Sub-THz wireless transport layer for ubiquitous high data rate

Claudio Paoloni, Engineering Department, Lancaster University, Lancaster, UK

Abstract

5G and the future 6G ambitions will be real when wireless "unlimited data' will be available. Multi-Gigabit per second or Terabit per second are the new units to measure the data demand of emerging applications such as 8K video, e-health, extended reality, vehicle to everything , and many others.

Actual wireless networks are based on the fiber substrate that feeds, by fixed access points, a wireless layer for distribution to users at much lower capacity, posing a limit to the introduction of data hungry applications. To increase the area capacity of the wireless distribution layer, an ubiquitous data source is needed. A wireless layer to transport data at rooftop level is conceived to replicate wireless the data provision of the fiber substrate, with unlimited access flexibility. This new layer is fed by fiber and provides to the wireless distribution layer links arbitrarily distributed, for a ubiquitous data distribution.

The architecture and enabling technology of the proposed wireless transport layer will be described.

INTRODUCTION

6G (Sixth Generation) extends 5G ambitions to orders of magnitude of complexity, challenges, service level and opportunities [1-7]. What was challenging in 5G introduction, in 6G it is pushed beyond the limits of the actual technology. The explosion of video demand started with 4G and fueled by 8K video with enhanced user experience, or Extended Reality (XR) on mobile, is already highlighting the data limits of the newborn 5G networks. Holographic telepresence, autonomous or semi-autonomous vehicles (including a vast variety of robots) always connected part of the unlimited Internet of Things (IoT) family, cannot be enabled without ubiquitous ultra-high capacity, that for some applications could be close to the Terabit per second threshold.

In addition, the full implementation of E-health, Industry 4.0, Vehicle to everything (V2x), only to cite some, needs an unprecedented amount of wireless data with ultralow latency. So far, no wireless network is able to support the foreseen rocketing traffic increase.

Long Term Evolution (LTE) networks have been introduced in 4G. 5G is extending the use of MIMO (Multiple Input Multiple Output) to massive MIMO and low millimeter wave bands (e.g., 28 GHz). Enhanced Mobile Broadband (eMBB), Big Communications (BigCom), Secure Ultra-Reliable Low-Latency Communications (SURLLC), Three-Dimensional Integrated Communications (3D-InteCom) are the new frontiers of 6G [3].

6G not only envisages multigigabit links, but a giant step forward to distribute high capacity ubiquitously, as an inexhaustible sea of data.

Wireless Transport Layer Concept

The actual wireless ecosystem is a three dimensional space (wireless distribution layer - WDL) fed by the fiber substrate. Data transported by fronthaul and backhaul networks are distributed to users by base stations in the 0.7 - 3.5 GHz range. Links in Ka-band (28 GHz), Q-band (40 GHz), V-band (60 GHz), up to E-band (71-76, 81-86 GHz) are deployed with different functions (transport, backhaul, fronthaul). Network slicing and virtualisation are widely adopted.

However, the area capacity provided by actual networks is limited by the cell data rate. Only a high density cell distribution could increase the area capacity. Considering that all new 6G applications will lie in the WDL, it is evident that they cannot be fully exploited due to the too low data density.

It is notable the substantial unbalance of data rate between the fiber substrate and the WDL. High capacity is available only at fiber access points, but not in arbitrary positions over the WDL. This physical limitation prevents one of the main expectations and requirement of 6G, ubiquitous high capacity.

Imagine a layer with capacity similar to the fiber substrate, placed on top of the WDL, where every point can be a wireless "point of

access”. This new layer, here defined Wireless Transport Layer (WTL), adds flexibility of accessing to high capacity everywhere, precluded to the fiber substrate, but in cooperation with the fiber substrate.
Cities will be enclosed by a vault of high capacity that will flexibly feed subnetworks in the WDL from the top, complementing data fed from fixed points of the lower fiber substrate. Substantial challenges have to be faced. High data rate needs wide frequency bands not available at microwave frequencies. Data have to be distributed over wide areas. This is in principle possible by point to multipoint (PmP) distribution [8][9], but the enabling technology beyond microwaves is needed [10].
This paper, after an overview on sub-THz frequencies and data distribution modality, will describe the conceptual structure of the new Wireless Transport Layer and its main enabling elements. A WTL deployment case in urban scenario will be discussed. The modality to bring data at sub-6 GHz, for fronthaul and backhaul, will not be topic of this paper.

Sub-THz wide bands for multigigabit data rate
The region of the spectrum at the verge of 1 Terahertz (10^{12} Hertz or 1000 GHz) is attracting high interest. The region 100 - 310 GHz, where millimeter waves and THz overlap, here defined “sub-THz”, offers more than 100 GHz disaggregated useful bands. If we would have an equipment providing Signal to Noise Ratio (SNR) equivalent to the one achievable at microwave frequencies (e.g., > 30 dB), a 100-GHz band with 256 quadrature amplitude modulation (256QAM), assuming 8 bit/second/hertz (b/s/Hz) theoretical spectral efficiency, would permit to transmit about 0.8 Terabit/sec (Tb/s). 1 Tb/s can be achieved with 1024QAM, assuming 32 b/s/Hz theoretical spectral efficiency. Even if 1 Tb/s could be theoretically achieved, in real environment it would be limited to a short distance (a few meters), due to the sharp degradation of the SNR. The free space path loss at the sub-THz region is more than 20 dB higher than at microwaves, in addition to its increase with the square of distance. Rain attenuation adds up to 20 dB per km. This simple estimation gives the sense of the challenges of Tb/s transmission wireless. However, the three wide bands in the sub-THz spectrum, W-band (92 - 114 GHz), D-band (130 - 174.8 GHz) and G-band (210 - 310 GHz) can support tens or hundreds of Gb/s. Several wireless front-ends up to 400 GHz were tested [7] [12], demonstrating that sub-THz wireless technology is promising, but not mature for the market yet, due to fabrication difficulties, short range, and need of high skill operators.

Radio
Wireless communications are based on the radio, that consists of a receiver and a transmitter (front end), to establish a reliable link in almost any weather condition.
It is worth to remind its simple structure to appreciate the technology challenges at sub-THz frequencies. Both the transmitter and the receiver include a low power section with the mixer for upconverting or down converting the signal from modems usually at C-band (4-8 GHz) to and from the carrier frequency. The receiver includes an antenna connected to a low noise amplifier (LNA) to enhance the signal quality, and a filter. The transmitter comprises a power amplifier to provide transmission power to the antenna. The power amplifier is the enabling component for long range and high modulation scheme. The described radio scheme is valid for any frequency, if the components are available.

Internet distribution
The two distribution modalities, point to multipoint (PmP) and point to point (PtP), have an equal importance in any wireless network architecture.
PmP is based on a transmission hub (TH) to distribute internet over a wide sectorial area with angle defined by a low gain antenna aperture, and range as a function of the SNR for a specified data rate [8] [9]. The TH feeds terminals distributed arbitrarily over a sector, connected by a high directivity antenna. The main difference between the transmission hub and the terminals is the transmission power of the radio dictated by the difference in antenna gain, up to 20 - 25 dBi less for the TH. The advantages of PmP are no need of frequency planning, flexibility of channel allocation and terminal deployment, low latency. For N links, 1 (TH) + N front ends are needed with benefit

on the Total Cost of Operation (TCO) and reduced installation burden. The main challenge for enabling sub-THz PmP is the availability of sufficient transmission power to compensate the low antenna gain and ensuring the SNR for the required range and data rate. Presently, no sub-THz PmP has been demonstrated or is available in the market.
Point to point (PtP) is based on a single link between two front ends, with a narrow beam produced by high gain antennas (> 38 dBi). In comparison to a N-links PmP, in a PtP layout the transmission hub is replaced by a cluster of N front ends. Each of them is paired to another front end to form the link. For N links, a total of 2N front ends are needed. The footprint of a PtP cluster of front ends is many times a PmP TH footprint. PtP links require lower transmission power for the same transmission distance than PmP, because the use of high gain antennas. Due to the high antenna directivity, the alignment has to be re-established every time the position of a link is changed. In case of wide antennas, the sway due to wind could affect the link performance. Presently, E-band PtP frontends are commercially available, with data rate higher than 1 Gb/s over 1-2 km range, depending on rain. E-band links use antennas with 20 to 90 cm diameter to compensate the low transmission power (< 30 dBm at E-band) of solid state power amplifiers (SSPA).
Further data distribution modalities are based on the use of beam steering or multibeam. They work in PtP, but by steering the beam or by multiple beams, they connect terminals sparse on a wide area as in PmP. Both beam steering and multibeam need of sophisticate antenna systems, with increase of latency, but front end are more compact than an antenna cluster in PtP. In the following, only conventional PmP and PtP will be considered.

THE WIRELESS TRANSPORT LAYER

The actual structure of network architectures in urban environment can be schematized by two layers. The fiber infrastructure (or substrate) is the layer that has "unlimited capacity". It is a cable system accessible only by fixed points. The second layer is the wireless distribution layer (WDL) that provides data coverage to users, filling the space up to rooftop. However, the frequency bands limited to the sub-6 GHz spectrum, the limited availability of fiber access points and the yet low number of base stations, make the area capacity of the WDL relatively low (a few hundred Mb/s/km^2). This creates an unbalance between the high capacity available by fiber layer and the low capacity of the wireless distribution layer.
Fiber cannot be deployed with high density for cost and environmental constraints. Deploying new fiber links in cities can exceed one hundred thousand euro per kilometer. Fiber is proprietary, so it could not be available to new operators or be expensive to rent. This represents a critical obstacle for the development of new services.
The WDL capacity will be increased by a high density of small cells, but how to bring data by a dense backhaul and fronthaul networks to a high number of nodes is an open question that cannot be resolved by fiber alone.
In summary, very high data rate is available from the fiber substrate without flexibility, low data rate is available from the wireless distribution layer with full flexibility. A layer with data rate close to fiber and flexibility as the WDL is missing.
A new layer called wireless transport layer (WTL), with capacity close to fiber, for providing ubiquitous wireless "point of access" at roof level, will be discussed.
The concept is to enclose the Wireless Distribution Layer between two "unlimited" capacity layers, fiber and WTL, to enable any possible configuration of data links, backhaul, fronthaul and to provide capacity for any application in 5G and 6G ecosystem.
The WTL will provide area capacity at level of tens or hundreds of Gb/s/km^2 and cover the full urban area. Main features are easy installation, total cost of ownership (TCO) competitive to the fiber, high signal-to-noise ratio (SNR) and spectral efficiency, and low latency. The WTL will be at the same time complement and alternative to the fiber. Finally, the implementation of the Wireless Transmission Layer is a compromise between traffic requirements and technology. In the following the main aspects of the WTL will be described.

Why sub-THz frequencies

Area capacity with tens or hundreds Gb/s/km^2 needs multi-GHz band wireless systems. Wide frequency bands are only available in the sub-THz spectrum.

The W-band provides about 15 GHz, the D-band has about 27 GHz split in three sub-bands, and the G-band about 100 GHz. Those bands are light licensed or unlicensed, making their use attractive for the TCO, but difficult to use outdoor due to very high attenuation. If a 1 GHz wide channel is considered, more than 6 Gb/s at 64QAM can be provided (assuming 0.75 FEC - Forward Error Correction, that reduces the spectral efficiency). 30-GHz bandwidth can support about 180 Gb/s. However, high modulation schemes need the correct SNR. At sub-THz frequencies, the SNR is strongly affected by the atmosphere attenuation, range, and system losses. Without a suitable transmission power to compensate the impairments, the data rate above estimated is available only for short distance or clear sky.

To note that at sub-THz, the attenuation is critical for propagation, but it can be exploited to create a natural space division to effectively reuse the spectrum. Link capacity can be also increased aggregating different sub-THz bands.

A key constraint for transmission at sub-THz range is the propagation in line-of- sight (LOS) due to the low diffraction at those frequencies. LOS in an urban environment is not always possible due to different heights of buildings. To set a ubiquitous data distribution at roof level, a fully reconfigurable and flexible architecture has to be devised.

The proposed WTL concept is a mixed network of point to multipoint sectors connected by point to point links, exploiting the full sub-THz spectrum. Distribution, density and shape of sectors will be designed for the best coverage. The wireless transport layer is a giant leap to move traffic beyond 100 GHz for enabling the 6G concept.

Table 1 - Total path loss (dB) L_T

Freq	Distance (meter)			
GHz	50	100	500	1000
100	109	116	137	151
140	112	119	140	154
240	117	124	145	159
310	119	126	147	161

Sub-THz point to multipoint

Point to multipoint distribution is the most effective modality to flexibly cover wide areas with high capacity and low latency. The implementation of a PmP layer at sub-THz frequencies depends on which range and capacity make it cost effective and if the equipment will be available.

The first stage is defining if radios with proper specifications are available or feasible.

The link budget dictates the specifications.

The modified Friis law is used for the purpose:

$$P_r(dBm) = P_t(dBm) + G_t(dBi) + G_r(dBi) - L_T(dB) \quad (1)$$

Where P_r is the received power, P_t the transmitted power, G_r *and* G_t the receiver and transmitter antenna gains respectively. The total path loss L_T can be defined as the sum of three main components, the free space path loss L_{FS} (dB), the gaseous attenuation L_{Gas} (dB) and the rain attenuation L_R (dB/m):

$$L_T(dB) = L_R \times d + L_{FS} + L_{Gas} \quad (2)$$

where

$$L_{FS}\,(dB) = 20\log_{10} f + 20\log_{10} d - 147.56$$

with *d* distance (m) and *f* frequency (Hz).

A PmP transmission hub uses low gain antennas (16 - 25 dBi depending on the aperture angle), the terminal uses high gain antennas (> 35 dBi). Rain attenuation increases with the frequency up to about 100 GHz, then becomes almost constant. It increases at the increase of the rain rate for any frequency. The availability

Table 2 – Performance for different frequency bands (assuming FEC = 0.75 and 6 dB back off, 99.99% ITU zone K).

Band	Frequency (GHz)	Modality	Sat power (W) (dBm)	Range (m)	Aperture angle (degrees)	Modulation	Area capacity Gb/s/km^2	Data rate Gb/s
W	93 – 95	PmP	40 (46)	1000	40 - 90	64QAM 3/4	3.5	10
W	93 – 95	PtP	40 (46)	1500	2	64QAM3/4		10
D	141-148.5 (B1) 151 – 161 (B2) 161 – 174.8 (B3)	PmP	10 (40)	600	20 - 40	64QAM3/4	>100	30
D	151 - 174.8	PtP	10 (40)	1000	2	64QAM3/4		45
G	275 - 310	PtP	1-2 (30)	600	2	QSPK		30

is the percentage of time a link operates continuously. Typical requirement is 99.99%. It depends on the maximum rain attenuation expected for 99.99% of the time. In two main ITU (International Telecommunication Union) zones, H and K, the maximum rain rate for 99.99% of the time is 32 mm/h and 42 mm/h respectively. The corresponding attenuation to include in the link budget (above 100 GHz) is about 13 dB/km and 17 dB/km respectively. Humidity attenuation is up to 2 dB/km up to 200 GHz, and higher than 10 dB/km above 300 GHz. Table 1 reports the path loss (Eqn. 2) for different transmission distance. The sum of total antenna gain ($G_r + G_t$) and transmission power has to compensate that path loss to achieve the required SNR for a given modulation scheme.

High transmission power at sub-THz

SSPAs above 100 GHz are well below one Watt (30 dBm) [11]. Assuming 55 dBi total antenna gain for PmP links, their power is not sufficient for range longer than a few tens of meters.

The vacuum electronics offers a solution. Traveling wave tubes (TWT) are wideband amplifiers, normally used in satellite communications, available commercially up to 60 - 70 GHz in small production. Differently from SSPA, the amplification mechanism is based on an electron beam traveling in high vacuum in a specific waveguide (slow wave structure) where the radiofrequency signal propagates. The electron beam transfers part of its energy to the signal by an interaction process. The advantage of electrons traveling in vacuum is the support of much higher voltages than solid state junctions, and consequently higher power and better thermal behavior. TWTs output power is more than one order of magnitude higher than SSPAs at the same frequency.

Recently, a remarkable research effort has been devoted to produce sub-THz TWTs [12] for large scale affordable production. A 92 - 95 GHz TWT with 40W saturated power [13], a 140 GHz TWT with 10 W saturated power [14], and a G-band TWT with 1 W power [10] are reported. To note that as any other electronic device, the power decreases at the increase of frequency. The respective power level of the mentioned three TWTs will be assumed as a reference for defining the specifications for the new concept of sub-THz WTL.

Table 2 shows the performance achievable by using TWTs for the different frequency bands and the distribution modalities on the basis of the L_T in Table 1 (real link condition, 99.99% availability, ITU zone K). It is remarkable the data rate for PtP at D-band and G-band, 45 and 30 Gb/s respectively.

The D-band is regulated by 250-MHz channel

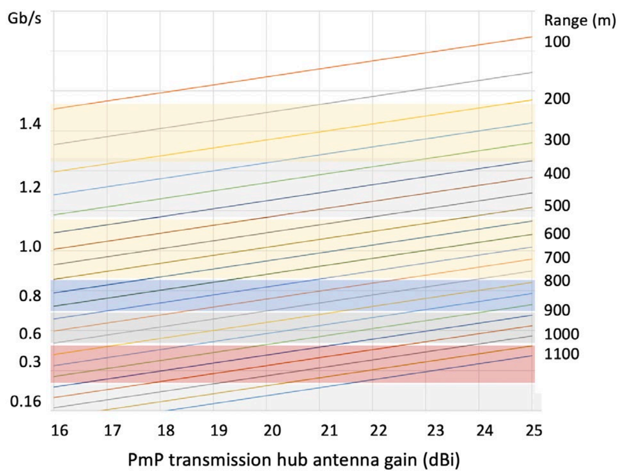

Fig. 1 Data rate for 250 MHz channel as a function of antenna gain and range at 147 GHz.

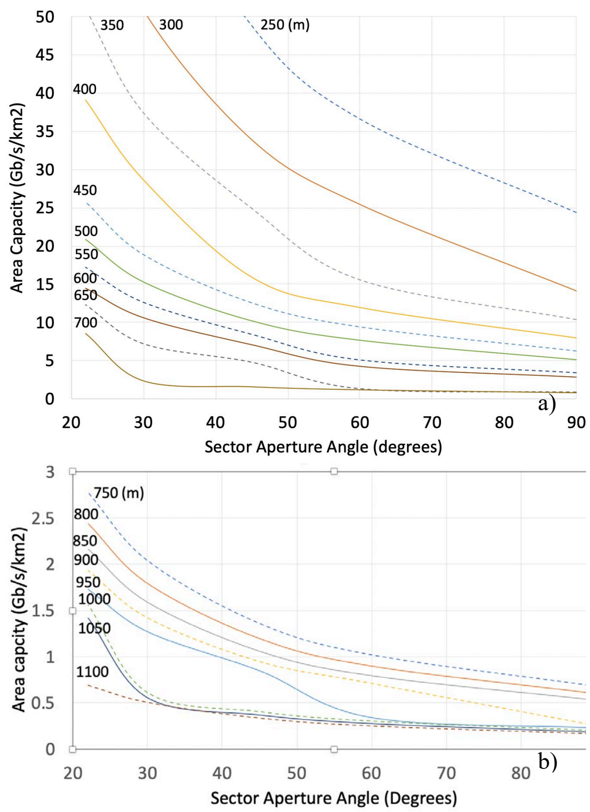

Fig. 2 Area capacity vs. aperture angle and range, a) range 250 – 700 m, b) range 750 – 1100 m.

arrangement [15]. The data rate for a 250-MHz channel (e.g. at 147 GHz), as a function of the transmission hub antenna gain and range is given in Fig. 1. It is derived by estimating the highest modulation order supported by the computed SNR. The different coloured areas represent the SNR range supporting a given data rate. As an example, with 20 dBi antenna gain, 1 Gb/s can be transmitted up to 600 m. Figure 2 shows the area capacity provided by the same 250-MHz D-band channel as a function of sector aperture angle and range. To note the high area capacity per channel at level of tens Gb/s/km^2 for ranges below 600 m. For range longer than 750 m, it is still high, but reduces below 2 Gb/s/km^2. The total area capacity of a sector, given by the area capacity per channel (Fig.2) multiplied by the number of channels, could reach hundreds of Gb/s/km^2. The graphs in Fig. 1 and Fig. 2 permit to quickly dimension the coverage by defining size and capacity for each sector.

Footprint and economy

In addition to performance, equipment footprint and economy are important parameters for the viability of the WTL.

Sub-THz antennas due to the short wavelength (e.g., 2.1 mm at 140 GHz) are much smaller than antennas with the same gain below 100 GHz. This permits to build compact front ends, of about a few cubic decimeters, of easy installation, deployment, low site renting cost.

Presently, sub-THz technology is in fast development, but still expensive [12]. Actual E-band links cost a few thousand Euro. In a few years, sub-THz equipment could reach a) the same cost. Transmission hubs able to replace tens of PtP links will reduce the cost per bit, making the sub-THz WTL an affordable solution. In terms of power consumption per bit, TWTs can reach 40 - 50% Power Added Efficiency (PAE) in comparison to the lower SSPA PAE (<25 - 30%) [11].

DEPLOYMENT SCENARIO

b)

As an example, a scenario of WTL deployment in urban environment (Fig.3) will be discussed. Two fiber access points (F1 and F2) are considered to feed two WTL sub-layers to cover an area of 2.1 x 1.8 km (the other sub-layers needed to cover the full city area are not shown). A sublayer includes one fiber access points (F1), a number of satellite clusters of D-band transmission hubs (S1, S2, S3, and S4) connected to the fiber by PmP G-band links (red). In the following, it is assumed 600 m range for all the links, 30º sectors, 1-Gb/s 250-MHz D-band channel, 1-Gb/s 1-GHz G-band channels in QPSK. Each sector has conservatively allocated 20 channels of the 108 channels available at D-band [15], for a total of 20 Gb/s, with area capacity of about 222 Gb/s/km^2. The cluster of THs at the fiber access point F1 can support any number of sectors with different size, depending on the required coverage, being data directly provided by the fiber. The availability of three sub-bands at D-band (B1, B2 and B3 in Fig.3) permits an effective frequency reuse and space multiplexing. In the architecture in Fig.3, the cluster F1 is assumed with ten sectors, each of them with 20 Gb/s (200 Gb/s total aggregated capacity) and 222 Gb/s/km^2 area capacity. To note that 200 1-Gb/s channels are provided by only 10 transmission hubs, instead of 100 - 200 PtP front ends.

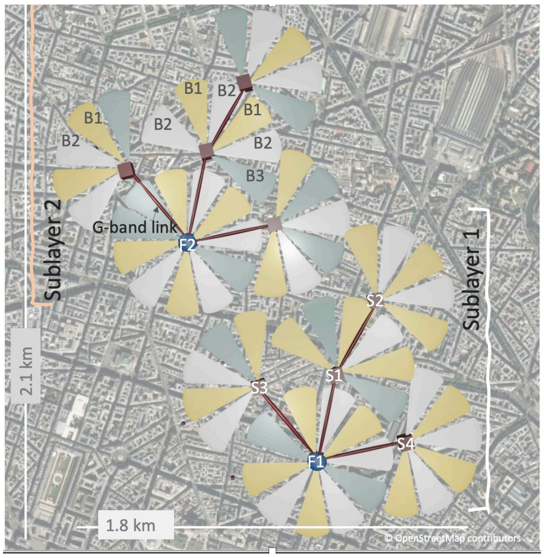

Fig. 3 Deployment of wireless transport layer in urban scenario (top view). F1, F2 fiber access points; S1, S2, S3 and S4 D-band clusters: B1,B2 and B3 D-band sub-bands. G-band links in red.

G-band links can transport e.g. about 30 Gb/s for 600 m by 30 GHz bandwidth (275-305 GHz). The cluster S3 will deliver 6 Gb/s per sector, with 67 Gb/s/km^2. The clusters S1 (6 sectors) and S2 (5 sectors) share the same G-band link, so each of them can distribute averagely about 15 Gb/s, with 3 channels per sector with about 33 Gb/s/km^2. More PtP G-band links at different frequency (e.g., 210 - 240, 240 - 275 GHz) can be used to increase the area capacity.

The channel allocation and the size of the sectors permits a full flexibility in terms of coverage and area capacity. Range and aperture angles of sectors can be arbitrary, so sectors can be adapted to the rooftop landscape and capacity requirements

Links at D-band instead than at G-band (Table 2), could be considered to connect the satellite clusters to increase range and capacity, if the architecture allows it. W-band links can be used when relatively low capacity over a wide area is needed. The layer architecture is robust to interferences by using frequency division alternating the various frequency sub-bands. The strong signal attenuation at sub-THz provides also a good "space division". It is notable that the high flexibility of the WTL permits to cover practically any traffic and coverage request.

CONCLUSIONS

The sub-THz wireless transport layer is a promising and effective solution for ubiquitous and malleable internet to support applications, systems, communications protocols and big communications that will be the core of 6G. The availability of tens or hundreds Gb/s/km^2 area capacity is tightly linked to technology developments. The availability of sub-THz TWTs will open scenarios so far not feasible due to the solid state amplifier limits. The development of technology for enabling the sub-THz WTL is in progress.

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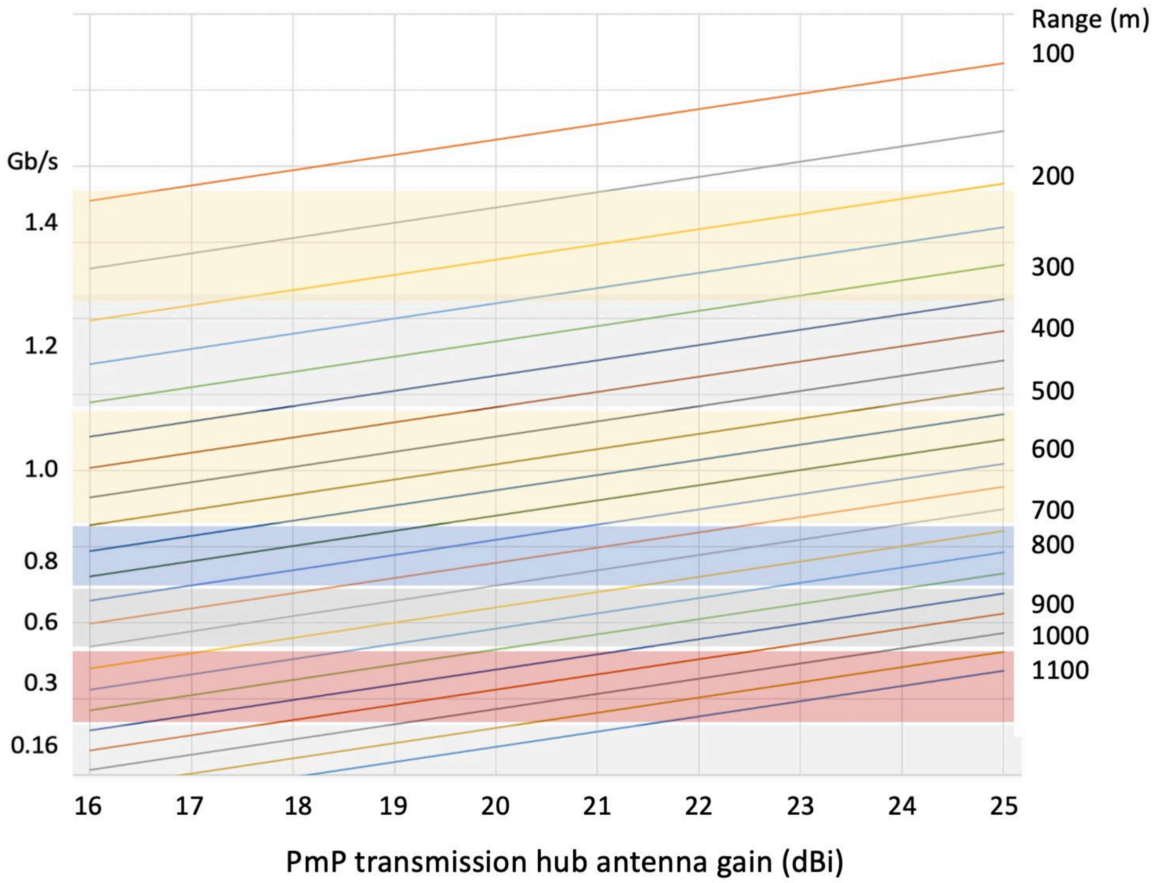
Claudio Paoloni [SM'11], since 2012, has been Cockcroft Chair with the Engineering Department, Lancaster University, U.K. Since 2015, he has been the Head of Engineering Department. He is member at large of the Board of Governor of the IEEE Electron Devices Society and was Chair of the IEEE EDS Vacuum Electronics Technical Committee. He is coordinator of two European Commission Horizon 2020 projects, TWEETHER and ULTRAWAVE. He is author of more than 240 articles in journals and international conferences in the field of sub-THz vacuum electronics and wireless communications.



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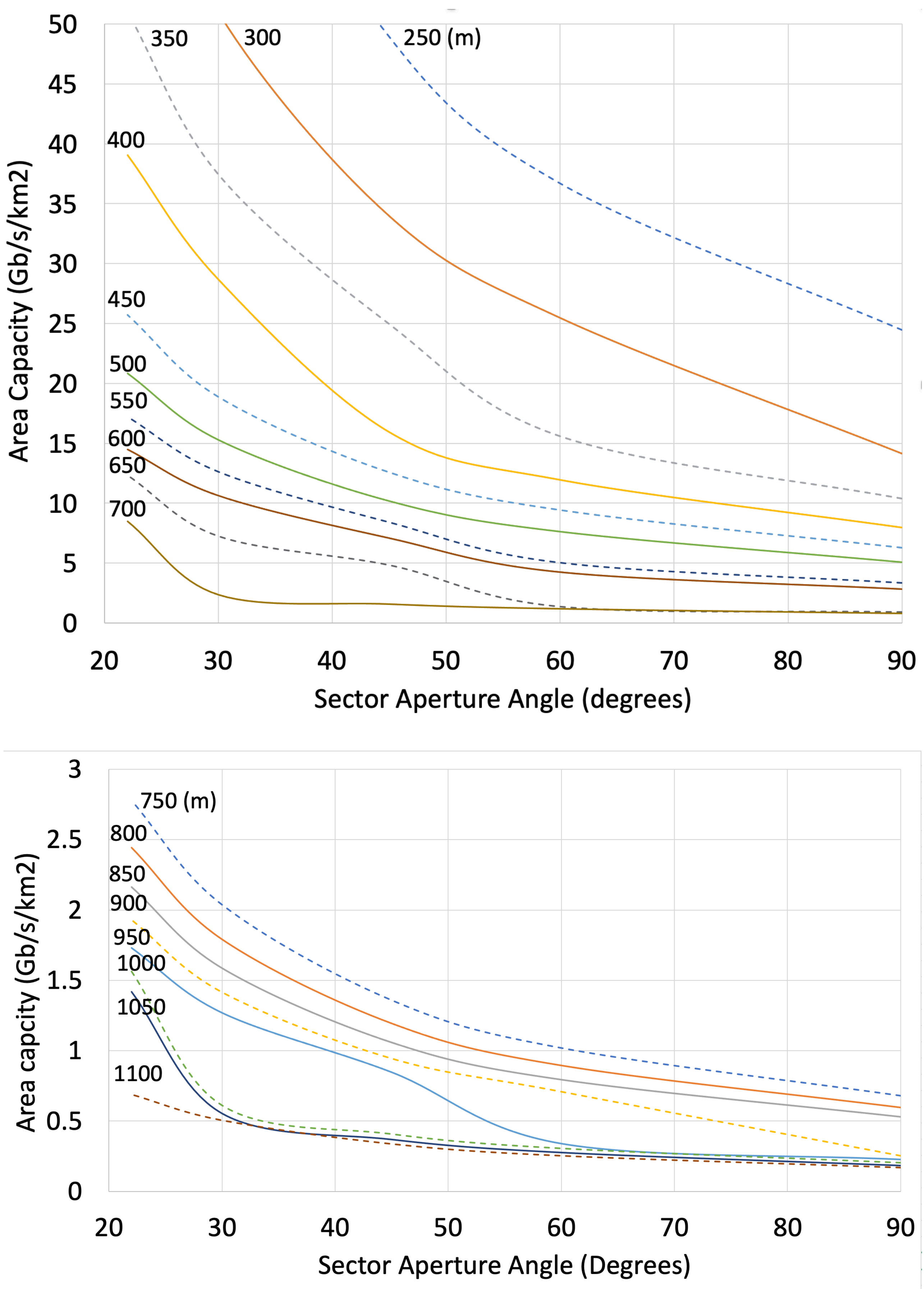

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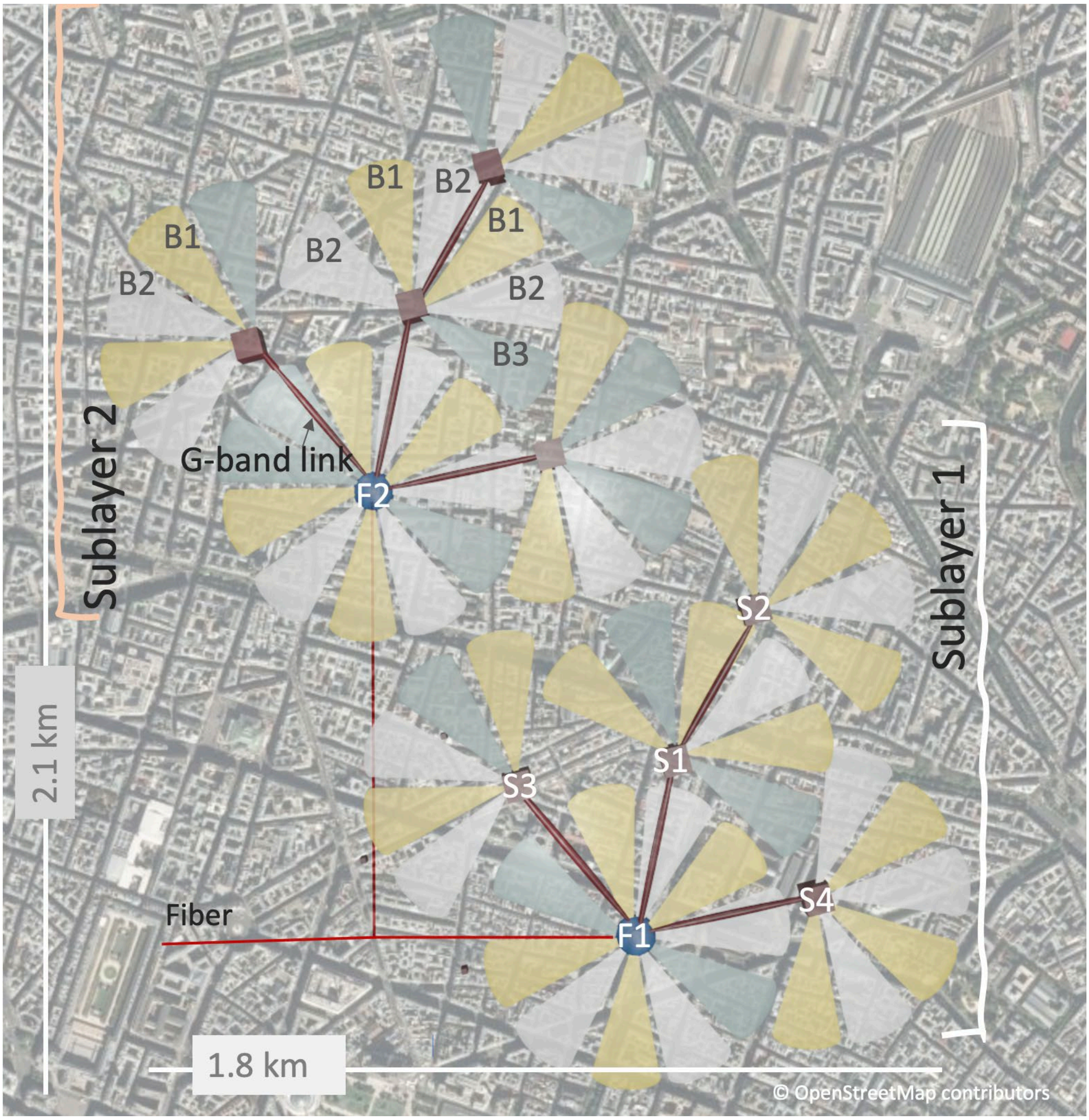

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