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RESEAUX DU FUTUR : 5G ET AU-DELA

Investigating Sub-THz PHY Layer for Future High-data-rate Wireless Backhaul

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Abstract

Spectrum above 90 GHz is a promising investigation domain to offer future wireless networks with performance beyond IMT 2020 such as 100+ Gbit/s data rate or sub-ms latency. In particular, the huge available bandwidth can serve the backhaul transport network in the perspective of future ultra-dense deployments, and massive front-haul data streams. This paper investigates the feasibility and characteristics of the sub-THz mesh backhauling either installed in the streets or inside a large venue. The study relies on the highly realistic simulation of the physical layer performance, based on detailed geographical representation, ray-based propagation modelling, RF phase noise impairment, and a new modulation scheme robust to phase noise. It is shown that each link of a dense mesh backhaul network can reliably deliver several Gbit/s per 1-GHz carrier bandwidth.

1 Introduction

The long-term limitations of 5G standards are stressed already by the telecommunication industry and community research, for e.g. the delivery of ultra-low-latency broadband services, or the emergence of ubiquitous intelligence [1]. Next-generation wireless networks are imagined to be faster (1 Tbps for instance), more reactive (sub-ms latency), ultra-reliable and denser, thus allowing for very accurate positioning, highly-immersive experiences, smarter autonomous objects, etc. The exploitation of new and wider bandwidths at higher frequencies is an obvious and promising solution towards significantly increased data rates and capacity in beyond-5G or 6G communication systems. The “sub-THz” spectrum from 90 to 300 GHz is definitively identified as a key enabler. An aggregated bandwidth of 58.6 GHz was identified in [2] as possibly available for terrestrial radio-communications between 90 and 200 GHz. Elaboration of future sub-THz systems is facing many challenges in particular at the PHY layer such as the strong propagation losses, or the increased phase noise (PN) w.r.t mmWave band, which are both considered in this paper. Due to the strong propagation constraints, the short-range connectivity is a relevant sub-THz target application. However, the huge available bandwidth can also serve the backhaul transport network, and offer the future capacity required by cloud-RAN, ubiquitous AI (artificial intelligence), etc. That is why the authors explore the feasibility, reliability and achievable data rates of such a backhaul solution, with specific focus on the propagation impact.

First, the paper addresses the design of robust communication from both receiver and transmitter perspectives. The optimum symbol detection criterion and the corresponding probabilistic demapper is derived for PN channel upon the maximum likelihood (ML) decision rule. We also propose a PN robust modulation scheme defined upon an efficient and structured constellation, adaptable to any signal-to-noise ratio (SNR) and PN variance. Second, the propagation channel properties are characterized and modelled to achieve a realistic evaluation of the proposed modulation. Only few sub-THz channel sounding campaigns have been published yet, as the equipments are new, complex and costly. Those recently realized inside a commercial hall [3], various indoor environments [4], a data center [5] or for outdoor-indoor penetration [6] are bringing valuable data that confirms the clear line-of-sight predominance, the channel sparsity and strong attenuations. Numerical simulation is a convenient solution to produce on-demand channel samples for any kind of scenario. The Volcano ray-based model [7], which has been updated up to the sub-THz frequencies, is employed in the present study to predict the propagation in two backhaul use cases: in-street outdoor, and inside a large venue. The performance of the proposed modulation scheme has been assessed considering this propagation data combined with highly-directive antennas and different phase-noise conditions.

The PN characterization and proposed modulation scheme are presented in section 2. The ray-based propagation model is described in section 3. Then both techniques are combined in section 4 to evaluate the performance of wireless outdoor and indoor backhaul scenarios. A conclusion is given in section 5.

2 Phase Noise and Proposed modulation

Oscillator PN in communications systems arises from the integration and amplification of noise sources within the circuitry by the phase-locked loop (PLL). Due to integration, PN presents a cumulative nature. Under the assumption that the oscillator is only subject to thermal noise, the oscillator PN is described with the superposition of a cumulative Wiener process (a Gaussian random-walk) and an uncorrelated Gaussian one. These stochastic processes respectively express the integration and amplification within the PLL of thermal noise. The spectrum of oscillator PN is in this case described by a colored characteristic (Wiener PN) and a white noise floor K_0 (Gaussian PN). However, it has been shown in [8] and confirmed in [9] that the impact on communication performance of the Wiener PN is negligible in comparison to the Gaussian in case of large bandwidth systems. Subsequently, for sub-THz systems, the impact of oscillator PN on received symbols may be efficiently modeled with a Gaussian distribution. That is

$$r = s \cdot e^{j\phi} + n,\ \phi \sim N(0, \sigma_p^2),$$

where r is the received symbol, s is the modulated one, ϕ is the oscillator PN, and n is the thermal noise with spectral density N_0. In the rest of the paper, a medium PN level has been considered with $\sigma_p^2 = 10^{-2}$. This corresponds to a floor noise spectral density of -110 dBc/Hz for a channel bandwidth of 1 GHz.

The design of the optimum modulation scheme for the PN channels has been largely investigated in the literature [10]. However many works derive complex optimization problems to determine the shape of a constellation, we have consider a pragmatic approach supported by a theoretical framework. Under a high-SNR assumption, it can be demonstrated that the PN channel in the polar domain (amplitude/phase) is highly similar to an additive white Gaussian noise channel in the complex plan [11]. It follows that the optimum modulation, *i.e.* minimizing the symbol error probability, is the constellation that maximizes the minimum distance. Then for a fixed modulation order and average power, characterizing the optimal constellation may be interpreted as finding the densest sphere packing in the polar domain. Therefore, the optimal constellation is defined upon an hexagonal lattice in the polar domain. Nevertheless, for implementation considerations, it is relevant to exploit a rectangular lattice since the corresponding demodulation and binary labelling are greatly simplified with minor loss in performance. As a result, we propose the polar quadrature amplitude modulation (P-QAM) that will be considered as the modulation scheme throughout the performance assessment.

3 Ray-based sub-THz modelling

The Volcano ray-based propagation channel model has recently been extended to support the sub-THz spectrum between 90 and 300 GHz [7], and serves in the assessment of new technologies and scenarios. Comparison to measurements has not been possible yet. However, the predicted mechanisms rely on a physical calculation approach -Fresnel reflection, Uniform Theory of Diffraction (UTD) and knife-edge diffraction-, which are already exploited and validated in the 5G millimeter-wave (mmW) spectrum. Major mmW trends are supposed to persist: diffractions become negligible; critical blockage may come from environment details, in particular furnitures and trees; reflections are still strong except when impacted by local surface roughness.

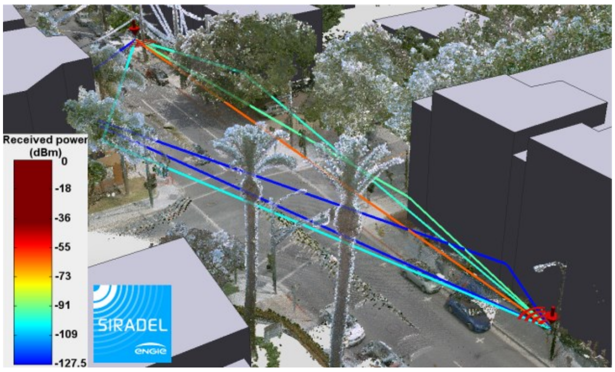

Figure 1: Propagation path withing LiDAR data

Parameter	Outdoor node-to-node	Indoor node-to-node	Indoor node-to-relay (DL)
Frequency band		150 GHz	
Signal BW		1 GHz	
Tx power/ch.	1 W	0.1 W	0.1 W
Tx antenna		25.0 dBi	
Rx antenna	25.0 dBi	25.0 dBi	8.0 dBi
Th. noise floor		-84.0 dBm	
Noise figure		10.0 dB	
Rx sensibility	-98.2 dBm	-98.2 dBm	-81.2 dBm
Implement. loss		3.0 dB	
Rain	12.5 mm/h	N/A	N/A
Adj. factor		[-5;+5] dB	

Table 1: System parameters

The validity range of the ITU attenuation models for rain and atmospheric gas [12], which are implemented in Volcano, includes the target sub-THz frequencies. Besides, the update of the dielectric materials properties (permittivity and conductivity) has been done by following a non-rigorous approach. In absence of reliable and generic sub-THz figures, we have decided to extend the application range of the ITU dielectric values [13 – Table 3] beyond the recommended upper limit, typically 100 GHz.

Volcano predicts 3D ray-paths from the combination of multiple reflections, transmission and diffractions, based on a fast ray-launching technique, the UTD and knife-edge diffraction coefficients. It applies to outdoor, indoor and mixed environments. As illustrated in Fig. 1, for the outdoor scenario presented in this paper, Volcano is taking benefit of a LiDAR point cloud representation. This data allow the model to evaluate the blockage and transmission losses due to the trees and street furniture in a more realistic way compared to conventional geographical database.

4 Backhaul evaluation result

4.1 System parameters

Mapping between SNR levels and spectral efficiency is derived from the previously described P-QAM modulation scheme and following assumptions. A perfectly synchronized single-carrier modulation is considered. The channel phase shift is perfectly estimated and corrected. A Forward Error Correction (FEC) scheme based on the 5G-NR LDPC with an input packet size of 1500 bytes is considered with a coding rate ranging from 0.3 to 0.9. The performance of the physical layer were first assessed to determine the best set of parameters: coding rate, modulation order and modulation shape given the SNR, the PN level and the targeted packet error rate of 10-2. Resulting spectral efficiency goes from 0.6 bps/Hz at -0.8 dB SNR, to 7.2 bps/Hz at 29.7 dB SNR.

The system is operating in the 150 GHz band, with a bandwidth of possibly several tenths of GHz, divided in 1-GHz channels. The effective bandwidth of the signal is 800MHz with a 20% overhead due to the control plane. The maximum reachable throughput is then 4.6 Gbps/channel. Parameters regarding the transmit power, antenna, and link budget are given in Table I for each simulated scenario. The adjustment factor in the last row of the table is used as a varying parameter to evaluate the sensibility of the simulated system to any change or uncertainty in the link budget. As an exemple, a positive adjustment can be used to assess the impact of a larger transmit power or reduced noise figure.

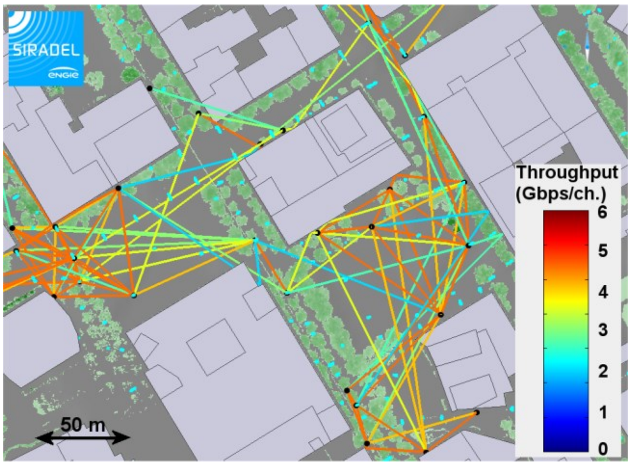

Figure 2 : Mesh links in the outdoor backhaul network

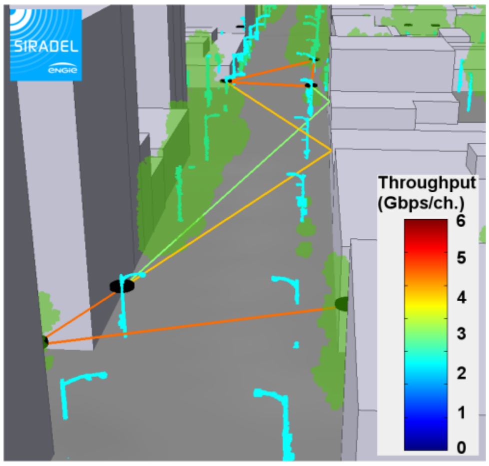

Figure 3 : Direct and indirect connections

4.2 In-street scenario

The in-street backhaul scenario is run in a dense-urban densely-vegetated environment, actually in San José downtown, California. The digital geographical data is composed of 3D vector buildings and a point cloud LiDAR data that includes trees and furnitures such as lampposts.

A subset of 134 lampposts in this area is used as virtual sub-THz device positions. Antennas are localized at 8 meters above the ground. All possible lamppost-to-lamppost links with range lower than 200 meters are computed at frequency 150 GHz, leading to a total of 1873 predicted links. First, the link visibility is determined: 136 line-of-sight (LoS) links; 553 vegetation obstructions; and 1204 building obstructions. A total of 585 links have sufficient SNR to establish a connection if antennas at both ends are perfectly aligned on the strongest propagation path. Fig. 2 shows the simulated connections with their achievable throughput in part of the study area; maximum throughput can be reached in clear LoS, while the vegetation significantly degrades the performance. We note that a few connections are allowed in building shadowed area due to indirect paths. Fig. 3 zooms on some particular links and displays the main propagation paths, either line-of-sight or reflected along a trajectory out of any tree's obstruction.

Fig. 4 gives statistics on the achievable throughput versus the distance between antennas, and for two different situations: 1) in case of LoS or tree's obstruction; 2) in case of a building obstruction (NLoS). In first case, 98% links with range below 25 meters reach a peak throughput greater than 4 Gbps/channel; the percentage drops to 81% and 52% for respectively the ranges]25;50] and]50;75] meters, due to more likely and longer obstructions. It further decreases below 35% when the range is longer than 75 meters. This result demonstrates that sub-THz hops longer than 75 meters can provide more than 4 Gbps/channel, but need to be carefully chosen, based on an accurate knowledge of the environment. Fig. 4 also gives the statistics for the Non-LoS links, and shows that indirect propagation paths can sometimes lead to high-throughput links, in particular for ranges below 75 meters, which may be very useful for creating a link between orthogonal streets or as a backup connection. Finally, in the last 175-200 meters range, the performance is strongly degraded for most of the predicted links; high-throughput connection is hardly possible.

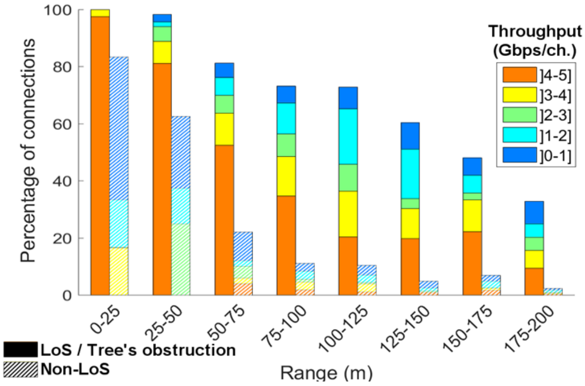

Figure 4: Percentage of links reaching a given throughput vs. distance.

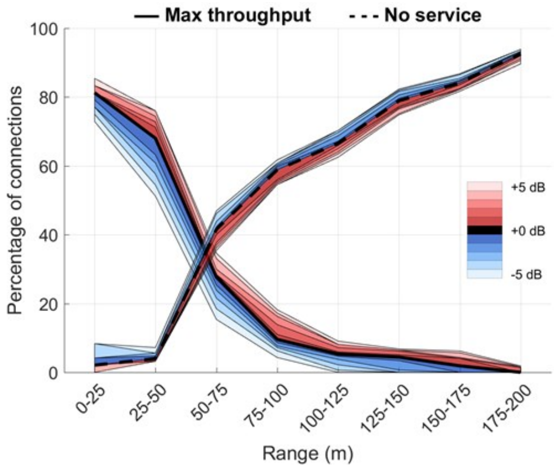

Figure 5: Percentage of links reaching a given throughput vs. link budget gain.

The sensitivity of those results to the considered link budget parameters is illustrated in Fig. 5, where the percentage of connections is plotted as a function of the distance and an additional gain in range [-5;+5] dB. A 4 dB adjustment in the link budget leads to 100% connection in the]0-25] meters range, while 8% links in same range are losing connection with -5 dB adjustment. Besides, the [-5;+5] dB gain converts into maximum 25% variation in the high-throughput connection rate, as observed in the]25-50] meters range.

Link diversity is a critical factor for reliability of such a network in order to optimize routing, to minimize interference, but also to combat temporary blockage on the best propagation path. In this study, the link diversity has been characterized by counting the average number of available connections per node. Fig. 7 gives the average number of connections as a function of a target peak throughput, and for both kinds of alignment approaches. As an example, the average number of connections above 1 Gbps/channel at any node of the backhaul network is 5.1, when the system aligns on the strongest path. Some improvement is observed when comparing the strongest-path alignment to the direct-path alignment; however, the clear direct propagation path is often the dominant component.

4.3 Large venue scenario

The sub-THz transport network could also be deployed as a complement to the optical fiber inside large venues, e.g. airports, railway stations, stadium, campus, or commercial halls. While the optical fiber is distributing strong capacity in the different blocks of the venue, the wireless mesh backhaul may be the final link to some fixed, portable or even mobile (e.g.. flying) access points. If combined with efficient auto-alignment and dynamic routing algorithms, the sub-THz transport layer can adapt to changes e.g. related to densification, maintenance, event, or construction works.

The strong obstruction losses oblige the sub-THz hops to be deployed in a clear space, typically in large rooms or open areas, above most furniture and bodies. Fiber relays can be used to extend the network coverage to another room.

The evaluation study is carried out in a model of commercial hall. Fig. 6 shows the two-floor 120m□80m building, which is composed of a large entrance area, large alleys with few obstacles (booths, vegetation, and pillars), and a succession of shops. Each floor is five meters high. A mesh sub-THz network has been designed to feed the wireless access points located at the first floor and entrance area. Two different kinds of access points are considered: those inside the shops, which require a sub-THz relay to be positioned on the outer surface of the shop window; and those connected to a portable/mobile sub-THz relay installed outside the shops.

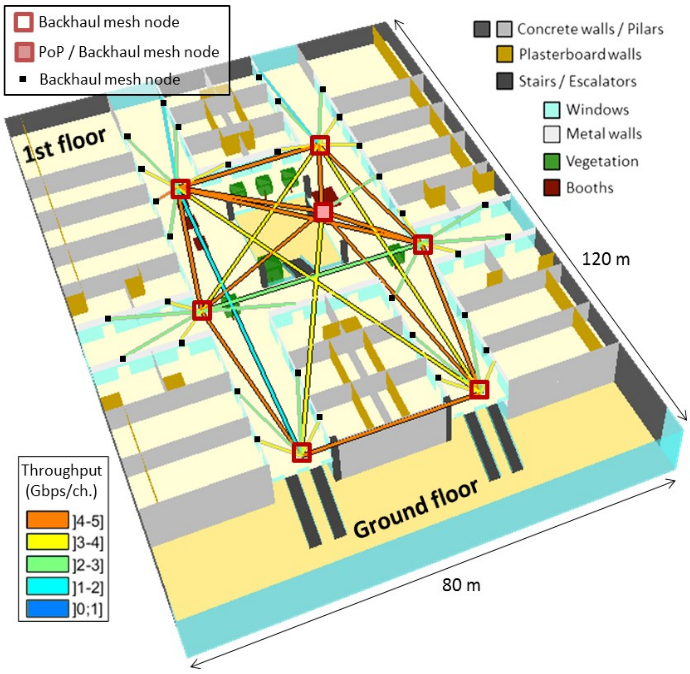

Figure 6: Main connections between mesh nodes, and to the shop-relays

The sub-THz backhaul network is composed of 6 mesh nodes at height 4 meters, i.e. below the cables, pipes or lights installed below the roof, but above most ground obstacles; one of those nodes is directly connected to a fiber Point of Presence (PoP). The following kinds of radio link are evaluated: 1) node to node; 2) node to the fixed shop relays at height 4 meters; 3) node to any portable/mobile relays at height 2 meters. The sub-THz system parameters are given in Table I. The propagation model is enabling a maximum of two reflections and one diffraction along each ray path. Reflections on the ceiling or floor surfaces are not allowed as they are likely to be obstructed. Shop windows are assumed as opaque surfaces for the considered frequency.

The peak throughput on each radio link is predicted in two different ways: either the antennas are aligned on the direct-path, or aligned on the strongest propagation path. Fig. 7 depicts the latest calculated throughput for all mesh connections and the best shop-relay connections. Every mesh node is linked to the PoP with maximum two hops having a peak throughput greater than 4 Gbps/channel. All shop-relays are attached to the mesh network with more than 2 Gbps/channel peak throughput.

The right plot in Fig. 8 indicates how many different propagation paths can be used by the system (with automatic antenna alignment) to connect a node and reach a given peak throughput level. When aggregating all paths from all neighbor mesh nodes, the average number of potential paths that offer more than 1 Gbps/channel at a mesh node is 123, which might guarantee very good service availability.

Finally, the sensitivity of those results to the considered link budget is illustrated in Fig. 8, where the average number of connections is plotted as a function of an adjustment factor in range [-5;+5] dB. The shop-relays reliability is significantly affected by this adjustment factor. The average diversity at 2 Gbps/channel is 1.8 with initial settings; it goes to 3.6 when adding 5dB, and degrades to 1.2 when removing 5 dB. Besides, thanks to many LoS links and strong reflections, the considered mesh network remains viable with 5dB degradation but still 3.4 connections per node.

5 Conclusion

The presented simulation studies demonstrate the feasibility of sub-THz mesh backhaul networks, using a PN-robust modulation scheme, and considering real propagation constraints. This study shows the potential of the sub-THz technology to reach multi Gbps link in indoor and outdoor in-street typical scenarios. This work must be continued for other applications such as kiosks or hotspots, considering other antenna configurations and propagation constraints.

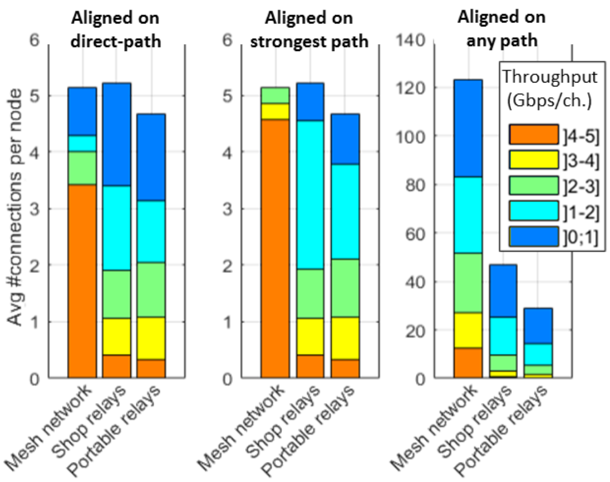

Figure 7: Number of connections per throughput range

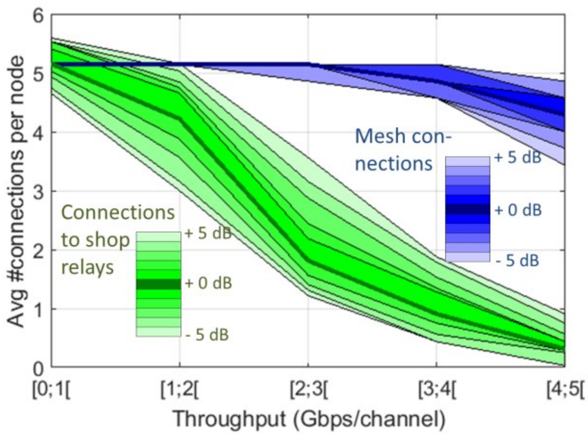

Figure 8: Number of connections per throughput range vs. link budget adjustment

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