatially flat would also mean that there is no gain in a certain direction, as this would more or less reflect an isotropic approach.

Table 11-17: Emission levels as summarized in the CEPT study [8]

	ITU-R SM.329 Category A / B levels [dBmW/MHz]	3GPP 5G unwanted (out-of-band & spurious) emission levels [dBW/200MHz]	IMT unwanted emission into the passive band (reference level) based on 5G parameter [dBW/200 MHz]	Required improvement of 5G unwanted emissions	CEPT ECC Decision (18)FF [dBW/200 MHz TRP]	Concession on the protection of passive sensors	ESA/EUMETSAT/ EUMETNET study result [dBW/200 MHz]
BS	-13.0 -30.0	-13.0	-23.8	18.2 / 20.2 dB*	[-42.0/ -44.0]	12.2 / 10.2 dB	-54.2
UE	-13.0 -30.0	-13.0	-20.0	18.0 / 20.0 dB*	[-38.0/ -40.0]	12.4 / 10.4 dB	-50.4
Comment	= -20.0 / -37.0 dBW/200 MHz	= -20.0 dBW/200 MHz	BS emission mask:20.0 MHz ≤ Δ*f* < 400 MHz: = -26.4 dBW/200 MHz Δ*f* > 400 MHz: = -20.0 dBW/200 MHz				

* These levels are consistent with calculations from Ericsson (doc. 5-1/235) and Nokia (doc. 5-1/284), taking into account the additional 2 dB channel aggregation factor agreed in ECC/PT1.

11.5 Statement of World Meteorological Organisation

World Meteorological Organisation (WMO) has formulated its position on WRC-19 agenda item 1.13 which addresses the protection of EESS. It is accepted that there is a large interest in using the mmWave bands by MNOs.

Regarding the protection of EESS (passive) bands, WMO stipulates the following protection levels for applications in the 24.25 – 27.50 GHz band:

- -55.0 dBW/200 MHz for base stations,
- -51.0 dBW/200 MHz for user equipment.

WMO will stay with these limits unless new compelling arguments as well as detailed measurements or better modelling will be shown.

11.6 Commission Implementing Decision (EU) 2019/784

Recently, the European Commission has released decision 2019/784 [13] on the harmonization of the 24.25 – 27.5 GHz band for terrestrial systems. There, it is stated that this frequency band can be used by terrestrial systems also in Europe "as long as it complies with international and cross-border obligations under ITU Radio Regulations". In paragraph (10) of [13] it is stated that existing satellite services "should be appropriately protected from terrestrial wireless broadband electronic communication services". Paragraph (11) highlights the protection of satellite earth stations. In paragraph (19) it is stated that the terrestrial services "should provide appropriate protection to the EESS (passive) in the 23.6 – 24.0 GHz frequency band.

Article 3 (a) states that terrestrial systems appropriately protect "systems in adjacent bands, in particular in the Earth Exploration Satellite Service (passive) and in the Radio Astronomy Service in the 23.6 – 24.0 GHz frequency band;". Article 3 also provides statements for other satellite services.

Next to the protection of satellite systems the decision also covers the protection of existing terrestrial systems.

Table 11-18: Emission level as defined in EC decision

	Transitional region power limit (In-band, out-of-block) [dBW/200 MHz]	**Baseline power limit for synchronized operation (In-band, out-of-block) [dBW/200 MHz]**	**Additional baseline (OOB) power limit [dBW/200 MHz]**
BS	-12.0	-20.0	-42.0
UE			-38.0

12 Short Discussion on Amplifier Linearities

Peter M. Asbeck et al. recently published an overview over different amplifier designs [35]. It presents a review of of key power amplifier (PA) performance requirements for millimeter-wave 5G systems and also compares the potential of different technologies. Output power, efficiency, and linearity considerations are displayed. They emphasize on silicon technologies and especially on CMOS-SOI. Their focus is on 28 GHz with peak power added efficiency (PAE) of up to 46% with a saturation power (Psat) above 19 dBmW. There are also implementations using a backoff of 6 dB at Psat of 22 dBmW. For high constellations like a 64 QAM OFDM modulation, 13 dBmW of output power and 17% of PAE at a bandwidth of 800 MHz is reported.

The following Figure 12-1 gives an overview on the different available technologies for PA implementations in the different frequency ranges.

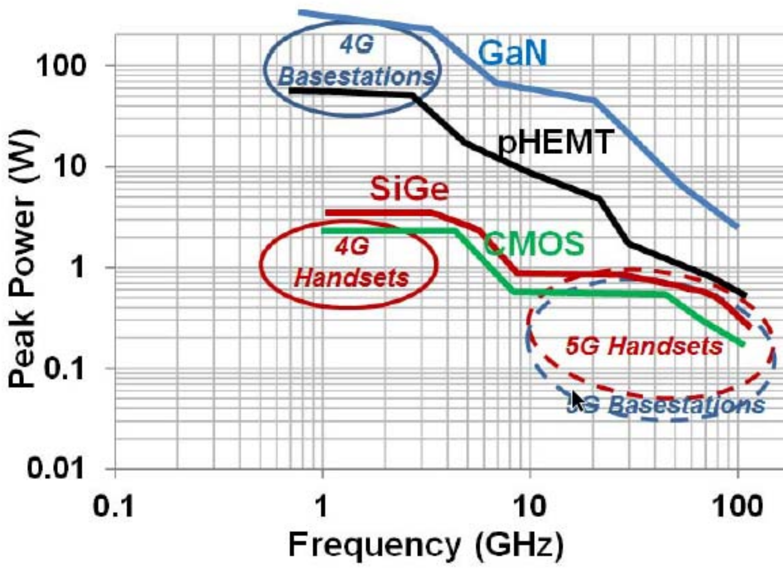

Figure 12-1: Estimated power ranges for 5G mm-wave PAs and estimated, taken from [35]

This implies that especially in the mmWave bands technologies like SiGe and CMOS seem to be feasible for an easy integration in the related chipsets. They achieve peak powers of up to 500 mW in the relevant frequency ranges.

The following Table 12-1 summarizes the different performance figures achieved in that paper. It shows the capabilities currently available. There, it is also stated that the field is very dynamic and changes rapidly.

Table 12-1: Summary of different reported PA properties in [35]

	Psat (dBm)	PAEmax (%)	PAE (-6dB)	Pout (dBm)	PAE (%)	DPD?
	CW	CW	CW	64 QAM OFDM	64 QAM OFDM	64 QAM OFDM
nMOS 2-stack [10]	18.5	40.5%	23%	9.8	14.8%	No
nMOS 4-stack [13]	23.6	32%	17%	15	14%	No
pMOS 2-stack [16]	19.5	46.7%	24%	9.2	17%	No
SiGe Outphasing [22]	23	41.4%	34.7%	14.3*	25.3%	Yes
nMOS Doherty [26]	22.4	40.2%	27.9%	13	17.4%	No
nMOS Doherty (asymmetric) [29]	25	32%	28%	15.1**	19.2%	Yes

Signal bandwidth 800 MHz, except *80 MHz and ** 50 MHz.

It can be seen that reasonable PAEs can be achieved at output powers between 9 dBmW and 15 dBmW operating at backoffs between 8 dB and 10 dB without using a digital predistortion.

Considering some current research on mmWave amplifier technologies the above specified ACLR of -17 dBc seems to be quite relaxed.

Hu et al. report on a multiband implementation of mmWave amplifiers in [36]. That paper presents a first 28-/37-/39-GHz linear Doherty power amplifier (PA) in silicon fully integrated in a standard 130-nm SiGe BiCMOS process. With a saturation power Psat of +16.8-/+17.1-/+17-dBmW it achieved a significantly better PAE than class-B operation at a 5.9-/6-/6.7-dB backoff at the respective frequencies.

They also report a comparison of different technologies and the associated key performance parameters. As we focus here on linearities and especially on the ACPRs that part will be further summarized.

The implementation of Hu et al. achieves an ACPR of -28 dBc for an output power of 9.2 dBmW at 28 GHz and 500 MHz signal bandwidth as can be seen in the following Figure 12-2.

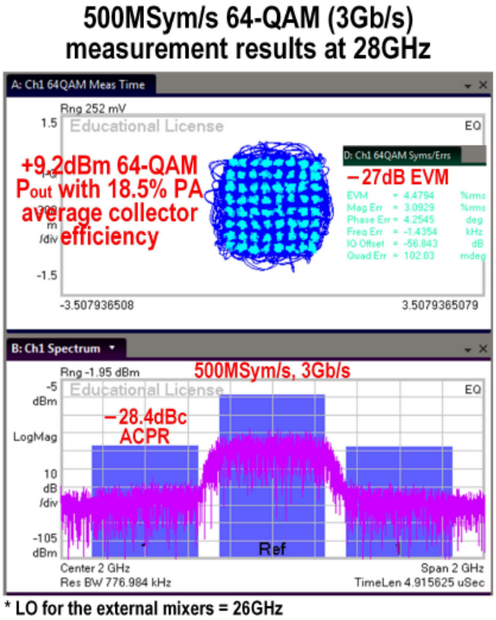

Figure 12-2: Signal quality and ACPR as reported in [36]

In Table II in [36] they compare their implementation with other implementations. In summary almost all the other cited papers achieve similar ACPRs, in essence all below -25 dBc.

Compared to the requirement of -17 dBc the state-of-the-art shows some 8 dB better performance – especially to achieve the required EVM-values.

Additionally, there are already plenty of approaches for increasing the linearity behavior using digital predistortion techniques which can be applied in modern chipsets.

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