Sub-THz X-Haul Architecture with Ultra Capacity Wireless Distribution and Transport

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***Abstract*—X-haul is a key evolution in novel 5G and 6G RAN architectures to transform the traditional backhaul-fronthaul scheme in a more complex nodes structure, introducing midhaul links, to satisfy the growing demand of traffic and quality of service. As an alternative to fiber based deployment, wireless ultra capacity, tens or hundreds of gigabits per second (Gb/s), for flexible and low latency architectures can only be supported by the wide unexploited frequency bands in the sub-THz spectrum (70 - 300 GHz). In particular, the development of new radio technology at D-band (110 - 174.5 GHz) and G-band (190 - 310 GHz) enables ultra capacity links for backhaul, midhaul and fronthaul with tens of Gb/s throughput.**

A novel sub-THz X-haul architecture will be described focusing on features such as capacity, adaptive distribution, low latency, efficiency and flexibility, relevant for enabling the three main classes of applications defined in 5G, Extreme Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC) and Massive Machine Type Communication (mMTC). This new network concept will be surely one of the enabling elements of the future 6G, leading to unifying the satellite and terrestrial networks.

***Index Terms*—sub-terahertz, x-haul, backhaul, fronthaul, midhaul, point-to-multipoint, 5G, 6G, wireless**

I. Introduction

In initial 3G and 4G deployments, a RAN (Radio Access network) was mainly a base station with monolithic or split architecture installed at the remote sites from where several coverage sectors provided service to users. RAN has now become a complex network beyond the terrestrial networks, extended to satellite and airborne networks to enable the 6G ecosystem. A substantial effort is devoted to maximize efficiency of distribution and transport [1], [2]. In 4G LTE, distributed RAN (D-RAN) and cloud (or centralized) RAN (C-RAN) allowed remote or centralized baseband units (BBU) to be used, connected to remote radio units or base stations (RRU), via an enhanced Common Public Radio Interface (eCPRI), defined as fronthaul. In 5G, a BBU will be further split into a distributed unit (DU) and a central unit (CU), and these two new units will be connected by links defined as midhaul. Backhaul is the link between the Core and the Central Unit. Collectively, the aggregation of the three RAN links, backhaul, midhaul and fronthaul, is defined X-Haul.

A high density deployment of the X-haul needs flexibility and cost-efficiency which can be achieved through the use of wireless links, to make it economically viable and quicker to deploy due to the avoidance of civil works typical of fiber, that can hamper deployment in protected areas such as historical quarters. The predicted high data traffic X-haul will support requires high capacity links, in the range of tens or more Gb/s. This data rate can be only achieved by using very wide frequency channels in untapped bands at the millimeter wave spectrum and above, e.g. E-band (71 - 76 GHz and 81 - 86 GHz) and the sub-THz spectrum (more than 100 GHz in the range 110 - 310 GHz). Around 50% of backhaul between the edge and the core network is predicted to be wireless (CAGR of 11.14$\%$ from 2021 to 2028 [3]). E-band front ends are already available in the market with a few Gb/s capacity, but higher throughput is required for fiber-like capabilities. A substantial effort is devoted worldwide to realize front ends at sub-THz frequencies to support tens of Gb/s over a single links. The high free space path loss, rain and gasses attenuation pose substantial technology challenges to achieve the best balance range - capacity performance to make economically viable a sub-THz wireless deployment. In the frame of the Horizon 2020 project "ULTRAWAVE" two full systems at D-band and G-band, from modem to antenna, were designed and fabricated [4]. The flexibility of the system makes it suitable for both transport and distribution.

In this paper, a novel implementation of X-haul wireless network architecture for RAN at sub-THz frequency (140 - 305 GHz), supported by novel sub-THz electronics components and systems [4] will be discussed. Ultra capacity and range are enabled by the use of traveling wave tube amplifiers

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(TWTAs), that provide more than one order of magnitude output power than solid state power amplifiers (SSPA) at the same frequency [5]. This is a breakthrough for new ultra capacity wireless network architectures. Each front end will be capable of ensuring long X-Haul segments from the Core, to intermediate nodes and to remote radio units, with tens of Gb/s capacity, for small cells or fixed wireless access.

II. Sub-THz Spectrum for Beyond 5G

The sub-THz spectrum includes three main frequency bands, namely W-Band (75 - 110 GHz, including E-band), D-band (130 - 175 GHz) and G-band (190 - 310 GHz). The total permitted aggregated band is wider than 100 GHz. The use of the sub-THz spectrum is key for efficient deployment and very competitive links: huge spectrum, re-usability thanks to limited propagation distance, space division and very low antenna sidelobe levels. However, the sub-THz spectrum poses serious challenges. One is the propagation in line of sight LoS (the introduction of Reflective Intelligent Surfaces will relax this condition). The free space path loss (FSPL) is tens of dBs higher than at microwaves. Rain attenuation adds about 17 dB/km in ITU zone K (42 mm/h rain intensity for 0.01% of the time) to consider to achieve 99.99% availability. Gas and humidity add further attenuation variable in time. A typical link budget for 1 km range can exceed 120 - 140 dB, in comparison to 70 - 80 dB at microwaves. The low transmission power available from sub-THz SSPAs is not sufficient to balance the total link attenuation. Less than a few hundreds meters links are reported in literature [6] [7], [8] achieved by expensive and extreme high gain antennas (e.g. 70 dBi).

The short sub-THz wavelength (1 - 3 mm) requires components (antennas, filter, active devices) with small dimensions to be produced by high accuracy and expensive fabrication processes. The reduction of cost of sub-THz components is necessary for their commercial viability. At the same time, small footprint front end at sub-THz frequencies, in particular the small antenna size, permits light and small equipment, easily carried and installed by one person, with very low visual pollution. Table I compares typical antenna dimensions of E-band mm-wave links with equivalent D-Band and G-Band antennas. It is notable that D-band antennas could be half of the size of an E-band antenna with the same gain. A G-band antennas is one quarter the size of the E-band antenna.

TABLE I
High directivity antenna dimensions

	80 GHz		140 GHz		290 GHz	
Gain (dBi)	45	51	45	51	45	51
Aperture angle (degrees)	1	0.5	1	0.5	1	0.5
Diameter (cm)	30	60	17	34	9	18

III. X-haul architecture

X-haul is defined as the ensemble of backhaul, midhaul and fronthaul. The backhaul connects the edge of the 5G core (5GC) to Distribution Units (DU). The fronthaul connects Distribution Units to an arbitrary number of Remote Radio Units (RRU). The internal links of the network between central units (CU) and distribution units (DU) are defined as midhaul. Each of these network segments requires very high data rate and proper frequency allocation. The sub-THz spectrum supports the required high data rate with flexibility to allocate frequency bands where needed, with frequency reuse, space division and band aggregation. The schematic of the proposed X-haul RAN architecture is shown in Fig. 1. To note that multiple intermediate sub-central units could be included between edge and DUs with different midhaul segments.

The proposed subTHz wireless X-haul architecture provides a cost-effective solution compared to optical fiber deployments. Wireless links are quicker and simpler to deploy than fiber. Laying new fiber could cost between 10000 and 100000 Euro per kilometer depending on the site [9], whereas the cost for a wireless link is an order of magnitude lower. Furthermore, in a complex urban environment, it can often be impossible to lay new fiber due to bureaucratic and environmental constraints. The architecture also benefits from the latency of wireless links about 50% lower than fiber links for long distance.

IV. X-haul for RAN

The primary requirement is to build a system that fits the new RAN (Radio Access Networks) architectures already defined by 3GPP initiative specifically:

– Distribution and transport of relevant capacity between the various nodes of the RAN;
– Adaptation to the various topologies operators would deploy considering site acquisition constraints and their legacy;
– Transparency to the various functions of the whole network as Network functions virtualization (NFV);
– Minimum latency round trip from terminals to the edge;
– Slicing of applications to optimise QoS (Quality of Service) or SLA (Service Level Agreement);
– Load balancing between application class, DL/UL (Download/Upload) and RRU load;
– Orchestration;
– Edge Computing.

The X-haul has to be designed to serve the three major classes of applications:

– Extreme Mobile Broadband (eMBB): higher number of users and connection time, high throughput for video (or in future XR - Extended reality). Challenge: Mobile fronthaul with one or two orders of magnitude more capacity delivered by dense distribution of small cells.
– Ultra-Reliable Low Latency Communications (URLLC): e.g. V2X (vehicle to everything) including secure navigation and autonomous transport in cities. Challenge: reliable and low latency communication from RRU to edge.
– Massive Machine Type Communication (mMTC): dense device inter-enterprise networks that intermittently transmit small amounts of traffic. Challenge: Reliable edge

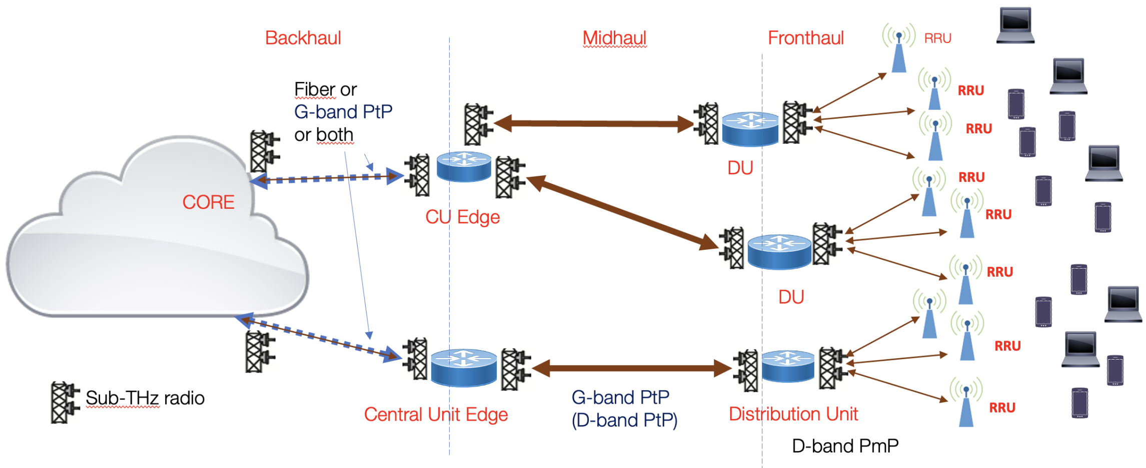

Fig. 1. X-haul architecture: simplified RAN architecture (CU Central Unit, DU Distributed Unit, RRU Remote Radio Unit).

computing with highly adaptive capacity and latency (as for medical tactile operations or industrial controlled and secured processes), often private network with no RRU.

The scenario beyond 5G and toward 6G includes most of the applications envisioned by 5G. RANs will expand for extended reality (XR) in eMBB, more private networks in professional mMTC and strong secure links in uRLLC, e.g.,V2X [10].

The growing deployment of robots (one of the IoT families) is posing new challenges: machines will become new users requiring secured communication with an inverted DL/UL ratio, whereas robot sensors information is needed for their control. The third dimension of Non Terrestrial Networks (NTN) from low altitude UAV (Unmanned Aerial Vehicles or flying robots) to low orbit (LEO) satellite constellations is now fully embedded in the 6G ecosystem. Finally, unified big 5G and 6G X-haul networks will growth in Tier 1 operators but many ad hoc private networks will locally be deployed by small specialized operators.

V. D-BAND AND G-BAND SUB-THZ X-HAUL ARCHITECTURE

A new technology for new network architecture concept has been developed by combining distribution and transport and exploiting the 27 GHz available at D-band (141 - 174.8 GHz) and 30 GHz at G-band (275 - 305 GHz), with possible addition of more than 30 GHz allocated in the 210 - 250 GHz band. A novel concept of wireless network with distribution at D-band (in the sub-band 141 - 148.5 GHz) and transport at G-band (275 - 305 GHz) was proposed [11] [4]. The novelty of the concept is the introduction of novel sub-THz traveling wave tube amplifiers (TWTAs) [12] as power amplifiers. TWTAs can provide more than one order of magnitude power than SSPAs at the same frequency. In particular, a TWTA with 10 -12 W output power in the 141 - 148.5 GHz band (SSPAs are limited to about 200 mW) and a TWT with about 2 W output power(SSPAs are limited to about 20 mW) in the 275 - 305 GHz band (SSPAs are limited to about 20 mW) have been designed and are in advanced fabrication stage [12]. Sub-THz TWTs are state of the art devices with substantial fabrication challenges not yet commercially available. Presently a few prototypes at D-band and G-band were demonstrated at laboratory level [5]. The design specifications were defined to ensure 99.99% availability in ITU zone H and K (42 mm/h rain for 0.01 % of the time in zone K). The achievable data rate is 30 Gb/s (64QAM) in PmP in the 141 - 148.5 GHz band and 30 Gb/s (QSPK) in the 275 - 305 GHz band. The description of transmission hubs and terminals at D-band is given in [4]. The high flexibility and ultra capacity of the architecture make it the enabling technology for X-haul high capacity and range segments. In the following, the different sub-THz X-haul segments enabled by the wireless system developed in [4] will be described. The link range is dictated by the balance between antenna gain and available transmission power. One key feature of proposed architecture is the transport of one or more classes of applications on the same segment. Point to multipoint (PmP) with a single wide beam, or with narrow multiple beams is considered for specific midhaul segments and fronthaul. A transport segment in Point to Point (PtP) will be used for backhaul and midhaul.

A. Point to multipoint distribution

The architecture is based on RRUs that are fed by wireless fronthaul links, implemented by D-band Point-to-Multipoint distribution. PmP can be implemented or as wide area coverage with single beam to all terminals or multiple links from a single transmission hub to terminals. The proposed PmP system distributes several channels per sector with arbitrary bandwidth comprised between e.g. 40 - 1000 MHz in 141 - 148.5 GHz frequency band.

A D-band a sector with aperture angle of 30^o, obtained by a 20 dBi horn antenna gain, assuming 10 W saturated power with 6 dB back-off for supporting 64QAM, will have 600 - 700 m range. The D-band transmission hubs can use a kit of antennas with various gain and aperture (examples in Table II)

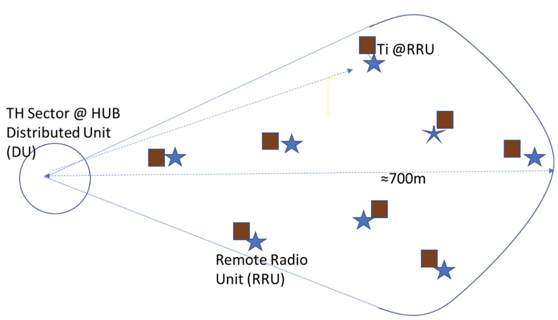

Fig. 2. Example of distribution of D-band terminals (square) over one sector (stars are connected Remote Radio Units)

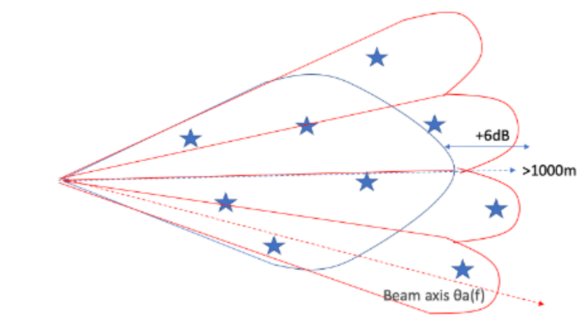

Fig. 3. Multibeam distribution over a D-band sector (stars are the connected Remote Radio Units)

to optimize the sector coverage. The D-band terminals use lens antennas with high directivity and gain in the range 38 dBi to 45 dBi to connect to the transmission hub powered by SSPAs. Figure 2 shows an example of sector with about 700 m radius with distribution to 8 terminals feeding the RRUs with the Transmission Hub (TH) at the DU. Each terminal T_i receives power (pr_i) with level to match the best C/N (Carrier to Noise ratio) for the selected modulation scheme of each link.

TABLE II
ANTENNA APERTURES FOR D-BAND TERMINALS

Antenna Aperture	30^o	45^o	60^o	90^o
Gain (dBi)	20.5	19	17	16

B. Point to multipoint by multibeam distribution

PmP distribution by a single wide beam permits an arbitrary and flexible deployment of terminals, but some power is lost in areas where there are no terminals. An effective alternative, when the position of terminals is fixed and limited flexibility is needed, is to replace the horn antenna at the transmission hub by an antenna with beamforming capability to split the main beam (e.g. 30° in the previous example) in several narrower higher directivity beams directed to their respective terminals. A schematic of coverage is shown in Fig. 3. The multi-beam principle uses an array of several horns (instead of one), the phases of which are modified with frequency (as in SIW, Substrate Integrated Waveguide) to achieve the required beam deviation from the axis of the "in phase" array. This approach permits an antenna gain increase up to 6 dBi, obtaining enhanced capacity or range with the same transmission power. As an example, assuming e.g. 10 beams, 200 m increase of the link range in comparison to wide beam sector, with 22 dB SNR to support 64QAM is obtained.

C. Point to point transport

A Point-to-Point (PtP) link in G-band (275 - 350 GHz) is designed to transport N channels aggregating the traffic to and from each of the sectors served by the fronthaul in DUs. Assuming 1 W saturated output power and 38 dBi antenna gain, links 600 - 700 m long supporting QSPK (30 Gb/s if the full band is used) are enabled. As further solution, links in FDD (Frequency Division Duplex) using the 151 - 174.8 GHz portion of the D-band were designed for long range and high throughput (45 Gb/s) to be added to the G-band transport capabilities [13].
The main parameters for each link are summarized in Table IV.

TABLE III
MAIN PARAMETER OF THE D-BAND AND G-BAND LINKS

	D-band PmP	D-Band Multibeam	D-band PtP	G-band PtP
Frequency GHz	141 - 148.5	141 - 148.5	151 - 174.5	275 - 305
Link	Fronthaul	Fronthaul	Backhaul Midhaul	Backhaul Midhaul
Range m	600	700	1000	600
Data rate Gb/s	30	30	45	30
Saturated transmission power W	≈ 12	≈ 10	≈ 10	≈ 2
Latency RTT microsec	≈ 1	≈ 1	≈ 5	≈ 4
DL / UL	4 / 1	4 / 1	4 / 1	4 / 1 - 2 / 1
Modulation	64QAM	64QAM	64QAM	QPSK
Availability	$\geq 99.99\%$	≥ 99.99	≥ 99.99	≥ 99.99

VI. SUB-THZ X-HAUL KEY FEATURES

In summary, n fronthaul D-band channels serving one PmP sector are aggregated into midhaul G-band channels at the DU. The PtP G-band link transporting N channels will be able to feed N fronthaul sectors at the DU. This ensemble would contain as many VLAN as needed both for control plane (CP) and user plane (UP) (Fig. 1).

The presented X-haul architecture has several key characteristics:

– TWTs provide high C/N at D-band to support high modulation order (from 16QAM to 64QAM depending on antenna and range)
– Large bandwidth at G-band permits high capacity by using low modulation schemes (QSPK, BPSK, possibly 16QAM for short links) suitable for the low C/N due the low transmission power at these frequencies. This huge bandwidth combined with low sidelobe antennas offers dense spectrum coverage.
– Multiplex of adaptive TDD channels permits an efficient PmP architecture, load balancing and slicing.

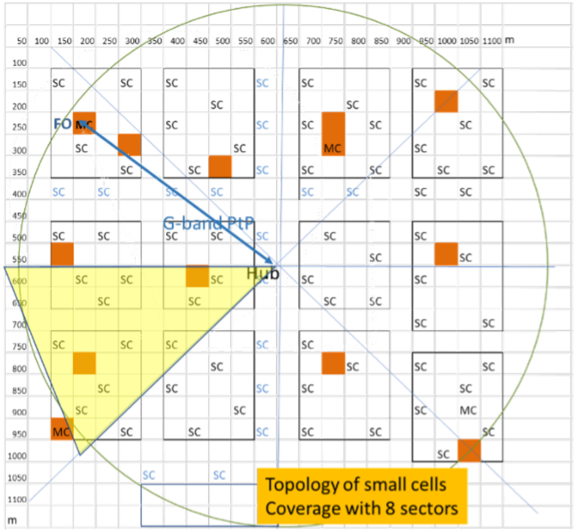

Fig. 4. Deployment of fronthaul with eight sectors (sc: small cell)

– Equipment with very low footprint (e.g. more than five time smaller than an equivalent E-band deployment) which reduces TCO (Total Cost of Operation) for site leasing.
– Re-use of baseband and intermediate frequency architectures optimized for highest capacity, high coverage, high availability and ultra-low latency.

A. Modem

The choice of modems is functional to support bandwidth, capacity and adaptive capabilities requirements of the various links (channel bandwidth and modulation scheme). The IEEE 802.11ac or the IEEE 802.11ax standard can be adopted for fronthaul distribution where large channels are not necessary. The wide channels of IEEE 802.11ay are suitable for PtP high capacity links for backahul and midhaul. As an example, a 250 MHz channel with 64QAM and 0.75 FEC (Forward Error Correction) supports 1 Gb/s. The power of each modem at the Transmission Hub is managed so that only the desired received power (Received Signal Strength Indicator, RSSI) is delivered at the corresponding modem at the receiver, with improved energy efficiency.

B. Latency

Latency at submillisecond is a key challenge to solve. The predominant latency contribution in the proposed sub-THz X-hual network, assuming backhaul and midhaul links 600 m long and fronthaul links 50 m long, is given by the propagation time in air. The return path from the edge to users can be estimated with latency in air at about 8 micro seconds. Including about 2 microsecond of front ends latency (radio is a very low latency topology), about 10 microsecond latency is obtained.

VII. Applications

The effectiveness and features of the sub-THz X-haul architecture will be discussed for two classes of application,

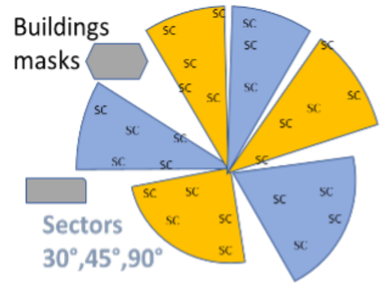

Fig. 5. Deployment with variable aperture sectors to adapt to blockage (sc: small cell)

Enhanced Mobile Broadband (eMBB) and V2x Ultra Reliable Low Latency Communication (V2x uRLLC). The deployment parameters of the wireless architectures were designed to match the specifications of each class. Ten characteristics influencing the deployment parameters of the RAN distribution and transport will be considered.

A. Application 1: Enhanced Mobile Broadband (eMBB)

This class of application is the mobile radio service already offered by 4G for video to smart phones, tablets and laptops. In 6G, the video services (e.g. XR) require much more throughput and a much larger number of connections. Table IV presents the requirements of eMBB (computed for ITU zone K and availability 99.99%)

TABLE IV
SPECIFICATIONS FOR ENHANCED MOBILE BROADBAND

Capacity at RRU	0.3 - 0.7 Gb/s
DL / UL	4 / 1
Latency RTT	¡ 25 ms
Range Cell	100 - 200 m
Range fronthaul	≈ 700 m
Active users	≈ 1000
QoS	Best effort
Multi-access edge computing (MEC)	No
Availability	≥ 99.95%
Wi - Fi Off load	e.g. IEEE 802.11ay

Fig. 4 shows an example of a regular deployment of small cells (SC, each of them fed by a terminal), installed roughly every 150 m with 100 m radius upon a dozen of blocs of buildings, supported by PmP Fronthaul (circle) and a PtP midhaul (blue arrow). Orange squares represent macro cell sites already connected or legacy. The X-haul network is connected to a fiber node (F.O.) at the edge of the network. Eight sectors of 45°each are considered as coverage hypothesis. The optimized power (RSSI) and the C/N obtained are compatible with 64QAM 3/4. 80 terminals are served with a rough global capacity around 56 Gb/s. Some considerations based on performance and specifications are:

– When rain increases (e.g. over 42 mm/h for 0.01% of time) modems activate ACM (Automatic Control Modulation). Then, upon RSSI, tests would indicate the

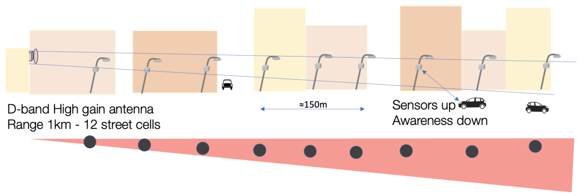

Fig. 6. V2X deployment: street fronthaul. Narrow sector for small cell along a road. (below: Antenna beam top view)

throughput temporarily obtained. This indication will be useful to operators to assess performances/availability.

– For cost reduction in case of low traffic, an operator may prefer to install only 6 sectors with 90º antennas reducing the antenna gain and consequently the modulation to 16QAM. If terminal antenna gain is increased to 42 dBi, 64QAM modulation can be used.
– Reducing the number of sectors implies to increase the terminals per sector with the need of more channels and more allocated spectrum for each sector. The wide available band (27.5 GHz) at D-band makes it possible.

The deployment could be progressive according to coverage and demand growth per areas. Sectors will be designed and deployed depending on the topology and operator's site acquisition rhythm. In reality, the small cells deployment is not regular, and masks are present. One of the advantages of wireless X-haul architecture is its ability to adapt its coverage with sectors of various aperture and range (Fig. 5).

B. Application 2 - uRLLC for V2X

Ultra Reliable Low Latency Communication (uRLLC) [1] is a key 5G and 6G application, applied to Time Sensitive Networks (TSN). For example, certain industrial applications require uRLLC and TSN, with performance that cannot be achieved by Wi-Fi, for, e.g. periodic updates of pressure values of a critical industrial machine. One missed measurement could mean a damaged machine and lost productivity.

uRLLC is of relevance for V2x (Vehicle to everything). Vehicles would be able to receive and send relevant data in real time for enhanced safety and comfort. The main URLLC parameters are listed in Table IV.

TABLE V
SPECIFICATIONS FOR V2X URLLC

Capacity at Street Cell	200 Mb/s
DL / UL	1 / 10
Latency RTT	¡ 1 - 2 ms
Range Cell	50 - 100 m
Range fronthaul	≈ 1000 m
Active users	≈ 100
QoS	Delivered
MEC	Yes
Availability	≥ 99.997%
Wi - Fi Off load	802.11ax

The presented architecture is well suited for very efficient fronthaul of RRUs dedicated to V2x in city environment, such as straight streets, boulevards and avenues. A narrow sector in PmP could connect a dozen of RRUs over e.g. a one kilometer length, as shown on Fig. 6. The same tower can support sectors with different direction and could connect, e. g.,more than 50 cells in 4 directions. An equivalent fronthaul with conventional PtP wireless links at sub-6 GHz would require hundreds of microwave links [4].

CONCLUSIONS

A sub-THz X-haul architecture to distribute tens or hundreds Gb/s to support the main 5G and future 6G application classes has been discussed. The use of sub-THz spectrum provides the best optimization of coverage-capacity and spectrum use for the future increasing traffic requirements. Architecture and technology developments will foster the future adoption of affordable sub-THz wireless segments for backhaul, midhaul and fronthaul with low latency, high availability and high energy efficiency.

REFERENCES

[1] Z. Chen, C. Han, Y. Wu, L. Li, C. Huang, Z. Zhang, G. Wang, and W. Tong, "Terahertz wireless communications for 2030 and beyond: A cutting-edge frontier," *IEEE Communications Magazine*, vol. 59, no. 11, pp. 66–72, 2021.
[2] M. Matthaiou, O. Yurduseven, H. Q. Ngo, D. Morales-Jimenez, S. L. Cotton, and V. F. Fusco, "The road to 6g: Ten physical layer challenges for communications engineers," *IEEE Communications Magazine*, vol. 59, no. 1, pp. 64–69, 2021.
[3] "https://www.verifiedmarketresearch.com/product/global-mobile-and-wireless-backhaul-market-size-and-forecast-to-2025/,"
[4] C. Paoloni, V. Krozer, F. Magne, T. Le, R. Basu, J. M. Rao, R. Letizia, E. Limiti, M. Marilier, G. Ulisse, A. Ramirez, B. Vidal, and H. Yacob, "D-band point to multi-point deployment with g-band transport," in *2020 European Conference on Networks and Communications (EuCNC)*, pp. 84–88, 2020.
[5] C. Paoloni, D. Gamzina, R. Letizia, Y. Zheng, and N. C. L. Jr., "Millimeter wave traveling wave tubes for the 21st century," *Journal of Electromagnetic Waves and Applications*, vol. 35, no. 5, pp. 567–603, 2021.
[6] T. Maiwald, T. Li, G.-R. Hotopan, K. Kolb, K. Disch, J. Potschka, A. Haag, M. Dietz, B. Debaillie, T. Zwick, K. Aufinger, D. Ferling, R. Weigel, and A. Visweswaran, "A review of integrated systems and components for 6g wireless communication in the d-band," *Proceedings of the IEEE*, vol. 111, no. 3, pp. 220–256, 2023.
[7] H.-J. Song and N. Lee, "Terahertz communications: Challenges in the next decade," *IEEE Transactions on Terahertz Science and Technology*, pp. 1–1, 2021.
[8] S. S. Dhillon and *et al.*, "The 2017 terahertz science and technology roadmap," *Journal of Physics D: Applied Physics*, vol. 50, p. 043001, Jan 2017.
[9] N. Bradley, "http://www.beyondbroadband.coop/kb/installing-fibre-optic-cables-underground."
[10] W. Hong, Z. H. Jiang, C. Yu, D. Hou, H. Wang, C. Guo, Y. Hu, L. Kuai, Y. Yu, Z. Jiang, Z. Chen, J. Chen, Z. Yu, J. Zhai, N. Zhang, L. Tian, F. Wu, G. Yang, Z.-C. Hao, and J. Y. Zhou, "The role of millimeter-wave technologies in 5g/6g wireless communications," *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 101–122, 2021.
[11] C. Paoloni, "Sub-thz wireless transport layer for ubiquitous high data rate," *IEEE Communications Magazine*, vol. 59, no. 5, pp. 102–107, 2021.
[12] R. Basu, J. M. Rao, T. Le, R. Letizia, and C. Paoloni, "Development of a d-band traveling wave tube for high data-rate wireless links," *IEEE Transactions on Electron Devices*, vol. 68, no. 9, pp. 4675–4680, 2021.
[13] C. Paoloni, R. Basu, L. B. R., J. R. M., R. Letizia, Q. Ni, E. Wasige, A. Al-Khalidi, J. Wang, and R. Morariu, "Long-range millimetre wave wireless links enabled by travelling wave tubes and resonant tunnelling diodes," *IET Microwaves, Antennas Propagation*, vol. 14, pp. 2110–2114(4), December 2020.