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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 in-street sub-THz mesh backhauling. 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. The achievable throughput is studied, and it is shown that each link of a dense mesh backhaul network can reliably deliver several Gbit/s per 1-GHz carrier bandwidth. The multi-path diversity is assessed, as well as the impact of rainfall and phase noise level.

Keywords. Sub TeraHertz, Backhaul, Propagation model, Modulation, Physical layer, 6G.

Available online 6th May 2021

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

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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 channel with PN 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 in-street propagation. 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 backhaul links: throughput versus range, multi-path diversity, robustness to rainfall and phase noise. A conclusion is given in Section 5.

2. Phase noise and proposed modulation

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 K0 (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

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

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 with $\sigma_p^2 = 10^{-2}$ or a strong PN level with $\sigma_p^2 = 10^{-1}$ have been considered. This corresponds to a floor noise spectral density $N_0 = -110$ 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 considered a pragmatic approach supported by a theoretical framework. Under a high-SNR assumption, it can be demonstrated that the channel with PN in the polar domain (amplitude/phase) is highly similar to an additive white Gaussian noise channel in the complex plane [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 [12] that will be considered as the modulation scheme throughout the performance assessment.

3. Ray-based sub-THz modelling

The Volcano ray-tracing 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. Only few measurements have been published at those frequencies, e.g. [4]. 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 (mmWave) spectrum. Major mmWave trends are supposed to persist: diffractions become negligible; critical blockage may come from environment details, in particular furniture and trees; reflections are still strong except when impacted by local surface roughness.

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. Both the transmission through the vegetation and the diffraction on bottom and top of the foliage are considered. The transmission is computed from an average linear loss (dB/m) that is multiplied by the propagation length inside the foliage. As illustrated in Figure 1, Volcano does support LiDAR point cloud data for outdoor predictions. 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.

The ray-tracing simulations, using LiDAR data, have been compared to in-street point-to-point measurements carried out with a Terragraph beamforming equipment at 60 GHz [13]. It was shown that with a precise representation of the trees and a proper calibration of the vegetation linear loss, the simulator can reproduce similar path-loss and channel properties (i.e. same propagation path sparsity) as observed in the measurements.

Some of the ray-tracing parameters and calculation methods are derived from ITU recommendations. The validity range of the ITU attenuation models for rain and atmospheric gas [14] encompasses the considered sub-THz frequencies. However, the application range of the ITU dielectric material properties, such as permittivity and conductivity, is not covering the sub-THz domain [15] (Table 3). We then have decided to employ the existing values beyond the recommended upper limit, which is typically 100 GHz, as in absence of any other simple alternative, this might be an acceptable assumption for exploration and preliminary studies.

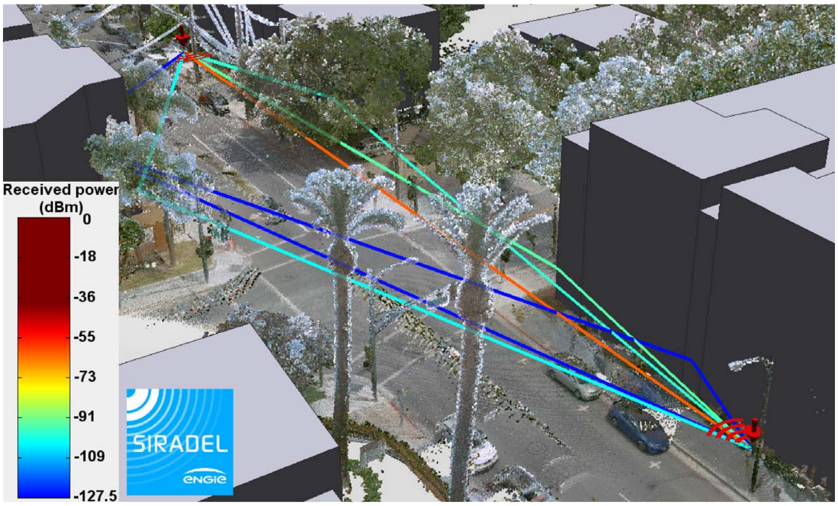

Figure 1. Multi-path propagation considering fine 3D tree's representation.

4. In-street backhaul evaluation

4.1. *System parameters and scenario*

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

The in-street backhaul scenario is run in a dense-urban densely-vegetated environment, San José downtown, California. The digital geographical data is composed of 3D vector buildings and a point cloud LiDAR data where trees and main street furniture e.g. lampposts are identified. A subset of 134 lampposts in this area is used as virtual sub-THz device positions. Antennas are localized at 8 m above the ground. All possible lamppost-to-lamppost links with range lower than 200 m are computed at frequency 150 GHz, leading to a total of 1873 predicted links.

4.2. *Performance evaluation*

The visibility conditions is first determined for each node-to-node link: 136 line-of-sight (LoS) links; 553 vegetation obstructions (Obstructed-LoS or OLoS); and 1204 building obstructions

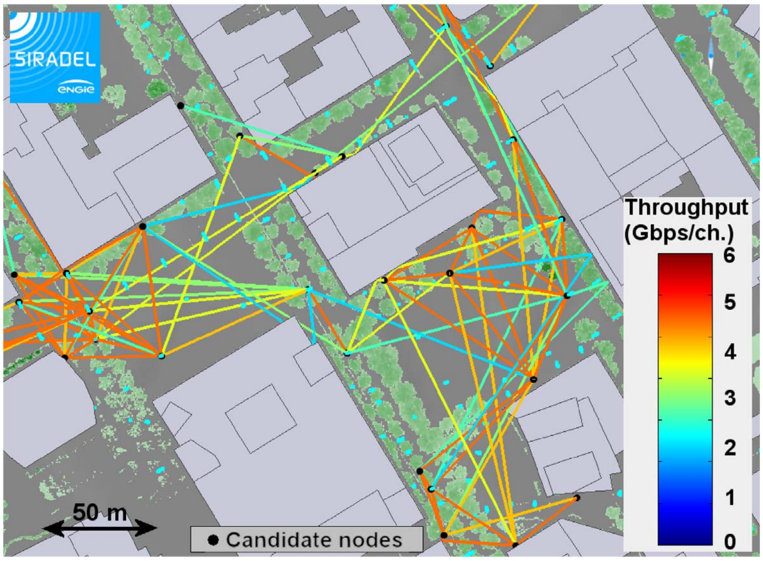

Figure 2. Mesh links in the outdoor backhaul network.

Table 1. System parameters

Parameter	Value
Frequency band	150 GHz
Channel BW	1 GHz
Tx power/ch	1 W
Tx antenna	25.0 dBi
Rx antenna	25.0 dBi
Th. noise floor	−84.0 dBm
Noise figure	10 dB
Rx sensibility	−98.2 dBm
Implementation loss	3.0 dB
Default rainfall rate	12.5 mm/h
Default PN level	Medium ($\sigma^2 = 10^{-2}$)
Adjustment factor	[−5;+5] dB

(Non-LoS or NLoS). 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. Figure 2 shows the simulated connections with their achievable throughput in one 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. Figure 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.

Figure 4 gives statistics on the achievable throughput versus the distance between antennas, and for two different situations: (1) in case of LoS/OLoS visibility; (2) in case of a NLoS building obstruction. In first case, 98% links with range below 25 m reach a peak throughput greater than 4 Gbps/ch; the percentage drops to 81% and 52% for respectively the ranges]25;50] and]50;75] m, due to more likely and longer obstructions. It further decreases below 35% when the range is longer than 75 m. This result demonstrates that sub-THz hops longer than 75 m can provide

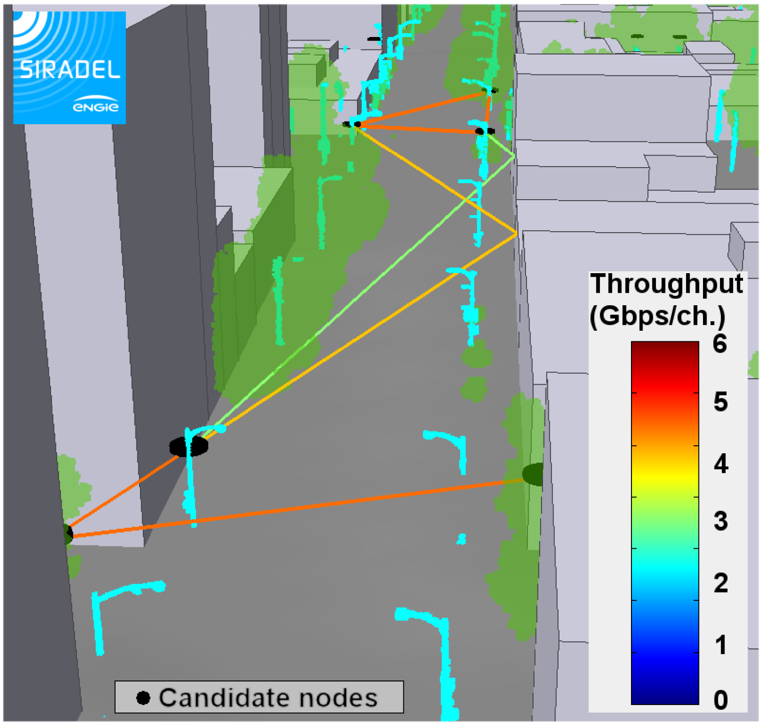

Figure 3. Direct and indirect connections.

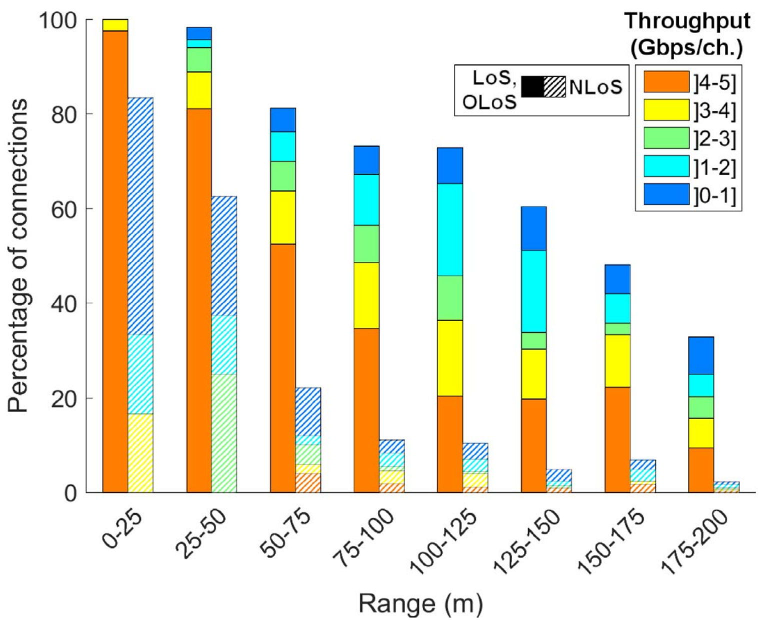

Figure 4. Percentage of links reaching a given throughput versus distance.

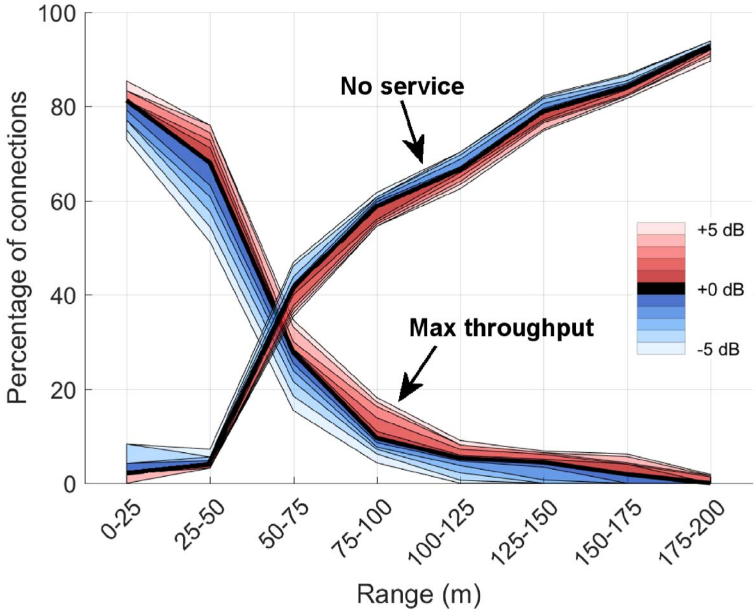

Figure 5. Percentage of links reaching a given throughput versus link budget gain.

more than 4 Gbps/ch, but need to be carefully chosen, based on an accurate knowledge of the environment. Figure 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 m, which may be very useful for creating a link between orthogonal streets or as a backup connection. Finally, in the last 175–200 m range, the performance is strongly degraded for most of the predicted links; high-throughput connection is hardly possible.

The sensitivity of those results to the considered link budget parameters is illustrated in Figure 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] m 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] m range.

Figure 6 indicates how many different propagation paths can be used by a node-to-node link in order to get connected, assuming the system is able to automatically align the Tx/Rx antenna beam towards the right departure/arrival directions. This result was computed from all links in range 0–200 m, whatever the visibility situation, but with a non-zero data rate. About 50% of those links do have a single connection path (due to the propagation channel sparsity), while respectively 30% and 10% of the links benefit from 2 or 3 possible connections paths. This number is actually a kind of diversity indicator. Depending on the communication system, the available diversity may be exploited in different ways, either for overcoming an obstruction on the dominant path, or optimizing the routing and inter-link interference, or transmitting several data streams on separated beams. We imagine the links with more than one possible connection path are better candidates when designing a network.

Finally, we have studied the impact of the rainfall rate on the link performance. Previous results were obtained for a rate of 12.5 mm/h, which is exceeded for approximately 0.1% of the time over a year. The same simulation was run for a clear weather and a 30 mm/h rate (0.01% of the time). The resulting throughput statistics are plotted as a function of the distance in Figure 7,

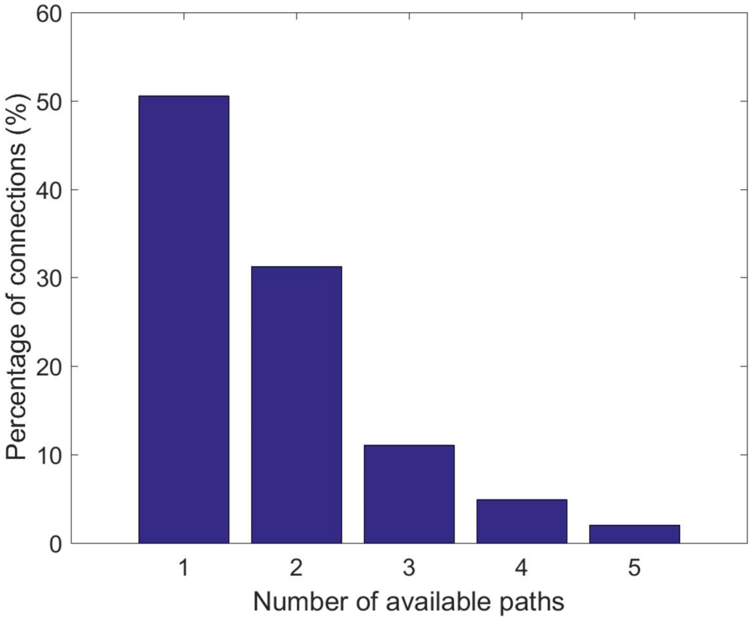

Figure 6. Statistics on the path diversity.

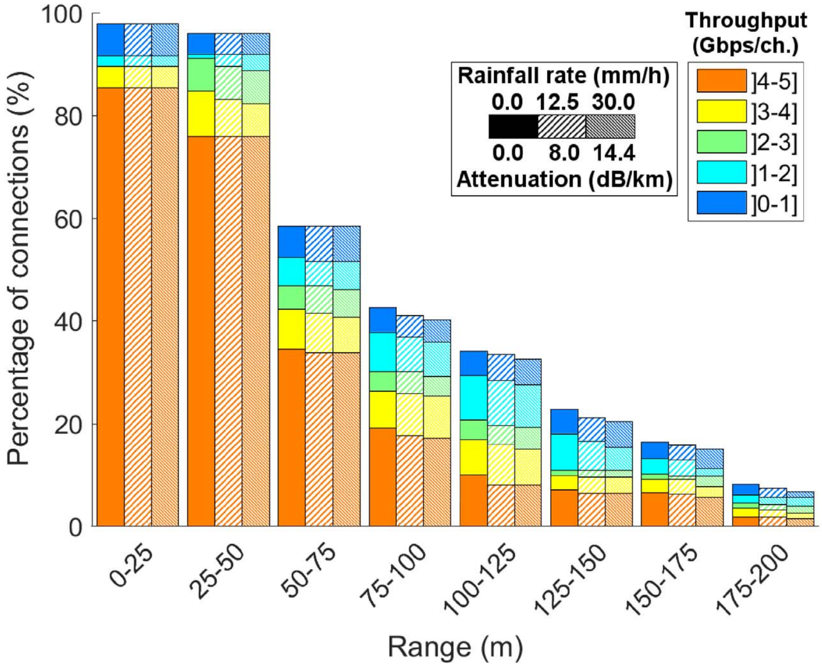

Figure 7. Impact of the rainfall rate on the achieved throughput.

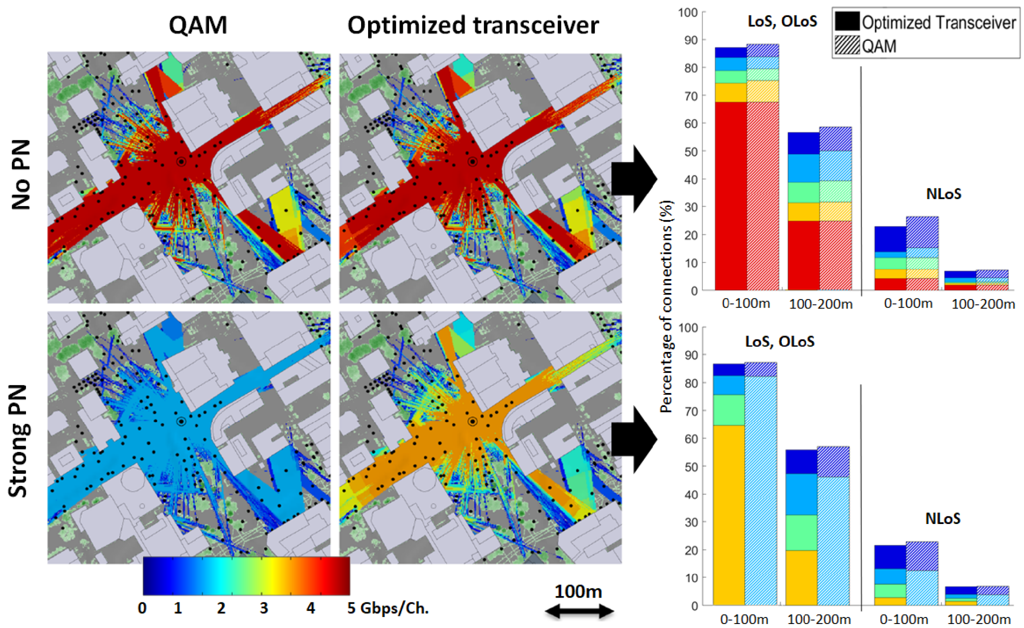

Figure 8. Performance for different PN levels and modulation schemes.

and compared. The different visibility conditions are not distinguished here (contrary to Figure 4) in order to make the illustration more compact. We observe the rainfall rate has no impact on the achievable throughput at ranges below 25 m, which is normal as the attenuation is proportional to the distance. Throughput degradation increases with the range, as expected, but it remains small. When assessing the link performance at such ranges below 200 m, the rain attenuation may be considered, but is obviously not a dominant factor. Precise knowledge of the geographical environment, presence of trees, or antenna misalignment issues, are more critical aspects.

4.3. *Impact of the phase noise level*

The phase noise (PN) level at the receiver might strongly affect the sub-THz backhaul link performance, and the modulation scheme must be appropriately selected depending on its robustness against PN impairments. Those considerations are illustrated in Figure 8, where coverage maps and throughput statistics are obtained with either no PN or strong PN ($\sigma_p^2 = 10^{-1}$), based on the traditional QAM or proposed P-QAM (named as the "optimized transceiver" in the figure). The coverage maps have been computed from a central transmitter node to any surrounding receiver pixel at 8 m above the ground (remark the lampposts i.e. candidate node positions are represented by black circles). And the throughput statistics were simulated from the same links as presented above in the article. The QAM does slightly overperform the P-QAM modulation in absence of any PN, with 2% more connected links in average. Same kind of improvement is observed under strong PN conditions, but then, the achievable throughput is limited below 2 Gbps/ch, while 64% of the LoS or obstructed-LoS links at ranges up to 100 m can still reach between 3 and 4 Gbps/ch thanks to the P-QAM optimization.

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 outdoor in-street typical scenarios, even in presence of strong phase noise. It is also observed that 50% of connected links have some multi-path diversity, which may be used for improving the capacity or protection of the network. The rainfall attenuation is found to have limited impact when radio links have a range inferior to 200 m. And finally, the simulation illustrates the benefit of the P-QAM modulation, which permits a large amount of links to reach a throughput greater than 3 Gbps/1 GHz channel in presence of strong PN impairments.

This work does continue today, with objective to demonstrate, dimension and assess future sub-THz mesh backhaul infrastructures.

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