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Tera**h**ertz end-to-end wireless systems supp**o**rting ultra-high data **R**ate applications

ThoR

Deliverable D2.1

Requirements for B5G backhaul/fronthaul

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PP	**Restricted to other programme participants (including the Commission Services)**	
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Contents

Change register

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1. Statement of independence

The work described in this document is genuinely a result of efforts pertaining to the ThoR project. Any external source is properly referenced.

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2. Abbreviations

5G	5th generation of cellular mobile communication systems
5G NR	5G New Radio – new air interface being developed for 5G
B5G	Generation(s) Beyond 5G
BBU	Baseband Processing Unit
BFSK	Binary Frequency Shift Keying – a digital modulation format based on changing the carrier signal frequency
BH	Backhaul
BS	Base Station in cellular communication systems
CAPEX	CAPital EXpenditure
CEPT	European Conference of Postal and Telecommunications Administrations
CPRI	Common Public Radio Interface – standard defining fronthaul interface
CU	Central Unit
DL	Downlink
DU	Distributed Unit
ECC	Electronic Communications Committee
EIRP	Effective (or Equivalent) Isotropic Radiated Power
FDD	Frequency Division Duplex
FH	Fronthaul
FSO	Free-space Optical Communication – use of visible or infrared light (laser beams) to wirelessly transmit data
MAC	Medium Access Control layer
mmWave	Millimetre Wave frequencies (30 to 300 GHz; wavelength 1 cm to 1 mm)
NGMN	Next Generation Mobile Networks alliance
ITU	International Telecommunication Union
P2P	Point-to-point link/communication

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P2MP	Point-to-multipoint link/communication
PDCP	Packet Data Convergence Protocol layer
PRB	Physical Resource Block - consisting of twelve consecutive subcarriers: the smallest unit of resources that can be allocated/scheduled to a user.
PSK	Phase Shift Keying – a digital modulation format based on changing the phase of the carrier signal
QAM	Quadrature Amplitude Modulation
RLC	Radio Link Control layer
RRC	Radio Resource Control layer
TDD	Time Division Duplex
UL	Uplink
WRC	World Radiocommunication Conferences (ITU)
XPIC	Cross-Polarization Interference Cancelling technology

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3. Introduction

Fast growing network traffic and increasing demand for high speed connectivity over the next years require new wireless technologies to build communication systems supporting ultra-high data rates. The demands of a fully connected society (e.g. Internet of Things, Internet Everywhere) are characterized by the tremendous growth in connectivity and the density/volume of traffic. In addition, the associated multi-layer densification, and the broad range of use cases and business models that are expected, will be key characteristics of next generation 5G networks incorporating advanced connectivity. The networks need to provide optimal connectivity with respect to access technology and service quality, to enable a plethora of relevant services towards the customers and run in a highly efficient manner, leveraging network automation to the greatest possible extent. Traffic densities of several Tbps/km^2 are already predicted for the foreseeable 5G access networks in the near future [1].

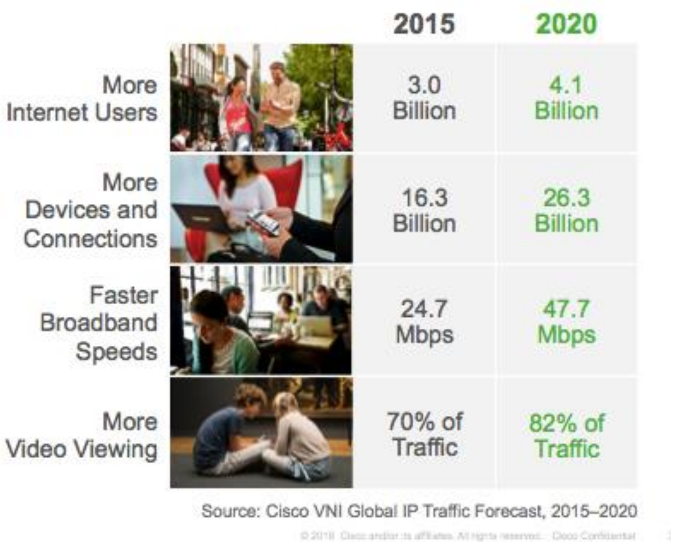

Figure 1 Global data traffic and service growth drivers [2]

This data traffic, capacity and connectivity growth in access networks must also be reflected in transport networks. In order to increase capacity and improve the coverage of access networks, the physical and interference footprints of base stations must be decreased. Such densification must also be supported by proper transport solutions. The base stations (macro as well as small cells) are connected to the core network through wired or wireless transport networks, often with extreme requirements in terms of capacity, latency, availability, energy and cost efficiency. Current network architectures will not be sufficient to support such requirements, and new solutions and approaches must be assumed.

In general, wireless systems offer important advantages over optical fibres and free-space optical (FSO) alternatives not only for mobile and nomadic terminals, but also in numerous fixed communication scenarios. In fixed outdoor applications, such as backhauling, fronthauling, last-mile access and *ad hoc* networks for big events or in case of natural disasters and crises, the deployment of optical fibre (or any other wired alternative) is often prohibitively expensive, technically unfeasible or too time consuming. On the other hand, FSO communication using infrared (IR) laser light can avoid the aforementioned drawbacks of optical fibre, but compared to THz wireless communication, the IR signal is significantly more attenuated by the presence of dust in the air than the THz signal which undergoes almost no degradation [3]. In general, wireless systems profit from fast deployment, flexibility and easy reconfiguration, as well as lower deployment costs (CAPEX). It is expected that more than 60 % of the base stations worldwide will

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still be connected wirelessly via microwave technology in 2022 [4]. The share of optical fibre will continue to increase mainly at the expense of copper links (e.g. from 30 % today to 36 % in 2022) while the share of microwave links will slowly decrease by about 2 % over the next four years. However, these changes will be significantly slower in the next four years in comparison with the previous four years, reaching almost constant shares of fibre and microwave after 2022.

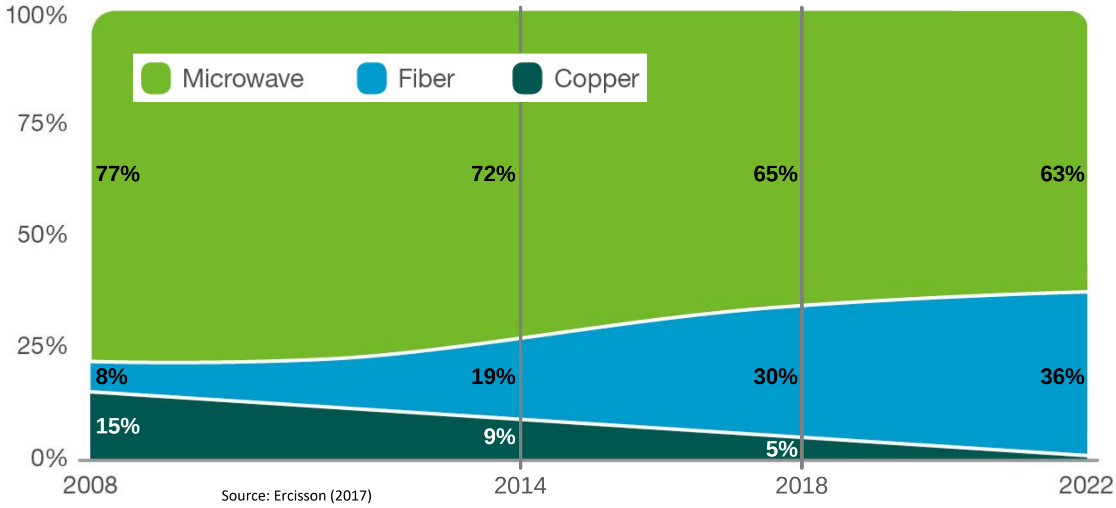

Figure 2 Worldwide backhaul media distribution, excluding China, Japan, Korea and Taiwan [4]

In addition, for high data rate indoor applications, such as machine-to-machine/device-to-device communication in data centres, wireless local and personal area networks, smart offices and home theatres, the versatility of wireless communication systems is a major asset over any kind of wired solution (e.g. optical fibres).

Furthermore, 5G access networks will extend the applied frequency spectrum above 6 GHz (e.g. to the 26/28 GHz, V-band) where wireless transport links are currently operated. Hence, the further improvement in data capacity of wireless transport networks will be limited by the availability of frequency spectrum below 100 GHz, which will be intensively used by 5G services. Significant allocation of higher frequency bands beyond 100 GHz is expected to be necessary for the next generation(s) of wireless transport networks. Large-scale deployment of wireless transport links beyond 100 GHz between 2025 and 2030 is foreseen in [4]. Various wide and currently unallocated frequency bands[1] are available in the terahertz spectrum beyond 270 GHz, which is also in the focus of interest. Commercial terahertz communication solutions are expected soon, enabled by current technological improvements. The promising terahertz transmission regions, where up to 10 Gbps/GHz of spectral efficiency can be expected, are depicted in Figure 3 [5].

[1] The frequency spectrum beyond 275 GHz is not allocated to any specific radio service. However, footnote 5.565 in [6] implies some regulations w.r.t. the use of this spectrum.

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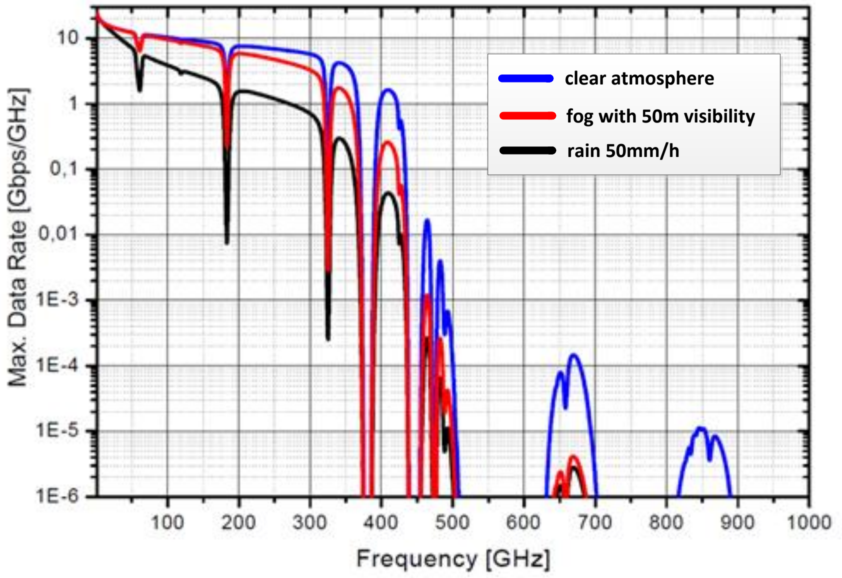

Figure 3 Expected maximum spectral efficiency assuming different weather conditions (link distance = 1km, transmit power = 10 dBm, antenna gain 40 dBi)

The ThoR project targets wireless transport networks (assuming fixed services) exploiting terahertz frequency spectrum (252-325 GHz as a possible candidate band), which is expected to play a significant and necessary role in the next generation(s) of communication systems, 5G and beyond 5G. The performance requirements for such wireless transport networks (including backhaul and fronthaul links) are mainly determined and driven by the following domains which will be elaborated in the following chapters:

- Available frequency spectrum and its characteristics
- End-user use cases and applications
- Network architecture and deployment scenarios.

4. Overview of frequency spectrum available for BH/FH

The characteristics of the most significant and promising frequency bands used in current or future multi-gigabit wireless transport networks (fixed services) are listed in the following sub-sections and summarized in Table 1.

Table 1 Characteristics of the frequency bands under consideration

	Frequency [GHz]	Total BW [GHz]	Type of licensing	Max EIRP [dBm]	Max link capacity [Gbps]	Max link length [km]
V-band	57 – 66 (51 - 71)	9 (14)	Unlicensed	40	1-2	<1
E-band	71 - 76 81 - 86	10 (5+5)	Lightly licensed	70	10-20	2-3k
W-band	92 - 94 94.1 - 100 102 - 109.5 111.8 - 114.25	17.85	Lightly licensed	NA	expectation ~40	<1
D-band	130 - 134 141 - 148.5 151.5 – 164 167 - 174.8	31.8	NA	NA	expectation ~40	<1
THz-band (ThoR)	252-325	73	NA	NA	expectation > 100-200	<1

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The W-band and D-band have been already considered in the table of frequency allocation issued by the ITU-R Radio Regulations for fixed wireless services [6]. The frequency spectrum beyond 275 GHz has not yet been allocated, but it is a key agenda item for the ITU World Radiocommunication Conference (WRC) 2019 [7].

The rest of the chapter is organized as follows. Section 4.1 describes the propagation characteristics of all bands under consideration followed by five sections describing the characteristics of available systems at V-, E-, W-, D- and Terahertz bands. The currently available or near-term roadmap state-of-the-art products from various manufacturers active in the market is also reviewed.

4.1. Propagation characteristics

Frequency-dependent attenuation of electromagnetic radiation in standard atmosphere (atmospheric pressure of 101.3 kPa and temperature of 15°C) due to atmospheric gases (atmospheric attenuation) and rainfall for the considered bands are shown in Figure 4 and Figure 5, respectively. In the same figures, the attenuation is compared with free space loss and propagation loss at a link distance of 100 m. The calculations are based on ITU-R atmospheric gas [8] and rainfall attenuation [9] models.

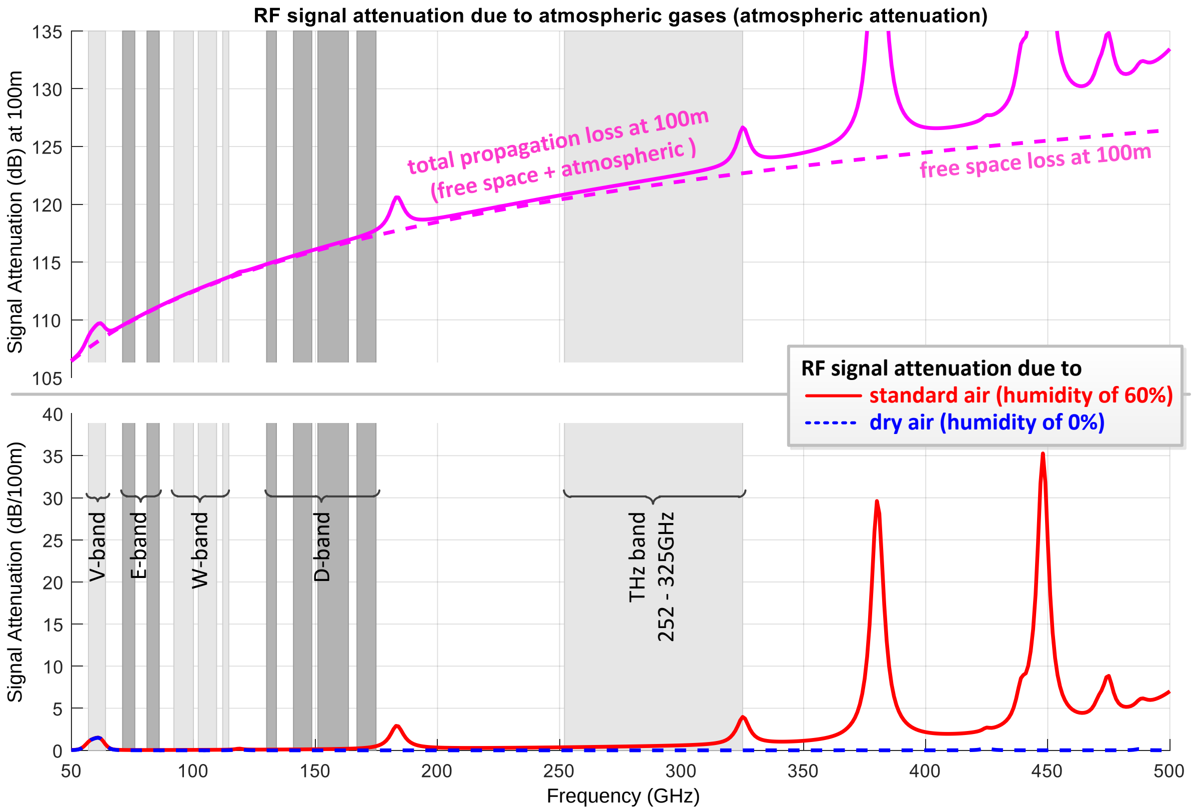

Figure 4 Frequency-dependent RF signal attenuation due to atmospheric gases (atmospheric attenuation), and as a reference, total propagation loss (free space loss + atmospheric attenuation) at a distance of 100 m. [Generated in Matlab using gaspl and fspl functions]

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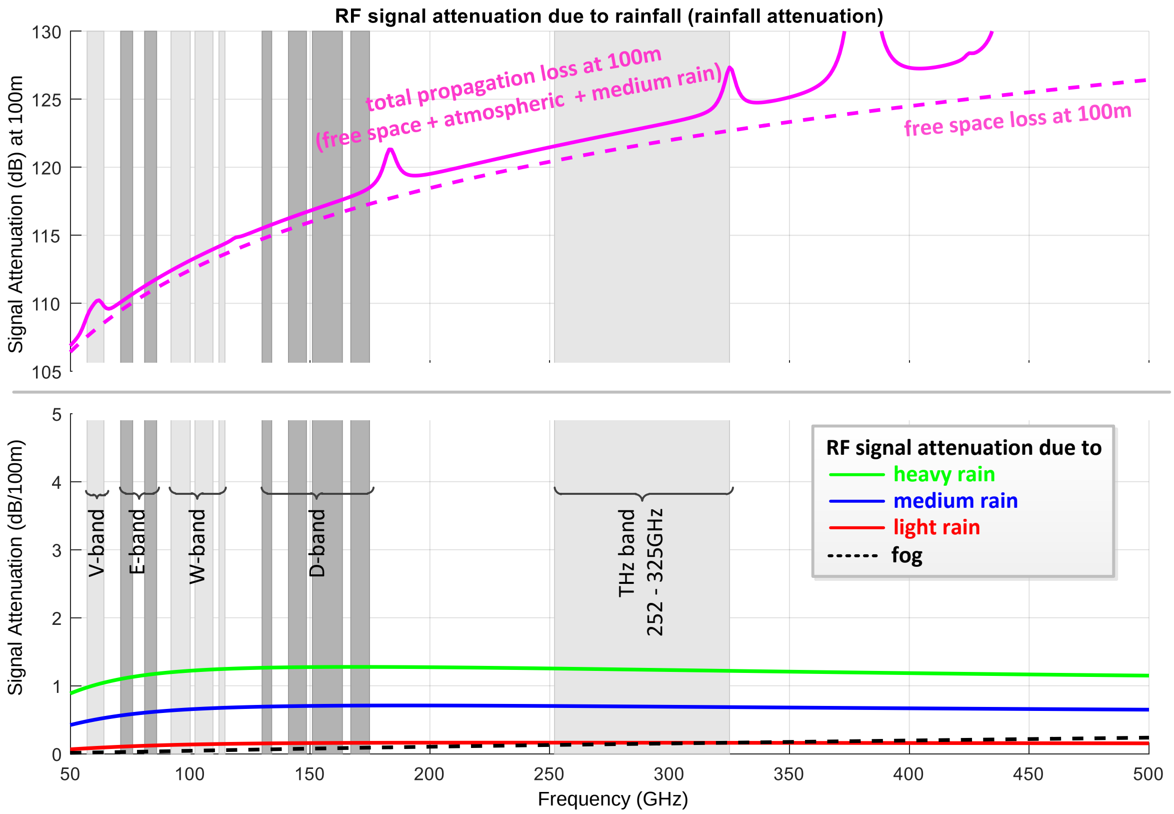

Figure 5 Frequency-dependent attenuation of RF signal due to rainfall (rainfall attenuation), and as a reference, total propagation loss (free space loss + atmospheric attenuation + medium rain attenuation) at a distance of 100 m. [Generated in Matlab using rainpl and fspl functions]

The attenuation of RF signals due to rainfall (Figure 5) is practically constant across all the bands under discussion, i.e. from V-band up to the novel THz band around 300 GHz (i.e. 252 to 325 GHz) considered within ThoR. This kind of attenuation varies on average from 0.2 dB/100 m (i.e. 0.2 dB loss for each 100 m propagation distance) in case of light rain (1 mm/hr) up to 1.2 dB/100 m in case of heavy rain (25 mm/hr). Fog and clouds are the same atmospheric phenomenon, differing only by height above ground. The attenuation caused by fog causing visibility around 50 m is similar the attenuation of light rain, i.e. around 0.2 dB/100 m.

On the other hand, the atmospheric attenuation of RF signals (Figure 4) varies with frequency assuming a standard air with relative humidity of 60 % (moisture concentration of 7.7 g/m^3) [8]. Apart from V-band (which exhibits up to 1.5 dB/100 m of atmospheric attenuation), the other bands are not significantly affected by atmospheric absorption. The atmospheric attenuation across E-band and W-band is almost constant while varying in case of V-band and continually rises across D-band and the novel THz band. In case of E-, W- and D-bands, the atmospheric attenuation is less than c. 0.2 dB/100 m and rises above 0.5 dB/100 m only at the top edge of D-band. The atmospheric attenuation of the novel THz band (252 to 325 GHz) is still less than c. 0.75 dB/100 m at 310 GHz but steeply rises from 310 GHz to reach 4 dB/100 m at the top edge of the THz band. Thus, the lower frequencies (below c. 310 GHz) should be used to avoid the high atmospheric attenuation at the upper edge of the THz band.

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Figure 6 shows the average propagation loss (i.e. free space loss + atmospheric loss)[2] of all considered frequency bands as a function of link distance. The average propagation loss of the novel THz band is 6.6 dB higher than D-band, 10 dB higher than W-band, 12.4 dB higher than E-band and 13.1 dB higher than V-band for a link distance of 100 m. The free space loss is the dominant factor which limits achievable link distance. Due to high atmospheric attenuation in V-band (up to 1.5 dB per 100 m), the propagation loss rises more steeply than for the other frequency bands. For example, the propagation loss in V-band is lower than E-band at the link distance below 150 m, but higher than in D-band at link distances above 600 m. Note that due to additional atmospheric attenuation at V-band, there is no significant advantage of V-band over the THz band at link distances above 600 m.

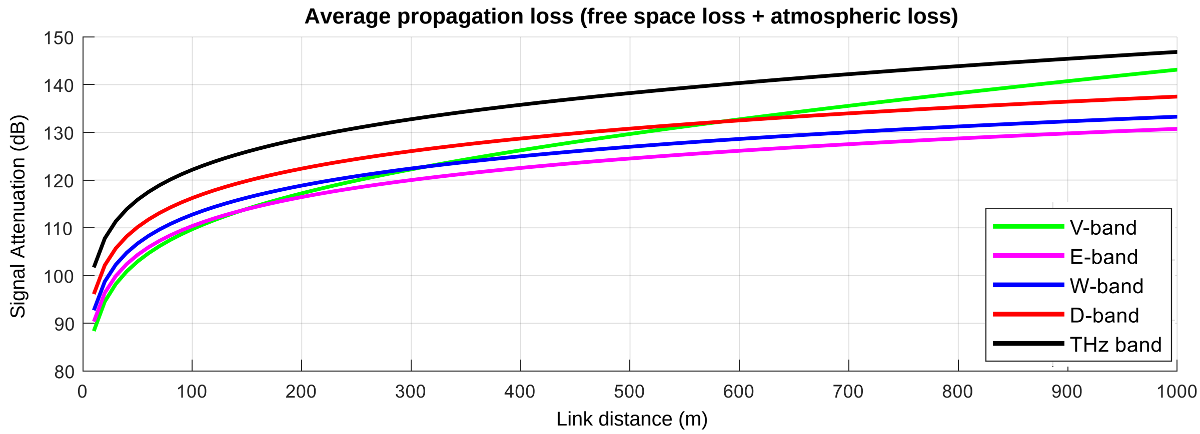

Figure 6 Average propagation loss as a function of link distance.

The band should be selected and channels should be arranged with regards to the specific attenuation due to atmospheric gases and free space losses (propagation loss) which may have a significant impact on the link budgets and link distances. It is noted that the range of validity of ITU-R regulation concerning propagation data and prediction methods is currently up to 100 GHz, i.e. they are not valid or defined for D-band, the novel THz-band or parts of W-band.

4.2. Description of V-band (60 GHz)

Millimetre wave band at 60 GHz traditionally spans the frequencies between 57-66 GHz where oxygen absorption is very high (i.e. up to 1.5 dB/100 m). However, this band has already been extended in some countries to include the entire range of 57-71 GHz (i.e. total bandwidth of 14 GHz). The allocations of allowed frequencies within this range can be different region by region (see Figure 7).

This band is currently not highly utilized by point-to-point (P2P) systems due to the relatively short distances it can support (practically up to about 1 km) given among others by the limited radiated power usually around 40 dBm EIRP. On the other hand, the spectrum is usually license-exempt, and high oxygen absorption allows high spatial reuse of frequencies and immunity from mutual interference. Systems in 60 GHz spectrum are nevertheless a promising option for the mobile backhaul of high-throughput communication systems, under some restrictions.

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[2] The average propagation loss is calculated for the frequency in the middle of given band, i.e. 61.5 GHz for V-band, 78.5 GHz for E-band, 103.13 GHz for W-band, 152.4 GHz for D-band and 288.5 GHz for THz band.

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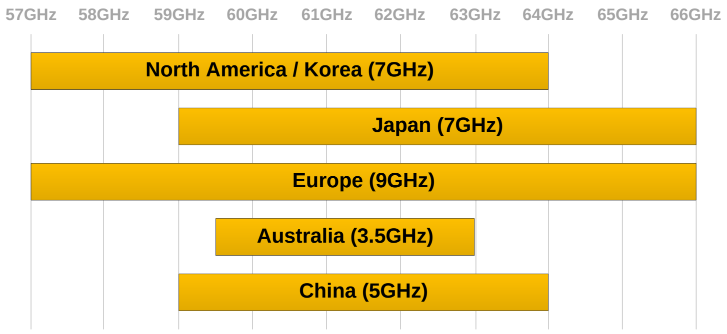

Figure 7 V-band spectrum allocation worldwide

Systems operating in this band are typically limited to about 2 GHz of channel bandwidth, otherwise the unevenness of oxygen absorption across the band (which has fluctuations of 0.8 dB/100 m; see Figure 4) creates noticeable non-flatness. Another limitation is the inefficiency of using FDD systems in this band, which is one contiguous spectrum block without any natural FDD guard band. Systems operating in this band can generally fulfil the requirement of delivering gigabits of throughput with operation in TDD mode. The carrier wavelengths in this band as compared to microwave bands are already short enough to result in favourable, narrow beam, low interference propagation conditions. From the cost point of view this band holds a promise to dramatically reduce the costs of the backhaul network, due to being license-exempt and requiring no license fees. The band allows use of point-to-point and in some countries also point-to-multipoint systems, which are also a suitable choice for 5G backhaul. On the disadvantageous side of outdoor scenarios, 60 GHz mmWave systems have range limitations due to high atmospheric attenuation that limits range typically to less than 1 km. This adverse phenomenon, however, can actually prove beneficial in high density scenarios because the strong oxygen-induced atmospheric attenuation and the narrow beam dimensions reduce interference from nearby transmitters at the same frequency. Indoor 60 GHz mmWave system scenarios are limited to single rooms, since walls introduce high attenuation, which may be advantageous with respect to reuse of 60 GHz mmWave systems in neighbouring rooms.

For passive antennas, antenna deflection limitations might exist. These systems have very narrow antenna beamwidths due to their high frequencies. Therefore, they must be deployed on structures with very little twist or sway, limiting the choice of towers. Due to this narrow beamwidth, antenna alignment can be difficult. To avoid antenna deflection or misalignment that can cause high attenuation, deflections should not exceed 2-3°. Point-to-multipoint (P2MP) systems in this band are typically based on WiGig (IEEE802.11ad) technology and feature beam-steering antenna arrays, however their use for backhaul applications is currently still quite limited. Achievable capacities in this band may support some fronthaul use cases, but they are not high enough to support the full range required by 5G access standards.

It is expected that the 5G and B5G mobile access networks will enlarge the usage of the frequency spectrum to the lower millimetre wave range (such frequency bands as 26-42 GHz (Ka-band) and even V-band). With the inclusion of the V-band to 5G and B5G mobile access networks, there is consequently a need to consider a coexistence with the V-band backhaul/fronthaul links. Since the V-band spectrum is license-exempt, the interference cannot be easily controlled via network planning, for example.

The “competitive” Wi-Fi standard IEEE 802.11ad/WiGig also utilizes this 60 GHz spectrum (four channels with bandwidth of 2160 MHz between 57-66 GHz) for very short ranges of up to 10 m focusing mainly on indoor applications (e.g. home Wi-Fi hotspots, wireless HDMI). V-band

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applications present a much stronger business case for silicon technology where adjacent WiGig–based applications drive very high underlying volumes to justify the initial investment.

The basic operation channel for P2P systems in the V-band spectrum has been 30 MHz or 50 MHz, but since channels can be bonded as desired and since the spectrum is license-exempt, practically all modern products use wider channels. Table 2 summarizes some of the available all-outdoor products and their features.

Table 2 Characteristics of representative V-band all-outdoor products

Vendor/ Feature	Siklu	Fastback	Huawei	Ericsson	BridgeWave	Intracom Telecom	Ceragon
Product name	EH-600T	V1000	RTN 360	MINI-LINK 6351	BW64E	StreetNode 6250 PTP	FibeAir IP-20V
Reference	[10]	[11]	[12]	[13]	[14]	[15]	[16]
Num. channels and channel bandwidth	11 ch., 500MHz	4 ch., 500MHz	3 ch., 200MHz	1 ch., 150MHz	1 ch., 1400MHz	3 ch., 250MHz	1 ch., 500MHz
FDD/TDD	TDD	FDD	TDD	FDD	FDD	FDD	FDD
Max modulation	64QAM	8PSK	32QAM	256QAM	BFSK	128QAM	256QAM
Max L1 throughput [Gbps]	1	1	0.8	1	1	1.65	2.5
Typical system Gain [dB]	162	146	145	132	149.5	151.5	121.7

Pictures of typical P2P all-outdoor products are shown in Table 3.

Table 3 Pictures of typical V-band all-outdoor products

		
Siklu EH-600T	Ericsson MINI-LINK 6351	Ceragon FibeAir IP-20V

4.3. Description of E-band (70/80 GHz)

E-Band consists of two continuous spectrum blocks split between 71-76 GHz and 81-86 GHz (i.e. 2×5 GHz bandwidth). This band enables both FDD and TDD P2P operation and supports theoretical channel bandwidth up to 4.5 GHz (although under current ETSI regulation channels are limited to 2 GHz). Propagation characteristics in the 70-80 GHz band are not as severe as those are at 60 GHz. Therefore, E-band has greater transmission range compared with V-band (see Figure 6). Atmospheric absorption at these frequencies is comparable with the microwave bands of 23 and 38 GHz. As with V-band systems rain causes additional attenuation. E-band is typically licensed or lightly licensed and therefore higher transmission powers and higher gain antennas are allowed (the practical limit is c. 70 dBm EIRP). The higher power and protection enabled by the licensed nature of the band allows use of spectrally efficient modulations and allows ranges to extend to 2-4 km based on rain zone and throughput.

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The basic operation channel at E-band is a 250 MHz channel and can be bundled (e.g. 500 MHz, 750 MHz). The basic operating speed is 1 Gbps, so product offerings typically start with 1 Gbps throughput over 250 MHz or 500 MHz channels. Regulation further supports cross-polarization interference cancelling (XPIC) mode operation, which practically doubles the possible throughput per link. The 10 Gbps products currently represent the cutting edge of products that are out in the field or planned in the near term, and most leading vendors have one. Table 4 lists most of the available all-outdoor products and their features.

Table 4 Characteristics of representative E-band all-outdoor products

Vendor/ Feature	Siklu	Huawei	NEC	SIAE	Ericsson	BridgeWave	Intracom Telecom
Product name	EH-8010FX	RTN 380H	iPASOLINK EX Ad.	ALFOplus 80HDX	MINI-LINK 6352	FLEX4G-10000	UltraLink-GX80
Reference	[17]	[18]	[19]	[20]	[21]	[22]	[23]
Channel bandwidth range [MHz]	250-2000	250-2000	250-2000	250-2000	125-2000	500-2000	250-1500
Number of adaptive modulation and coding (ACM) profiles/states	9	9	7	10	15	6	7
Max modulation (QAM)	128	1024	256	256	256	256	256
Max channel bandwidth at Max modulation [MHz]	2000	500	500	1000	750	500	1500
Max L1 throughput [Gbps]	10	10	10	10	10	9.7	10
System Gain [dB] at 10Gbps	64	55	58	60.5	64	57	60.5

Note that most of the vendors plan to offer the ability to bond two 10 Gbps radios together using cross polarization interference cancelation technology (XPIC) to provide a total throughput of 20 Gbps.

Pictures of typical P2P all-outdoor products are shown in Table 5.

Table 5 Pictures of typical E-band all-outdoor products

		
Siklu EH-8010FX	Huawei RTN 380H	Ericsson MINI-LINK 6352

4.4. Description of W-band (92-114.5 GHz)

W-band consists of spectrum between 92-114.5 GHz, but this band is highly segmented as only the portions 92-94 GHz, 94.1-100 GHz, 102-109.5 GHz and 111.8-114.25 GHz are allocated for fixed wireless service as a primary application as per ITU-R radio regulations [6]. There are two

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relatively large sub-bands of close to 6 GHz, and they could be used as a coupled pair for FDD operation (although the 2 GHz distance between them is somewhat less than desirable for easy, low cost diplexers). The other sub-bands are narrower and enable only TDD operation. ECC WGSE 19 (Working Group Spectrum Engineering – Fixed Services) approved two new work items (WI) with the scope to develop guidelines on deployment of fixed services operating in W-band (WI 37) and D-band (WI 38) [24]. Basic considerations assume the link capacity up to 40 Gbps at the distance of hundreds of meters. Channel allocations from the ECC are currently only available for the 92-94 GHz sub-band and the channels are limited to 400 MHz width. A new ECC WGSE 19 working item draft suggests that W-band channels should be aligned to the 250 MHz grid used in E-band (which will likely later be allowed to bond to wider channels, as in E-band). The sub-band allocation, however, prefers the use of high separation coupled bands, which means that effectively the FDD allocation is only up to 3.5 GHz of spectrum at any sub-band. One of the suggested channel arrangement with 29 paired and eight unpaired channels (each 250 MHz width) including guard bands is shown in Figure 8.

Overall, in terms of regulation and performance W-band seems to be going towards being very similar to E-band, including the licensing scheme which is suggested to be lightly licensed. No commercial P2P products are currently known to exist in this band. The first vendors are starting to trial their prototype products.

4.5. Description of D-band (130-174.8 GHz)

D-band is a wide band that consists of the spectrum between 130-174.8 GHz, with major chunks allocated for fixed services applications. These sub-bands are 130-134 GHz, 141-148.5 GHz, 151.5-164 GHz and 167-174.8 GHz. The sub-bands are wide enough (ranging from 4 GHz up to 12.5 GHz) and spaced (minimum duplex spacing of 3 GHz) such that they can be used in coupled pairs in more than one fashion. This flexibility allows also both TDD and FDD operations. A new working item draft on the ECC WGSE 19 table suggests to align D-band channels to the 250 MHz grid used in E-band (which will likely later be allowed to bond to wider channels, same as in E-band). The sub-bands are named a, b, c, d and contain 15, 29, 49, 30 channels respectively. A channel arrangement example with 44 paired and five (+30) unpaired channels (each 250 MHz width) is shown in Figure 9. It is believed that FDD use of the available ranges in D-band should profitably be limited only up to 164 GHz. The upper 167-174.8 GHz would be used only for unpaired applications.

In terms of regulation the licensing scheme for D-band is not yet determined, but it is also likely to be lightly licensed. Propagation performances for D-band already start to deviate somewhat from E/W bands because of slightly increased fog, water vapour and rain absorption; wider targeted channels which reduce receiver sensitivity thresholds and also because of technology gaps with regards to power amplifiers and low-noise amplifiers. As a consequence of the above factors, link distances in W-band are expected to be closer to those of V-band and generally <1 km. No commercial P2P products are known to exist in this band. The first vendors are starting to trial their prototype products.

In relation to W- and D-bands, the short wavelength (0.32-0.17 cm) allows design of very compact antennas. It should be further noted that the current commercial mmWave RF technology, which is based on pHEMT GaAs (pseudomorphic High-Electron-Mobility Transistor gallium arsenide), has a performance limit (transition frequency) around 160 GHz. Going above this could imply a completely new technology [25].

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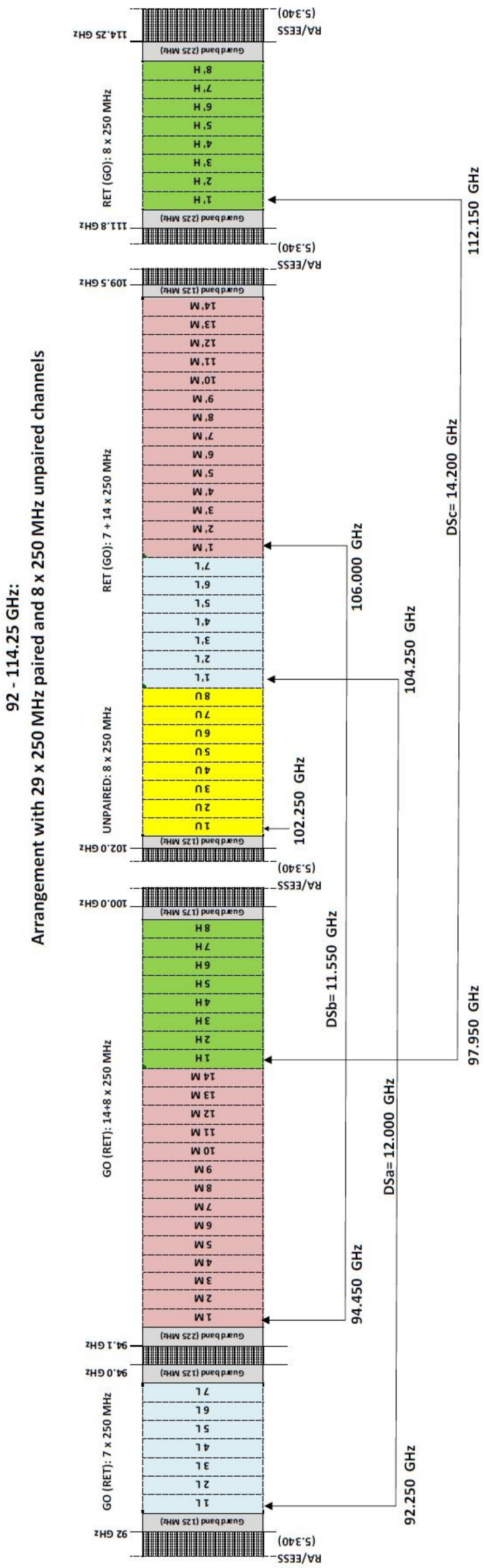

Figure 8 Example showing one of the suggested W-band channel arrangements (Source: [24])

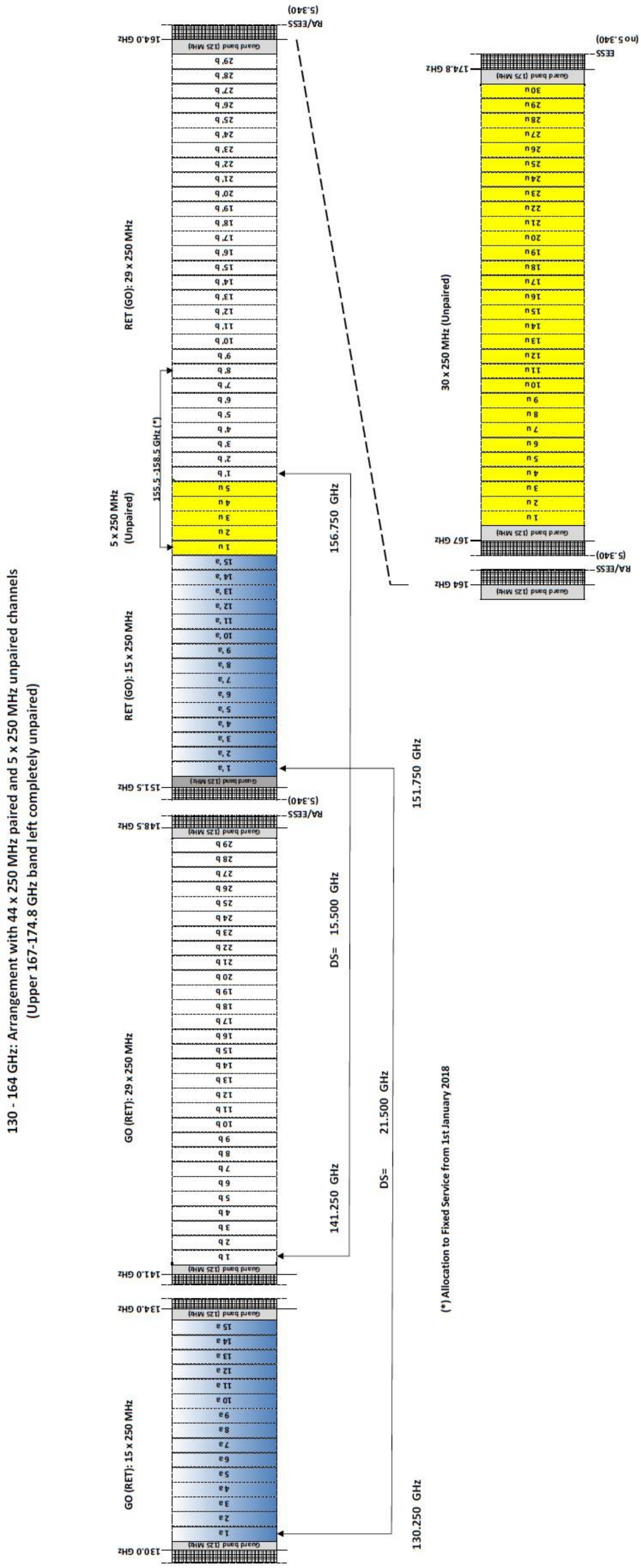

Figure 9 Example showing one of the suggested D-band channel arrangements (Source: [26])

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4.6. Description of Terahertz band (252 – 325 GHz)

Terahertz and sub-terahertz frequencies (300 GHz to 3 THz; wavelength range 1 mm to 100 μm) have been investigated as an ultra-high speed data transfer solution, especially for rural, distant or dense urban locations where extending the optical fibre network would be difficult (or even impossible) and very costly. Photon energies in the THz regime are less than the band-gap of non-metallic materials and thus THz beams can traverse through such materials (e.g. clothing, wood, paper, plastic and other non-conducting materials). Hence, aside from ultra-high speed data communication, the terahertz spectrum is also suitable for other kind of applications such as body screening in health care or advanced bomb detection to secure mass transportation. These adjacent applications could significantly increase the volume of production and consequently reduce the costs of terahertz components and equipment.

Although no dedicated allocation exists today in the radio regulation for spectrum beyond 275 GHz, the use of these frequency bands for wireless communications must ensure that passive services (e.g. radio astronomy and earth exploration satellite service) using this part of the spectrum are protected from harmful interference. The recent amendment to the standard IEEE 802.15.3d [27] defined eight different channels with bandwidth between 2.16 GHz and 69.12 GHz in the frequency range 252-325 GHz supporting ultra-high data rates up to 100 Gbps. This channelization enables the scalable approach followed in ThoR, where several channels with smaller bandwidths are utilized.

The conditions for the operation of wireless communications in the terahertz frequency spectrum will be defined at ITU WRC 2019 [7] through agenda item 1.15. It should be noted that the current ITU-R regulation concerning propagation data and prediction methods is valid up to 100 GHz. The ThoR project will work on the characterization of propagation environment and produce advisory documents, which will be fed into the ITU WRC 2019. Moreover, after ITU WRC 2019 ThoR will work on interference mitigation techniques and planning rules to enable the deployment of 300 GHz P2P links, which comply with the outcome of ITU WRC 2019. The ThoR project will also provide technical solutions for the wireless transport links operating in this novel terahertz spectrum range, which is able to cover the ultra-high data rates required for 5G and beyond 5G (B5G) systems.

5. End-user use cases and applications

The 5G networks need to satisfy the variety and variability of use cases and applications. The network operators grouped in NGMN alliance have identified twenty five representative use cases/services for 5G that are grouped into eight use case families with the end-user/customer and system performance requirements as follows [1]:

- Broadband access in dense areas (such as multi-storey buildings, dense urban city centres, stadiums or public events) including pervasive video, augmented reality, smart offices, cloud services, indoor ultra-high broadband access
  - User experienced data rate: 300-1000 Mbps in DL and 50-500 Mbps in UL
  - End-to-end latency: 10 ms
  - Connection density: 200–75000/km^2
  - Traffic density: 750–15000 Gbps/km^2 in DL and 125-2000 Gbps/km^2 in UL
- Broadband access everywhere (from urban to suburban and rural areas). The minimum data rate (e.g. 50 Mbps) needs to be guaranteed consistently everywhere, even at the cell edges.
  - User experienced data rate: 50 Mbps in DL, 25 Mbps in UL
  - End-to-end latency: 10 ms
  - Connection density: 100-400/km^2
  - Traffic density: 5-20 Gbps/km^2 in DL and 2.5-10 Gbps/km^2 in UL

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- Higher user mobility including mobile services (such as autonomous driving, enhanced on-board entertainment) inside and among vehicles, trains and aircrafts.
  - User experienced data rate: 15-50 Mbps in DL, 7.5-25 Mbps in UL
  - End-to-end latency: 10 ms
  - Connection density: up to 2000/km^2
  - Traffic density: 1-100 Gbps/km^2 in DL and 0.6-50 Gbps/km^2 in UL
- Massive Internet of Things including machine type communications (MTC), personal wearables, sensors networks, mobile video surveillance.
  - User experienced data rate: 1-100 kbps in DL, 1-100 kbps in UL
  - End-to-end latency: seconds to hours
  - Connection density: up to 200000/km^2
  - Traffic density: 0.1-20 Gbps/km^2 in DL and 0.1-20 Gbps/km^2 in UL
- Extreme real-time communications requiring real-time/immediate interaction at sub-millisecond basis. This use case includes autonomous driving, tactile internet, cloud computing, augmented and virtual reality, remote surgeries.
  - User experienced data rate: 50 Mbps in DL, 25 Mbps in UL
  - End-to-end latency: <1 ms
  - Connection density: not relevant
  - Traffic density: not relevant
- Lifeline communications including public safety and emergency services.
  - User experienced data rate: 0.1-1 Mbps in DL, 0.1-1 Mbps in UL
  - End-to-end latency: 10 ms
  - Connection density: 10000/km^2
  - Traffic density: 10 Gbps/km^2 in DL and 10 Gbps/km^2 in UL
- Ultra-reliable communications including automated traffic control and driving, automated industry with collaborative robots, remote surgeries and health-care critical operations.
  - User experienced data rate: 0.5-10 Mbps in DL, 0.5-10 Mbps in UL
  - End-to-end latency: 1-10 ms
  - Connection density: not relevant
  - Traffic density: not relevant
- Broadcast-like services including UHD/HD video broadcast with interactive feedback.
  - User experienced data rate: 200 Mbps in DL, 0.5 Mbps in UL
  - End-to-end latency: <100 ms
  - Connection density: not relevant
  - Traffic density: not relevant

Note that the *user experienced data rate* as well as *end-to-end latency* are measured at the application layer (i.e. user-perceived values). The required *user experienced data rate* is defined as the minimum data rate, and should be available in at least 95 % of the locations (including at the cell-edge) for at least 95 % of the time within the considered environment. *Connection density* is defined as the number of simultaneous active devices (connections), i.e. devices simultaneously exchanging data with the network, in a given area. *Traffic density* is defined as the total amount of traffic exchanged by all devices in a given area.

The video traffic represents the dominant part (70-80 %) of all internet traffic (Figure 10). The amount of consumed bandwidth will continuously grow as more video consumers are connected and higher quality videos are watched. The demand is coming from all types of internet video applications, including on-demand content like Netflix, webcam viewing and traditional TV options available over the internet (IP VOD).

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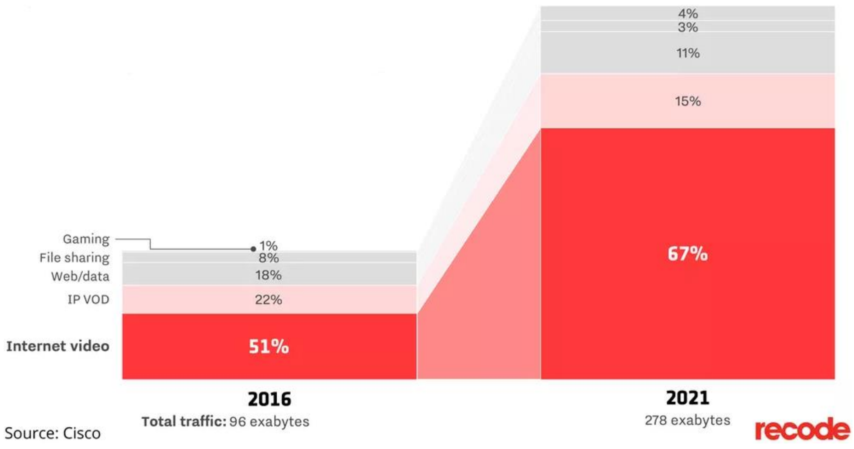

Figure 10 Global IP traffic forecast by Cisco [28]

It is expected that the augmented and virtual reality video applications will become the first most attractive as well as most data hungry 5G applications, and will drive and push network capacity improvement. The following examples illustrate the increase in required data rates for current and future video applications:

▪ Video conferencing	2 Mbps
▪ Two way telepresence	5 to 25 Mbps
▪ Video streaming with 4K Ultra HD resolution (3840×2160 pixels)	>25 Mbps
▪ 360° video streaming with 4K Ultra HD resolution (3840×2160 pixels)	10 to 50 Mbps
▪ Next generation 360° video streaming with 8K Ultra HD resolution (7680×4320 pixels)	20 to 200 Mbps
▪ 360° virtual reality with HD resolution (1920×1080 pixels)	>100 Mbps
▪ 6 Degrees of Freedom virtual reality	200 to 5000 Mbps

In summary, the 5G networks should be able to provide around **10 ms end-to-end latency** at the application layer in general, and 1 ms latency for the specific use cases requiring extremely fast interaction (e.g. autonomous driving, tactile internet, cloud computing, augmented and virtual reality, automated industry with collaborative robots, remote surgeries and health-care). These latencies are introduced mainly by the transport network while the processing time at the application layer is assumed to be negligible. The 5G user experienced data rate depends on the targeted application/use case, and ranges from few kbps in case of massive Internet of Things to hundreds of Mbps (up to a peak of several Gbps) in case of broadband access in dense urban areas and indoors. It is apparent that an improvement factor of approximately 5-10× can be expected in comparison with the currently commercially deployed LTE/LTE-A technology. In addition, to reduce the network deployment costs, multiple use cases will be in service simultaneously, and their end-user/customer and system performance requirements will be combined. For example, an urban network deployment should accommodate a combination of performance requirements for Broadband access use case, Lifeline communications use case, and Massive Internet of Things use case.

These use cases serve as an input for determining the requirements and defining the building blocks of the 5G network architecture. The end-user/consumer and system performance requirements in the access network subsequently affect and must be reflected in the architecture and performance requirements for (wireless) transport networks.

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6. Network architecture

In general, the transport network connects the mobile access site(s) with the aggregation point(s) and core network, and can contain so-called fronthaul, midhaul and backhaul links depending on the deployed type of network architecture and terminology. Note that different standards bodies/organizations use different terminologies and naming conventions as was overviewed in [29]. The distributed, centralized and centralized with functional split types of network architecture are considered as follows.

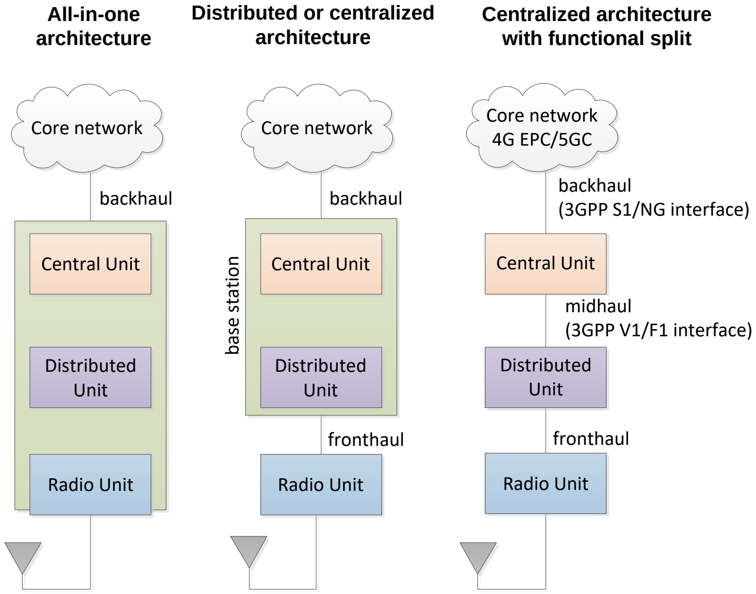

Figure 11 Types of network architecture and adopted terminology

- **Distributed architecture** (Figure 12) was introduced for 3G networks. In this architecture, the radio unit (remote radio unit (RRU)) is installed on the top of a tower close to the antenna(s), and connected via a short fronthaul link (tens of meters) with the baseband processing unit (BBU) located inside a cabinet nearby the tower. Fronthaul link is usually implemented as optical fibre cable carrying digital baseband signals using CPRI (Common Public Radio Interface) standard. The baseband unit is connected via a wireless or wireline backhaul link to an aggregation point or directly to the core network.

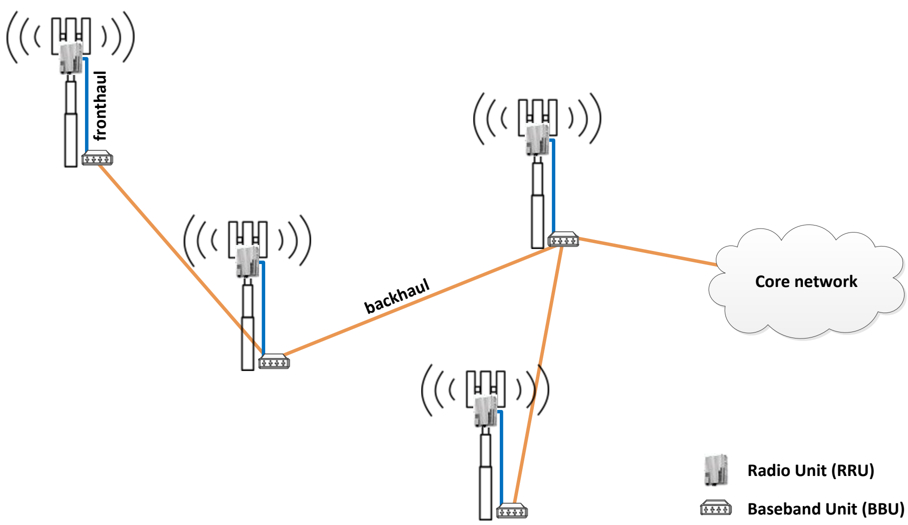

Figure 12 Distributed network architecture

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- **Centralized architecture** is an evolution of previous distributed architectures where the baseband processing units are centralized in a single location (baseband pool) and connected to the distant radio units via fronthaul links over a distance from hundreds meters up to few kilometres. The required capacity of the fronthaul link (carrying digital baseband signals) is a linear function of the base station's channel bandwidth and the number of antenna ports (one sector) as shown in Table 6– each antenna port or 10 MHz bandwidth adds approximately 490 Mbps. As can be observed, the required capacity of the fronthaul link is overwhelming – the 5G networks (with up to 1 GHz channel bandwidth and base station's antenna with up to 256 ports [30]) may require fronthaul capacity of hundreds of gigabits. Note that Table 6 shows fronthaul capacity requirements for single sector (e.g. a micro base station) but a macro base station has usually three or four sectors/cells. Hence, the requirements per macro base station are actually three to four times higher. For example, the current E-band products providing maximum throughput of 10 Gbps (section 4.3) can fronthaul only the few lowest configurations of a macro base station (with three sectors) as highlighted in orange in Table 6. However, all of these configurations are typical for 4G/LTE but not for 5G requiring base station's antenna with higher number of antenna ports (large-scale multi-antenna array) and wider bandwidth. It has become clear that **traditional network architecture and current V- and E-band based products simply cannot support the 5G and even B5G requirements**, and so new approaches and solutions have to be considered (e.g. the architecture based on functional splits and utilization of frequency spectrum beyond 100 GHz).

Table 6 The required peak data rate[3] of baseband signals via fronthaul link (i.e. link between baseband unit and radio unit) without any compression.

Number of ports at base station's antenna (single sector)	Aggregated channel bandwidth at access network (base station) [Gbps]				
	20MHz	40MHz	100MHz	200MHz	400MHz
2 (2T2R)	2	3.9	9.8	19.7	39.3
4 (4T4R)	3.9	7.9	19.7	39.3	78.6
8 (8T8R)	7.9	15.7	39.3	78.6	157.3
16 (16T16R)	15.7	31.5	78.6	157.3	314.6
32 (32T32R)	31.5	62.9	157.3	314.6	629.2
64 (64T64R)	62.9	128.8	314.6	629.2	1258.3
128 (128T128R)	125.8	251.7	629.2	1258.3	2516.6
256 (256T256R)	251.7	503.3	1258.3	2516.6	5033.2

- **Centralized architecture with functional split** (Figure 13) was proposed for 5G network deployment to reduce the demands on data rates and latencies, and consequently the deployment costs in transport networks. The functions (protocol stack) of the mobile base

[3] Data rate = Number of antenna ports * Sampling frequency (30.72 MSamples for each 20 MHz (2048 FFT)) * bits per sample (2*16 bits per I a Q samples). The CPRI protocol (incl. line coding) adds additional overhead of c. 33 %

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station (i.e. 4G eNB or 5G gNB) are split between Central Unit (CU) and Distributed Unit (DU). The individual functional entities (i.e. radio, distributed and central units) may be placed at different physical locations according to performance requirements and limitations. The CU is connected to the DU(s) via so-called midhaul links. The DU and Radio Unit can be packed into a single unit or separated and connected via a short fronthaul link. Multiple DUs can be connected to a single CU and multiple RUs can be connected to a single DU (working as an aggregation site). By centralizing resource and signal processing, this architecture can take advantage of cloud computing, flexible network configuration, virtualization and softwarization of network functions. In addition, operators are able to reduce site-leasing costs while distributing the radio units closer to the users.

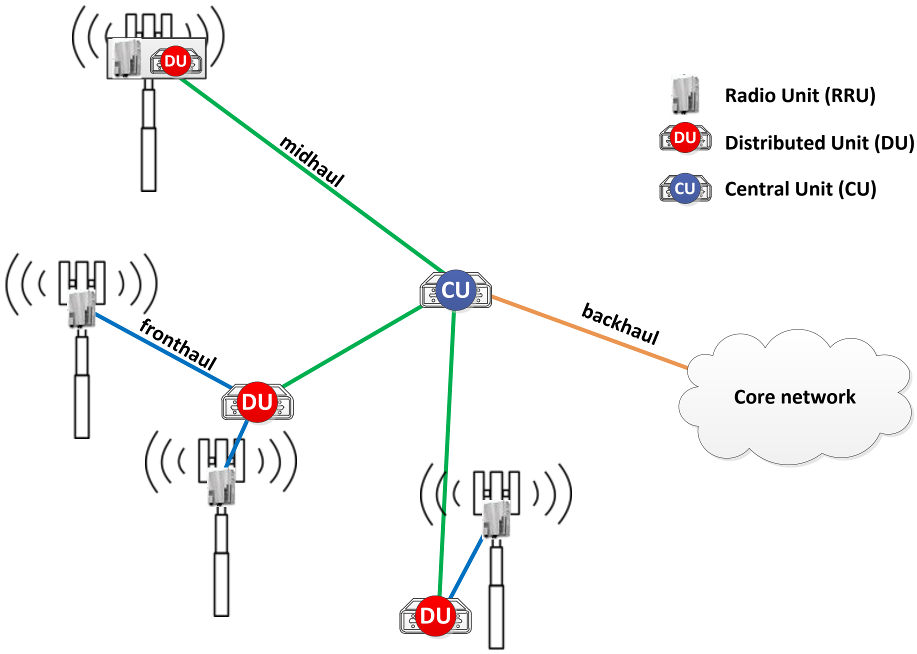

Figure 13 Centralized network architecture with functional split

The evolved **centralized architecture with functional split** is promising and preferred solution for incoming 5G network deployments to meet the different service requirements of a wide range of use cases, and the focus will be laid on this flexible (reconfigurable) and efficient architecture. Several standards bodies/organizations (such as 3GPP, eCPRI, Small Cell Forum, xRAN, IEEE 1914) are working on the identification and specification of different split points in the base station's protocol stack (aka RAN decomposition or disaggregation), as was summarized in [29]. 3GPP provides a general description of all possible functional split options, while the other standards bodies elaborate and specify the most promising and beneficial functional split options. The choice of functional split points depends on specific use case and application, and determines the performance requirements for the transport network. The overview of candidate functional split options is provided further in this chapter.

6.1. 3GPP functional splits

As a part of study item for 5G New Radio interface (5G NR – 3GPP Release 15), 3GPP started studying different functional splits between central and distributed units. For the initial phase, 3GPP has taken LTE protocol stack (E-UTRA) as a basis for the discussion, until RAN2 defines and freezes the protocol stack for New Radio (NR). They have proposed eight main split options [31] with lower layer splits requiring much larger transport data rates and shorter latency at the midhaul links than higher layer splits. On the other hand, fewer functions can be centralized with

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higher layer splits. The 3GPP functional split options between central and distributed units are elaborated below and shown in Figure 14.

- Option 1 (RRC/PDCP): In this highest layer split, RRC (Radio Resource Control) is in CU while the lower layers are kept in DU. The entire user plane is in the distributed unit (close to the transmission point) while RRC/RRM functions are centralized in CU.
- Option 2 (PDCP/RLC): RRC, PDCP (Packet Data Convergence Protocol) are centralized in CU while the lower layers are co-located in DU (ensuring tight synchronization between RLC, MAC, PHY layers). Option 2 was selected as the high layer split point and the interface between CU and DU was named as F1 Interface (carrying control signals and user plane data). The control and user plane functions inside CU were further separated into Control Plane Signalling (CU-CP) and one or more User Plane (CU-UP) logical entities. Consequently, the F1 interface was split into control (F1-C) and user plane (F1-U), and new interface E1 was opened between CU-CP and CU-UP entities. Option 2 has already been defined for LTE dual cell connectivity feature.
- Option 3 (Intra RLC): RRC, PDCP and high RLC (partial function of RLC) are in CU while the lower layers are kept in DU.
- Option 4 (RLC-MAC split): RRC, PDCP, and RLC (Radio Link Control) are in CU while the lower layers are kept in DU.
- Option 5 (Intra MAC split): RRC, PDCP, RLC and higher part of the MAC layer (High MAC) are in CU while the lower layers are kept in DU. Time critical functions (e.g. HARQ, radio channel and signal measurements from PHY, random access control) are located in DU (Low-MAC sublayer). From Option 5 onwards, the scheduling of data transmission can be centralized. Having centralized scheduling can provide benefit for interference management and coordinated transmission in multiple cells.
- Option 6 (MAC-PHY split): The MAC (Medium Access Control) and upper layers are in CU. Physical layer and RF are kept in DU. The interface between the CU and DUs carries data, configuration, and scheduling-related information (e.g. MCS, Layer Mapping, Beamforming, Antenna Configuration, resource block allocation etc.). From Option 6 onwards, delay critical CoMP features such as Joint Transmission and Reception are feasible.
- Option 7 (Intra PHY split): Part of the physical layer function and Radio Unit are in DU while the upper layers are in CU. This option has three different variants 7-1, 7-2, 7-3 (three for downlink, but only two of those apply to uplink) – see Figure 15.
- Option 8 (PHY-RF split): The lowest layer split allows separation of the Radio Unit and the physical layer. This split option can be realized by the conventional CPRI-based fronthaul used in distributed and centralized 4G architectures. This split enables centralization of processes at all protocol layer levels resulting in very tight coordination of the RAN, at the expense of very high demands for latency (few hundred μs) and throughput (hundreds of Gbps, see Table 6). This allows support of features such as CoMP, network MIMO.

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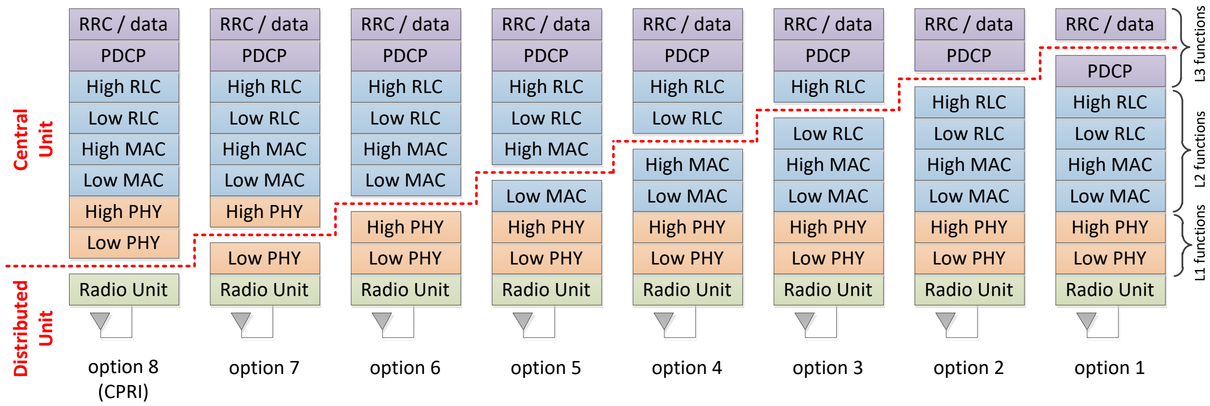

Figure 14 3GPP functional split options between central and distributed units

For different split options, the data is transported in different forms, e.g. I/Q samples for Option 7-1, L3 packets for Option 2, and consequently the required capacity is very different (see Table 9). The split Option 7-2 and higher scale with the number of MIMO layers rather than number of antenna ports, which allows the use of antennas with a high number of ports (enabling massive MIMO, FD-MIMO) without increasing the transport data rate. Hence, in the case of deployment of base station antennas with many ports (e.g. 64T46R) split options 7-2 and higher can reduce the midhaul capacity compared to option 7-1 or 8.

Table 7 Characteristics and features of different CU-DU split options

3GPP split option	1	2	3	4	5	6	7-3	7-2	7-1	8
Characteristics and supported features		Scale with MIMO layers							Scale with antenna ports	
	Multiple schedulers (independent per DU)				Centralized scheduler (common per CU)					
	Bits							I/Q samples		

It is expected that only the few most beneficial split options (e.g. option 2, 6, 7) in terms of minimizing complexity and costs while ensuring deployment flexibility will be fully standardized and supported in network deployment.

6.2. eCPRI function splits

The eCPRI (Common Public Radio Interface) specification [32] was born out of its predecessor CPRI in order to reduce the required throughput, to provide better OAM capabilities (possibilities to improve RF performance, SW upgrade capabilities, etc.), simplicity and reusability of existing technologies. These goals were mostly achieved, with a ~10× reduction of required throughput, flexible bandwidth support, flexible functional split point, and also allowed a transition to packet based Ethernet/IP media (eCPRI messages are transmitted in standard Ethernet frames, identified by a specific Ethertype 0xAEFE) which is cheaper and widely available compared with CPRI dedicated (usually fibre) transmission media. The eCPRI specification does not mandate the use of any specific network layer or data link layer protocols to form the transport network, but does post certain requirements to be fulfilled to ensure that eCPRI systems can use packet based transport network solutions and comply with the radio technology requirements relating to timing and frequency accuracy and to BW capacity.

The former CPRI specification is based on 3GPP functional split Option 8 (Figure 14 and Figure 15). The eCPRI specification focuses on intra physical layer splits (so-called low layer splits) thus

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creating a *de facto* standard for the low layer split. They introduced two possible splits in downlink (I_D, II_D) and one in uplink (I_U) – roughly corresponding to 3GPP functional split Options 7-2 and 7-3, which allow flexibility between the complexity of the RU/DU, and the efficiency of transmission. Functional splits inside the physical layer enable support of advanced coordination features such as network MIMO and CoMP. In addition to these low layer splits, eCPRI also defined split Options D, B, C, B, A corresponding to 3GPP split options 6, 4, 2, 1, respectively.

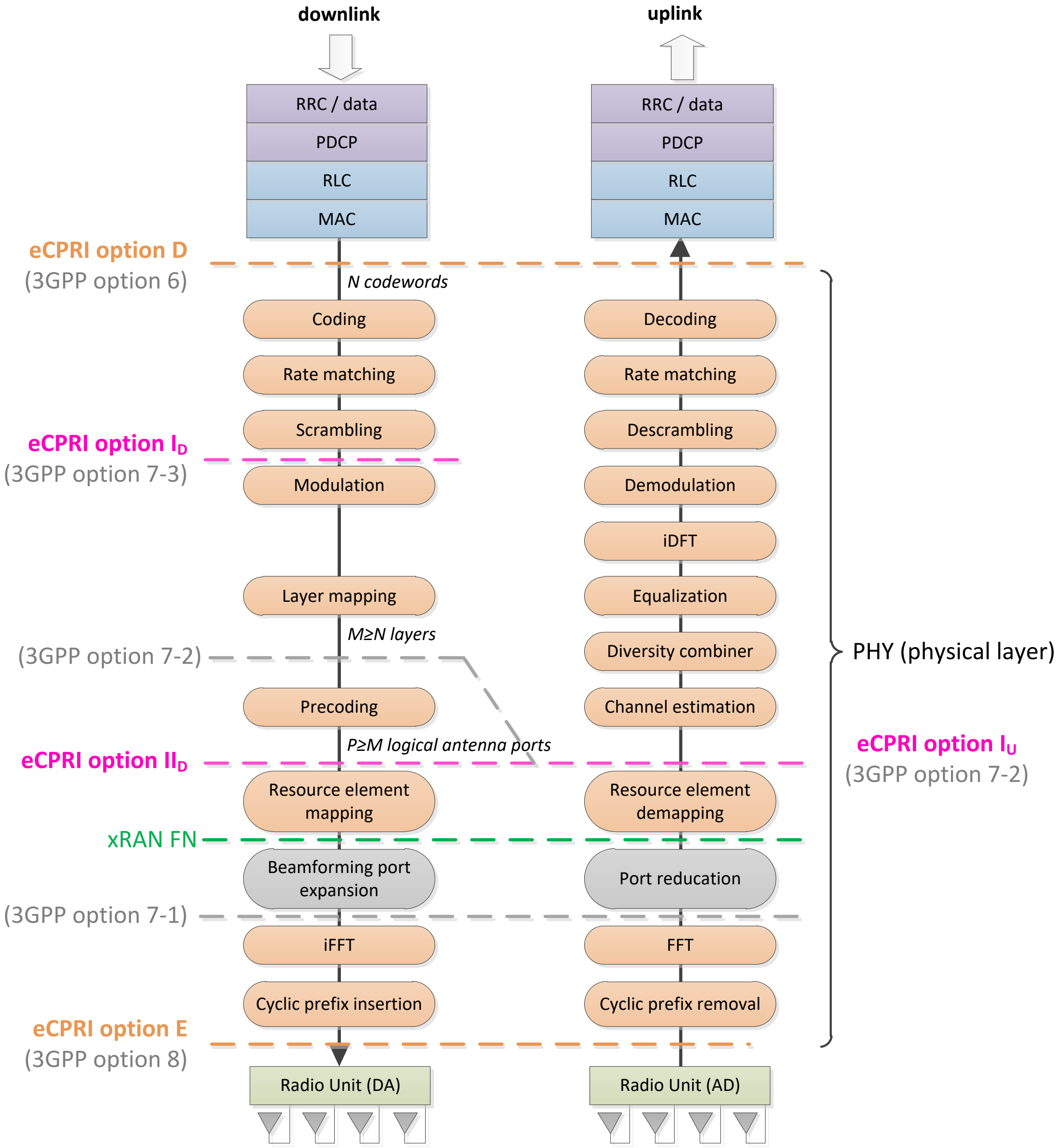

Figure 15 eCPRI lower layer functional split options including 3GPP and xRAN split options as a reference.

As opposed to CPRI, eCPRI is based on network distribution architecture rather than an aggregation point-to-point connection. The specification [32] defines aspects of data transmission and synchronization and Control & Management (C&M). The eCPRI control and management information is not be transmitted via the eCPRI protocol, and is not part of the specification. However, standard networking protocols (e.g. SNMP) may be used for such management. No special provisioning is required as C&M information is considered small in volume and not time-critical. Synchronization is part of the specification and eCPRI nodes are required to recover the

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synchronization and timing from a synchronization reference source such that the air interface of the feed by eCPRI meets the 3GPP synchronization and timing requirements. The synchronization information is not transmitted via any eCPRI specific protocol, and again, standard networking protocols may be used (e.g. SyncE, IEEE1588).

6.3. IEEE 1914

IEEE 1914 standard emerged out of the IEEE 1914 Next Generation Fronthaul Interface (NGFI) Working Group [33] which was formed early in 2016 to develop IEEE 1914.1 Standard for Packet-based Fronthaul Transport Networks. The specification is targeted for release by the end of 2018. The scope of this project included,

- Transport network architecture for the transport of mobile fronthaul traffic (e.g. Ethernet-based), including user data, management and control plane traffic
- Requirements and definitions for the fronthaul networks (including data rates, timing and synchronization, QoS, etc.)
- Analysis of functional partitioning schemes between Remote Radio Units and Base-Band Units that improve fronthaul link efficiency and facilitate the realization of functions, such as massive MIMO and CoMP.

Later the specification was split into two parts, P1914.1 and P1914.3. P1914.1 [34] focusing on a standard for packet-based fronthaul transport networks, including use cases and scenarios, architecture, requirements and functional split analysis. P1914.3 (ex1904.3) [35] focusing on encapsulations and mappings for a standard of radio over Ethernet, including I/Q (CPRI or other) encapsulations and mapping, I/Q in time and frequency domain.

The network architecture envisioned by IEEE 1914 anticipates the split of the overall network into several segments, each requiring its own version of fronthaul or backhaul transport service (Figure 16).

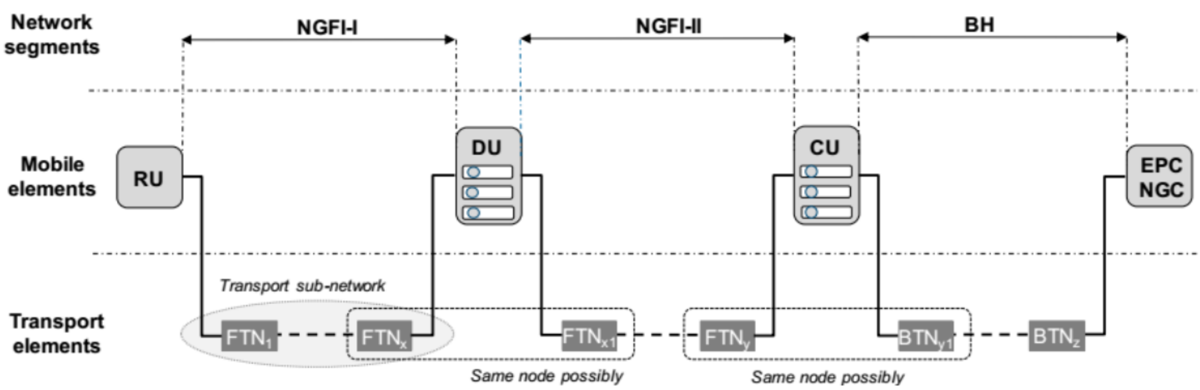

Figure 16 IEEE 1914 network architecture [36]

The fronthaul Domain I (NGFI-I, named as fronthaul in this document) is characterized by high bandwidth and stringent delay and synchronization requirement, so it is better matched for use of a low layer function split. The fronthaul Domain II (NGFI-II, named as midhaul in this document) is characterized by lower bandwidth and less stringent delay and synchronization requirements, so it is better matched for use of a higher layer function split.

A final specification for P1914.3 is not available at the time of writing, so things may still change. However, the current draft specification defines an extensive architecture, starting from topologies, underlying network assumptions, synchronization considerations and functional elements. The core of the specification is the Ethernet encapsulation itself which is based on the concept of

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mappers and de-mappers. These mappers/de-mappers are responsible for the mapping of the transport data (e.g. CPRI port) onto the Ethernet carrier based on the traffic types, a common frame format definition and timing and synchronization considerations. The mapping accounts for encryption and compression (both allowed but not specified) as well as the definition of the mapping itself. The specification supports both a structure-agnostic mapper, which assumes simple packing of a CPRI like source, and a structure-aware mapper, which enables definition of the frame structure of the source and thus more efficient mapping.

In summary IEEE 1914 fully overlaps eCPRI (and 3GPP) in terms of use cases and functionality, although IEEE 1914 is more elaborate both on the use cases and on the explicit provisions to achieve them on the Ethernet transport medium. In terms of efficiency, IEEE 1914 seems to offer greater flexibility by not having narrowed down the choice of split options. The drawback to this approach is that makes it a less interoperable standard, and one that might miss the main goal of a standard, which is to avoid market segmentation between different, incompatible implementations.

6.4. xRAN

The xRAN alliance was formed to develop, standardize and promote a software-based, extensible Radio Access Network (xRAN) and to specify critical elements of the xRAN architecture. The alliance is operator-driven with operators such as AT&T, Deutsche Telekom, SK Telecom, NTT DoCoMo, Verzion, KDDI to name a few. In June 2018 it was announced that xRAN would be merged into the newly formed O-RAN alliance, founded by AT&T, China Mobile, Deutsche Telekom, NTT DOCOMO and Orange.

In March 2018 the xRAN alliance released the first version of a specification attempting to standardize those parts of the fronthaul split which 3GPP failed to agree for Release 15. For the purpose of this section, the relevant part of that document is the choice of standardizing the fronthaul split point. In contrast to other standardization attempts that allow a lot of flexibility, and are thus leading to a situation where each RAN vendor chooses its own incompatible implementation, the xRAN alliance has decided to reduce flexibility and force implementers to one compromise choice whilst ensuring inter-operable multi-vendor deployments.

The xRAN alliance has chosen and focused on a single split point located between eCPRI option II_D and 3GPP option 7-1 (see Figure 15). This means that iFFT/FFT, Cyclic Prefix insertion/removal, and digital beamforming functions reside in the RU/DU, while the rest of the physical layer functions (e.g. precoding, layer mapping, modulation, scrambling, rate matching and coding) and other layers reside in CU. This split option was preferred due to the following reasons:

- Interface simplicity: Transfer of user plane data is based on Resource Elements (RE) or Physical Resource Blocks (PRB), which simplifies the data mapping and limits the required associated control messages
- Beamforming Support: The same interface design can support different beamforming techniques (digital, analogue or hybrid) and algorithms
- Interoperability: Fewer user-specific parameters are used compared with higher split options
- Advanced receivers and inter-cell coordination: Easy implementation of advanced receivers and coordination features, which bring benefit when most functions are placed at the CU.
- Lower RU/DU complexity: simple RU/DU compared with higher split options
- Future proof: Placing most functions at CU will allow the introduction of new features via software upgrades without inflicting HW changes at RU/DU

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- Interface and functions symmetry: Use of the same interface and split for DL and UL simplifies implementation

The second version of the specification was released in July 2018, including not only the expected Control/User/Synchronization Plane [37] but also the management plane specifications [38] that are key to ensure inter-operable multi-vendor deployments. The second version also added support for different types of RU/DU (based on whether precoding is located in the RU/DU or CU) as well as compression techniques to reduce required bandwidth.

7. Performance requirements for the transport network

The centralized network architecture with functional split (Figure 13) is expected to be used in incoming 5G network deployments to meet the different performance requirements of a wide range of 5G use cases and applications (see chapter 5). The choice of functional split point and consequently placement of RU, DU and CU determines the performance requirements of the transport network. Thus, the specific **performance requirements for the transport network** (mainly midhaul link between RU/DU and CU) **due to a certain functional split option** are elaborated in this chapter.

As an illustrative example and reference, Table 9 shows the expected performance requirements (throughput and latency) for the midhaul link between RU/DU and CU when considering different 3GPP functional split options and different configurations of mobile access network. The following 3GPP functional split options between RU/DU and CU were identified as the most beneficial and reasonable for further analysis. The 3GPP Option 2 was the favoured candidate of higher layer split point, which has already been specified for LTE dual cell connectivity. The 3GPP options 6, 7-3 and 7-2 were the favoured candidates of lower layer split point. Compared with 3GPP Option 8 commonly referred as CPRI, Options 7-3 and 7-2 significantly reduce the throughput demands but still give sufficient gain while using the coordination features such as CoMP. The 3GPP Option 8 serves as a baseline for comparison.

The scenario and requirements on mobile access network deployment are different in dense urban, urban and rural environments [30]. For example, the macro cells are smaller, inter-site distances are shorted, carrier frequencies are higher, aggregated bandwidth is larger, user density is higher and the number of macro antenna ports is higher in dense urban areas compared with rural areas. The 5G mobile access network shall support up to 1 GHz bandwidth, base station antennas with up to 256 antenna ports and UE antennas with up to eight antenna ports [30]. The resulting throughput requirements (Table 9) are calculated for the following configurations of 5G base station with one and three sectors/cells, which are expected to be adopted in typical 5G network deployments.

Table 8 Representative network configurations of 5G macro base station (per sector)

	Number of MIMO layers	Number of antenna ports	Aggregated bandwidth [MHz]	Sub-carrier spacing [kHz]
Configuration 1 LTE like	4	4	20 (106 PRB)	15
Configuration 2 5G NR like	8	32	40 (216 PRB)	15k
Configuration 3 5G NR like	8	64	100 (132 PRB)	60
Configuration 4 5G NR like	8	64	200 (264 PRB)	60
Configuration 5 5G NR like	8	128	2*200 (2*264 PRBs)	60

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3GPP technical reports and specifications [31], [39], [40], [41] are followed for the throughput calculation assuming the following parameters and values – common to all aforementioned network configurations (Table 8):

- Modulation: 256QAM (i.e. spectral efficiency 7.4063 bits/s/Hz)
- Sub-carrier spacing: 15 kHz is recommended for carrier frequency range 450 MHz – 6 GHz, while 60 kHz for carrier frequency range 24.25 GHz – 52.66 GHz
- Number of bits per I/Q sample: 32 bits (2*16 bits)
- Max FFT size: 4096 (scales with bandwidth)
- Min/Max number of Physical Resource Blocks: 20/275 PRBs

Note that some parameters, like the number of sub-carriers and the overall utilized bandwidth are important for the actual data rate, but less important when comparing efficiencies between various splits, as everything scales to them. Other parameters make a difference in different split points, such as number of bits per I/Q sample, number of antenna ports, modulation order.

For the sake of simplicity, we consider no I/Q sample compression technique and transmission of downlink user data (i.e. user plane) only. It should be noted that a compression technique or reducing sampling rate may be able to reduce the required throughput at split point 8. On the other hand, the transmission of necessary control data (control plane) requires additional throughput at all split points. However, the throughput required by control data is expected to be significantly lower than the throughput required by user data.

Table 9 Requirements for the transport network due to a certain functional split option.

3GPP split option			**2**	**6**	**7-3**	**7-2**	**8 CPRI**
Max one way latency between CU and DU (midhaul)			1.5 – 10ms	250 µs	250 µs	250 µs	250 µs
Throughput requirement between CU and DU (midhaul)	Configuration 1 20MHz, 4T4R, 4 MIMO layers	per sector/cell (micro BS)	0.42Gbps 11%	0.43Gbps 11%	0.54Gbps 14%	1.3Gbps 34%	3.9Gbps 100%
		per macro BS	1.26Gbps	1.3Gbps	1.6Gbps	4Gbps	11.8Gbps
	Configuration 2 40MHz, 32T32R, 8 MIMO layers	per sector/cell (micro BS)	1.84Gbps 3%	1.9Gbps 3%	2.3Gbps 4%	5.8Gbps 9%	62.9Gbps 100%
		per macro BS	5.4Gbps	5.6Gbps	7Gbps	17.4Gbps	189Gbps
	Configuration 3 100MHz, 64T64R, 8 MIMO layers	per sector/cell (micro BS)	4.37Gbps 2%	4.5Gbps 2%	5.7Gbps 3%	14.2Gbps 6%	252Gbps 100%
		per macro BS	13.2Gbps	13.6Gbps	17Gbps	42.6Gbps	755Gbps
	Configuration 4 200MHz, 64T64R, 8 MIMO layers	per sector/cell (micro BS)	8.7Gbps 2%	9Gbps 2%	11.4Gbps 3%	28.4Gbps 6%	503Gbps 100%
		per macro BS	26.4Gbps	27.2Gbps	34.1Gbps	85.1Gbps	1510Gbps
	Configuration 5 400MHz, 128T128R, 8 MIMO layers	per sector/cell (micro BS)	17.5Gbps 0.9%	18Gbps 0.9%	22.8Gbps 1.1%	56.8Gbps 2.8%	2014Gbps 100%
		per macro BS	52.45Gbps	54Gbps	68.4Gbps	170Gbps	6042Gbps

As can be observed the required throughput and latency of the midhaul link between CU and DU depend greatly on the particular split option, for example Option 7-2 usually requires less than 10 % of the throughput required by Option 8 (CPRI). In general, the lower the split point (towards Option 8) the higher the performance requirements (i.e. higher throughput and lower latency) of the transport network (midhaul link) and consequently the more difficult and costly the deployment in large networks. It seems to be obvious that the transport requirements of split point 8 (CPRI)

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are extremely high for most of the 5G network configurations, and that the optical fibre is the only transport solution - for example, the estimated data throughput of Option 8 exceeds 1500 Gbps for a macro base station with three sectors, 64T64R antennas and aggregated frequency bandwidth of 200 MHz. If the wireless connection is needed between RU/DU and CU (e.g. to ensure fast, flexible, and low cost deployment), a lower layer split point must be assumed. Nevertheless, even when assuming a lower layer split point, the current V- or E-band products providing maximum throughputs of 10 Gbps (section 4.3) cannot serve most of the configurations of 5G the macro base station. The combinations which could be served by current E-band products are highlighted in orange. In addition to these combinations, those which could be served by future terahertz-based products targeting throughputs beyond 200 Gbps are highlighted in green. Note that up to now a single macro base station connected to DU was assumed. However, in the field network deployment, a single DU working as an aggregation point can serve multiple base stations (Figure 13) which consequently requires multiple higher-order throughput on the midhaul link between DU and CU.

The 5G system should be able to provide around 10 ms end-to-end latency at the application layer in general and 1 ms latency for the use cases which require extremely low interaction [30], [1]. Use case specific latencies are specified in Section 5. These latencies are introduced mainly by the transport network while the processing time at the application layer is assumed to be negligible.

When using a radio link as a component in the transport network, and specifically when considering the link reliability, the issues of weather dependent RF propagation and antenna alignment should be addressed. As discussed in section 4.1, RF propagation depends on factors which are weather dependent, such as precipitation, fog and presence of water vapour. These factors have been modelled (e.g. by ITU-R) and can provide statistical guarantees for the reliability of the link as expressed in terms of availability. Another impacting factor is the antennas themselves which are also prone to weather conditions, including icing, water sheets on the face of the antenna during rain and misalignment due to wind. The means to negate these factors include heating of the antennas to prevent ice build-up and use of various coatings to repel water. The misalignment due to wind is related to the stability of the mounting structure, and would often limit the minimum usable antenna beamwidth. Unless beamforming is used, beamwidths below ~0.5° (equivalent to ~50 dBi) might already require careful evaluation of the mounting structure stability under windy conditions.

The required reliability rate of wireless transport links as a part of 5G systems depends on the supported use cases and applications (see Section 5). The wireless transport link should guarantee reliability rates of 99.999 % or higher for the Ultra-reliable communications and Extreme real-time communications use cases. For the other use cases for which reliability may be less important, e.g. Broadband access, Massive Internet of Things use cases, the reliability rate may be around 99 % or even lower [1].

The placement of CU and DU depends on the given application and use case, and determines the required length of midhaul wireless link. For ultra-low latency applications and use cases (such as tactile Internet, augmented and virtual reality, real-time gaming) requiring approximately 1 ms user plane end-to-end latency between UE and CU, the CU and DU must all be co-located at or near the cell site at tens of meters distance. This is necessary since the latency requirement is so stringent that any significant transport latency is not acceptable. In practice, this does mean that ultra-low latency capability is unlikely to be provided network-wide but in local areas such as stadia or campus sites. For non-latency critical 5G applications and use cases (e.g. broadband access) with the typical user plane end-to-end latency of approximately 10 ms, the DU would remain at or near the cell site while the CU can be separated and placed at an aggregation point or data centre (with optical fibre connectivity) at hundreds of meters distance. This would achieve

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the best compromise between centralisation gains while still being able to provide a service with approximately 10 ms end-to-end latency.

8. Conclusion

The volume of data traffic consumed by the 5G and beyond 5G (B5G) use-cases and applications will significantly grow in comparison to today's 4G/LTE generation (see chapter 5). To meet and support these demanding end-user/consumer performance requirements, the 5G and B5G mobile access networks are expected to enlarge the usage of the frequency spectrum to the lower millimetre wave range below 100 MHz (e.g. such frequency bands as 26-42 GHz (Ka-band) and V-band), where wireless backhaul networks currently operate. Such high frequencies are needed to enable wide bandwidth channels (up to hundreds of MHz) to support 5G and B5G use cases requiring end-user experienced data rates in the Gbps range. With the inclusion of the lower mmWave bands to 5G and B5G mobile access networks, there is consequently a need for consideration of new frequencies for wireless transport links to accommodate the growth of capacity requirements in mobile access networks. The unavoidable advance into the yet unregulated terahertz frequencies around 300 GHz and beyond (252-325 GHz as a possible candidate band) opens up more than enough channel bandwidths for wireless communication systems to enable 5G and B5G generations. The ThoR project is focusing on this novel and promising terahertz frequency range which provides enough spectrum to cover the growing capacity requirements of 5G and B5G networks. In addition, wireless communication systems profit from fast deployment, flexibility, and lower deployment costs (CAPEX) in comparison to optical fibre alternatives. It is expected that wireless links will also be important and necessary in 5G and B5G transport networks.

Evolving from 4G/LTE to 5G transport architecture, the main change is that the original single-node baseband functions in 4G/LTE are split between Central Unit (CU) and Distributed Unit (DU) (see Chapter 6) resulting in a so-called **centralized network architecture with functional split** (Figure 13). The advantages are obvious. This flexible and efficient architecture can deliver the different service requirements of a wide range of 5G use cases and applications (see Chapter 5). By centralizing resource and signal processing, the centralized architecture with functional split can also take advantage of cloud computing, flexible network configuration, virtualization and softwarization of network functions. The choice of functional split points depends on the specific use case and application, and determines the performance requirements for the transport network (i.e. fronthaul, midhaul and backhaul links) and consequently the capability of the mobile access network and end-user experience. The lower the split point (towards 3GGP Option 8) the higher the performance requirements (i.e. higher throughput and lower latency) of the transport network (namely midhaul link between DU and CU), and consequently the more difficult and costly the deployment in large networks.

On the other hand, the lower splits provide more coordination and more processing functions can be centralized. Using a higher layer split also makes it possible to use lower cost packet-based transport (e.g. Ethernet) for the midhaul link between CU and DU. The technical and economical trade-offs between the required throughput, latency and functional centralization should be taken into account depending on the given application and use case.

It has become clear that **traditional architecture and current V- and E-band products simply cannot support the 5G and B5G requirements in large scale network deployment**, and so new approaches and solutions such as the architecture based on functional splits and wireless transport links using terahertz frequency spectrum have to be considered.

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