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► To cite this version:

Laurent Maviel, Yoann Corre, Grégory Gougeon, Djamel Amar. Analysis of Residential Sub-THz Deployments from Accurate Radio Simulations and Planning Techniques. EuCAP 2022:16th European Conference on Antennas and Propagation, Mar 2022, Madrid, Spain. hal-03608910

HAL Id: hal-03608910

<https://hal.science/hal-03608910>

Submitted on 15 Mar 2022

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Analysis of Residential Sub-THz Deployments from Accurate Radio Simulations and Planning Techniques

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Abstract— High-capacity bandwidth makes sub-THz spectrum a key element of beyond-5G or 6G networks. However wireless communications at frequencies such as in W-band, D-band or above do suffer from strong constraints at the physical layer, they may be greatly beneficial for adequately chosen ultra-broadband applications and network topologies. Multi-hop backhauling and Fixed Wireless Access (FWA) networks are both candidates that we decided to assess as a combination. The physical-layer performance is estimated from LiDAR-based ray-tracing predictions and by considering a sub-THz polar-QAM modulation. The site placement is optimized by an automated heuristic method. Finally, analysis of a case study in a North American residential area demonstrates that a FWA design at 150 GHz is challenging due to propagation, but feasible. The comparison between a coverage-constrained sub-THz design and a capacity-constrained 5G design shows interesting complementarity.

Index Terms— Fixed Wireless Access; Wireless backhaul; Sub-THz; Network deployment

I. INTRODUCTION

5G standards and beyond aim at bringing broadband mobile connectivity everywhere. High-traffic areas such as urban centers are nowadays served through dense small-cell networks. Such high-capacity networks need appropriate backhauling and using sub-THz frequency bands is expected to be a key element to meet those requirements in the beyond-5G context [1][2]. Fixed Wireless Access (FWA) networks take advantage of progress in mobile technology to offer high-speed fixed connectivity at a low cost. Indeed, while 80 % of the data traffic takes place indoors, fiber may not be available everywhere as it is sometimes too much of an investment for Internet Service Providers (ISPs). Combining FWA with a wireless last-mile backhaul is a relevant step-by-step process for an ISP who wants to start addressing the fixed data demand for a neighborhood. The network can later be complemented with more fiber points if the capacity is not sufficient. Such 5G solutions are already operational based on sub-6GHz or millimeter-wave frequencies, especially in North America. Using sub-THz frequencies for the last-mile backhaul, but also the access layer is a relevant option with FWA as links are static, which allows the choice of an ideal receiver position (height, optical visibility).

In this paper, we aspire at assessing and highlighting the challenges of designing a combined FWA and backhaul wireless network at 150 GHz (D band) through a realistic use-case study in a North American residential area. The

study relies on accurate simulations, namely through detailed map data obtained with Light Detecting And Ranging (LiDAR) measurements; cutting-edge ray-tracing model adapted to high-frequency propagation [3]; performance of an adequate polar-QAM sub-THz modulation scheme [4]; and automated design (optimal site placement) to perform parametric studies. The latter feature is today the object of popular research activities; recently, the need for high-throughput wireless backhaul has pushed some actors to publish innovative methods for millimeter-wave network planning [5]. For the present study, the authors have developed a new approach, i.e. a heuristic method that selects the network node locations according to both the access coverage and the backhauling constraints, and with objective to minimize the size of the global infrastructure.

Based on this simulation framework, we assessed the required deployment for a given FWA coverage target and capacity demand in a residential area. The impact of few parameters (antenna gain and node's height) is evaluated. Finally, the D-band network design is compared to a 5G deployment using 3.5-GHz access and 28-GHz backhaul to reach the same objective; strong 5G densification is required due to the capacity target.

Section II describes the considered models and assumptions as well as the simulated scenarios. Section III presents the simulation results and discusses the relevance of using sub-THz for FWA and last-mile backhaul wireless networks. Finally, section IV draws some conclusions.

II. MODELS AND ASSUMPTIONS

A. Network architecture

The proposed case study addresses both the last-mile backhaul and access layers of the FWA network. The considered architecture is depicted in Fig. 1. The fiber Points of Presence (PoPs) are nodes where the last-mile wireless backhaul connects the optical fiber and the core network. Backhaul Units (BUs) are wireless backhaul devices. In our scenario, a wireless backhaul link is formed by two dedicated connected BUs with static antenna orientations. A BU is possibly installed at the same site as other BUs to form a hierarchical multi-hop backhaul architecture. The wireless backhaul network is connected to the fiber PoP with a tree topology, i.e. the network is an acyclic graph where any node is at least of degree 1. An Access Point (AP) is the ultimate network node that connects the Customer Premises Equipment (CPE). It is either co-sited with a BU or PoP for

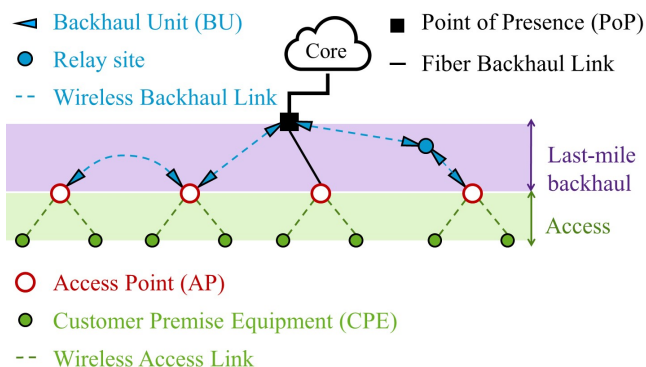


Fig. 1. Considered FWA network architecture

attachment to the backhaul and core network. Sites that connect APs to the core network without providing any access connectivity are called relay sites. Finally, the CPE is installed at the user house or premises to get fixed broadband internet access, and then feed the user's local area network.

B. 3D digital model & Propagation losses

The case study is conducted in Houston's suburbia (US), into a 0.52 km² wide residential area where LiDAR data was collected (Fig. 2). The data was processed and classified to get an accurate digital representation of the environment, including buildings, slanted rooftops, trunks, foliage, and poles. It is complemented with a vectorized representation of the building contours to form the 3D geographical digital model. This 3D model provides several important inputs to the case study including candidate CPE positions against the building vertical facades and candidate positions for APs and BUs such as lampposts and electrical poles.

The 3D digital model is also exploited for the construction of propagation multi-paths (reflections and diffractions on the vectorized building facades) and the computation of high-frequency propagation losses (obstruction by buildings and vegetation). Most buildings in this study are houses with slanted rooftops that are captured in the LiDAR-based map data and considered by the propagation model. This level of detail allows for accurate discrimination between Line-of-Sight (LoS) and Non-LoS (NLoS) situations and also prevents from the construction of



Fig. 2. Study area: vegetation, building footprint and site candidates (●)

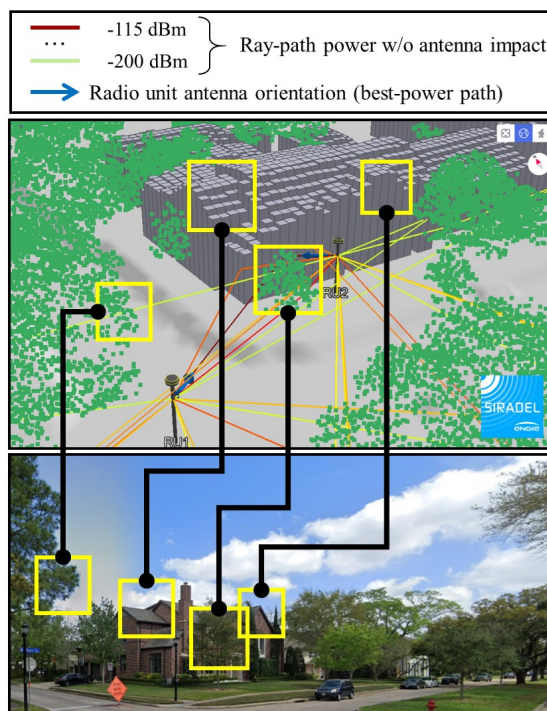


Fig. 3. Using LiDAR point cloud data for ray-tracing

erroneous reflections or diffractions at the higher part of the building facade. In the example of Fig. 3, the dominant path comes from a building reflection due to vegetation losses along the direct-path.

Besides, displaying radio network nodes and links on top of the 3D digital model offers a very comprehensible view of the proposed deployment and obtained performance.

C. System model

The link budget parameters for backhaul and access layers are given respectively in Table 1 and Table 2. BUs are supposed to have a directive high-gain antenna that may be perfectly aligned for a specific fixed radio link. The considered 32 dBi gain has been inspired by a beamforming hardware equipment based on transmitarrays demonstrated by CEA-Leti in the 120-160 GHz band [6]. The AP antenna is assumed to have lower gain because dynamic beam alignment is required, thus a larger beam is appropriate. The CPE is viewed as a simple low-cost device with limited performance i.e. low beamforming gain.

For simplification purposes, we have assumed that interferences could be neglected with beamforming antennas and we have considered a single-polarization system, with no spatial multiplexing. As discussed later, this rule disadvantages 5G in the forthcoming comparison as its capacity would have been significantly improved with multi-user multiplexing. However, it was preferred to have similar assumptions over all compared scenarios, and focus our analysis on factors that we know our tool can predict properly, i.e. impact of the propagation losses, phase noise and link budget.

Table 1: Backhaul radio parameters per scenario

| Scenario | 1) Baseline 150 GHz | 2) Greater CPE gain | 3) Greater node height | 4) 5G design |
|---------------------|------------------------|------------------------|---------------------------|-----------------|
| Carrier | 150 GHz | | | 28 GHz |
| Channel BW | 1 GHz | | | 0.8 GHz |
| #channels | Free | | | 1 |
| Tx power | 100 mW (20 dBm) | | | 1 W |
| Tx ant. gain | 32 dBi | | | 25.5 dBi |
| Rx ant. gain | 32 dBi | | | 25.5 dBi |
| Noise figure | 8 dB | | | 8 dB |
| Phase noise | Medium | | | Low |
| Implementation loss | 3 dB | | | 3 dB |
| Modulation scheme | Polar-QAM | | | QAM |
| Throughput table | [4] | | | [9] |
| Target throughput | ≥ 1024 Mbps | | | ≥ 1024 |
| Min. SINR | 5.9 dB | | | 5.0 dB |
| Confidence level | 99 % | | | 99 % |
| Error margin | 14.0 dB | | | 14.0 dB |
| MAPL | 135.6 dB | | | 135.5 dB |

The radio links at 150 GHz are supposed to suffer from medium-level Phase Noise (PN) [7] and therefore employs the proposed polar-QAM modulation (P-QAM [4]) that is robust to PN. Besides, the PN is neglected at 3.5 GHz and 28 GHz; hence, a conventional QAM modulation scheme is considered at those frequencies.

The D-band spectrum is divided into several channels of 1 GHz width, with channel bonding possibilities [8], in order to satisfy the DAC/ADC constraints. TDD with a DL/UL ratio of 3:1 is applied to all layers and frequencies.

The CPE coverage from the above-described system is computed by simulating the downlink received power and SNR each 2 meters along the building facades. The SNR is mapped to an achievable user throughput; the mapping table has been derived from published link-level simulations [4][9] and takes 36% overhead into account due to signaling and effective bandwidth usage. Then, a house is determined as eligible for FWA service if the throughput target in Table 1 is reached for at least one pixel along its facade.

The AP capacity is analyzed in a second step. As for a practical dimensioning exercise, it is assumed that only a portion of the eligible houses within the study area does subscribe to the ISP service. A subscription ratio of 50% has been set. The average traffic load for each AP i (TL_i) assuming a single allocated channel is estimated as follows:

$$TL_i = \gamma_s / \gamma_{DL} \times \sum_{k \in B_i} [Th_c / Th_k] \quad (1)$$

where B_i is the set of eligible customer buildings attached to AP i ; Th_k is the predicted peak downlink throughput to building k (Mbps); Th_c is the demanded downlink throughput by an average customer (Mbps); γ_s is the subscription ratio and γ_{DL} is the downlink occupation ratio.

In case of an access network that operates on a single channel (as considered at 3.5 GHz), the calculated traffic load must be kept below 1. If above 1, the access network must be densified to improve the radio conditions or to reduce the number of customer houses per cell.

Table 2: Access radio parameters per scenario

| Scenario | 1) Baseline 150 GHz | 2) Greater CPE gain | 3) Greater node height | 4) 5G design |
|---------------------|------------------------|------------------------|---------------------------|-----------------|
| Carrier | 150 GHz | | | 3.5 GHz |
| Channel BW | 1 GHz | | | 100 MHz |
| #channels | Free | | | 1 |
| Tx power | 100 mW (20 dBm) | | | 1 W |
| AP ant. gain | 28 dBi | | | 20 dBi |
| CPE ant. gain | 5 dBi | 12 dBi | 5 dBi | 5 dBi |
| Noise figure | 10 dB | | | 10 dB |
| Phase noise | Medium | | | Low |
| Implementation loss | 3 dB | | | 3 dB |
| Modulation scheme | Polar-QAM | | | QAM |
| Throughput table | [4] | | | [9] |
| Target throughput | ≥ 384 Mbps | | | ≥ 384 Mbps |
| Min. SINR | -0.8 dB | | | 13.5 dB |
| Confidence level | 95 % | | | 95 % |
| Error margin | 9.9 dB | | | 9.9 dB |
| MAPL | 112.9 dB | 119.9 dB | 112.9 dB | 112.6 dB |

In case several channels may be allocated to the AP (as allowed by channel bonding in D-band), the calculated traffic load is converted into a required number of bonded channels. This number is the inverse of the traffic load, rounded to the next higher integer. It is specifically calculated for each AP.

As for the access layer, the SNR and effective throughput is calculated for each backhaul link. The predicted traffic on each AP is then assumed to be transported through the backhaul links up to the closest fiber PoP in terms of hops. The aggregated demand on each backhaul link is compared to the link's throughput. A traffic load TL_l is calculated for each backhaul link l to detect any bottleneck issue (at 28 GHz), or to evaluate the number of bonded channels needed to satisfy demand (at 150 GHz). TL_l assumes the use of a single allocated channel.

$$TL_l = (1 + \gamma_{BO}) / \gamma_{DL} \times \sum_{i \in A_l} [Th_i / Th_l] \quad (2)$$

where A_l is the set of APs using the backhaul link l ; Th_l is the predicted peak throughput on backhaul link l (Mbps); Th_i is the demanded downlink throughput from AP i (Mbps); γ_{DL} is the downlink occupation ratio and γ_{BO} is an additional backhaul overhead due to the transport protocol and X2 layer, set to 15% [10].

D. Scenarios

We simulated and compared different deployment scenarios. For all of them, the CPE device is supposed to be installed on the house external wall or window, with its antenna beam pointing towards the best AP. The average downlink demand by a CPE is 150 Mbps. The APs and BUs are positioned at existing lampposts or poles, or are co-sited with a PoP. The wireless backhaul is connected to four PoPs distributed into the study area. The PoP capacity is assumed to be greater than FWA demand.

Network devices have been set-up using the link budget and deployment parameters presented before. We implemented four different scenarios:

- *Baseline scenario at 150 GHz*: the CPE has a low-cost large-beamwidth antenna with only 5 dBi gain; the APs and BUs are installed at 4 m above ground. The transmit power at all radio devices is limited to 100 mW for practical considerations.
- *Greater CPE gain*: same as the baseline scenario, except that CPE has greater performance with 12 dBi gain.
- *Greater node height*: same as the baseline scenario, except that APs and BUs are installed at 6 m above ground.
- *5G design*: same deployment configuration as the baseline scenario, but lower carriers and bandwidth are used, respectively 3.5 GHz / 100 MHz for the access and 28 GHz / 800 MHz for the backhaul; specific link budget parameters are considered, i.e. greater transmit powers, and lower beamforming antenna gains.

Although the detailed link budgets differ between the 150-GHz and 5G FWA networks, the maximum allowed path loss (MAPL) remain of a similar order. Hence the main factor that explains the evolution of the network coverage between 5G and sub-THz frequencies is the radio propagation.

Remark the study is carried out in a residential scenario with high vegetation density, which is quite a challenge for D-band propagation. This situation is actually well representative of the FWA networks currently deployed with 5G technology. We have set the average in-vegetation loss to 6 dB/m for sub-THz links [11], 1 dB/m for 28 GHz links and 0.2 dB/m for 3.5 GHz links.

E. Optimization

The AP and backhaul node positions are selected from an automated algorithm that aims at reaching the eligibility coverage target and the required capacity with minimum number of deployed antennas. A greedy algorithm iteratively picks the best candidate AP site among those whose coverage overlaps with at least one AP site already selected. Contrary to traditional radio-planning, our solution permits to optimize the access and backhaul segments jointly.

A preliminary study has shown how difficult it is for the

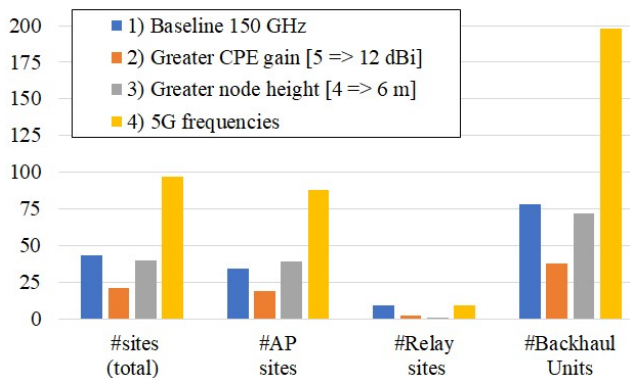


Fig. 4. Simulation results (network size) for all studied scenarios

baseline scenario to reach classical 90-95 % coverage level targets. The lack of appropriate pole candidates and the high obstruction losses make some remote densely vegetated areas unreachable. Only 13% of the backhaul links of length lower than 250 m are in Line-of-Sight (LoS); therefore, the possibilities for medium- or long-range backhaul links are limited. The number of required hops and relays does rapidly grow when aiming for a near full coverage.

As a result, the case study was conducted with a more reasonable coverage target, i.e. 55%. This means that 55% houses must be eligible to FWA service. The selected APs and backhaul links have to support the throughput demand from the customers who are expected to subscribe the service, i.e. half of the eligible houses.

III. SIMULATION RESULTS

Results are summarized in Fig. 4 and will be discussed in three different parts: *a)* result for the baseline sub-THz scenario, including an illustration of the network design, then *b)* comparison between 5G and sub-THz design challenges and finally *c)* other parametric scenarios.

A. Baseline sub-THz scenario

The resulting network design for the baseline 150 GHz scenario includes 34 FWA AP sites, 9 additional backhaul relay sites, and 39 point-to-point backhaul links (equivalent to 78 BUs for 0.52 km²) as illustrated in Fig. 4. Besides, Fig. 5 shows the downlink achievable throughput (per 1 GHz channel) at the CPE possible locations; this corresponds to the colored pixels along the building facades. Buildings completely surrounded by black pixels are not eligible. The colors associated to the APs (solid dots) and backhaul links (solid lines) indicate the number of required channels to resp. serve the CPEs of a cell or transport the aggregated user data streams. Maximum 3 channels are needed for an AP; and maximum 5 channels for a backhaul link.

B. Comparing 5G and sub-THz designs

The comparison between the baseline 150 GHz scenario and the deployment at 5G frequencies leads to interesting observations. 100% coverage is reached with the resulting



Fig. 5. Resulting network for the baseline sub-THz scenario

3.5 GHz access network, even in areas with low AP density. Actually the deployment of 4 APs at the PoP position would even be sufficient to achieve a wide coverage (91%). The reason why the 3.5 GHz access network has been densified is that the capacity of each AP is strongly limited due to the 100 MHz bandwidth; therefore, the optimization algorithm has dimensioned an AP deployment (and the required transport infrastructure) such that the number of subscribers per cell is compatible with this capacity. In the end, the number of APs and backhaul links is multiplied by 2.5 compared to the baseline 150 GHz scenario. In reality, such a 5G infrastructure has no chance of being deployed due to the cost and the imbalance between coverage and capacity. The target average throughput per subscriber would be set at a much lower value. The access capacity could be also boosted thanks to multi-user multiplexing. Nevertheless, by assuming constant multiplexing capabilities and constant throughput target, the current study does illustrate how the ultra-large bandwidth available in D-band can more than compensate for the additional propagation losses, and therefore is a possible alternative to 5G frequencies in perspective of high data rate FWA networks.

C. Other parametric scenarios

The improvement of the CPE gain from 5 dBi to 12 dBi allows a reduction in the number of sites by 51% and number of radio devices (APs and BUs) by 49%. Remark any gain of 7 dB in the access link budget would give same result, i.e. an infrastructure with size divided by 2.

Greater node's height (from 4 to 6 m) leads to a smaller infrastructure in terms of sites, but the overall benefit is not obvious. On one hand, the number of backhaul links is reduced by 8% as some propagation paths may travel above trees. But on the other hand, the number of APs has to be increased by 15% because the propagation from the AP to the facade CPEs (still at height 3.5 m) is slightly degraded due to additional vegetation losses. This study shows that the effect of the node's height is not homogeneous and cannot be easily anticipated; however, this also demonstrates there is an interest for smart radio-planning tools that would be able to optimize the height of each individual radio device.

IV. CONCLUSION

This case study allowed us to quantify the size of the needed sub-THz infrastructure for a realistic FWA deployment scenario into a residential environment. Of course, the considered downlink throughput (150 Mbps average per subscriber) is significantly higher than experienced in 5G commercial networks, thanks to the huge available bandwidth (between 1 to 7 channels of 1 GHz have been allocated to the predicted sub-THz devices).

The comparison between various scenarios has highlighted the effect of the CPE antenna gain (infrastructure divided by 2 for an additional gain of 7 dB), the height of the radio nodes (there are upsides and downsides to deployment heights of 4 m and 6 m), the frequency and bandwidth. Finally, it has been demonstrated three important results:

1. A FWA network with higher data rates than possible today looks feasible based on 150 GHz devices. Transmit power is supposed to be limited to 100 mW, but is compensated by antenna gains up to 32 dBi and perfect alignment at backhaul units. This must of course be further validated and refined in the future, with real sub-THz radio measurements and effective equipment performance.
2. A full coverage target may be very costly at such high frequency. Thus it looks like a better approach to design the D-band network for a reasonable coverage objective, and then complement with additional connections in a lower frequency band. The opposite procedure may also be implemented, where an existing full-coverage 5G network is upgraded with D-band devices to locally boost the capacity for the backhaul and/or access layer.
3. Smart radio-planning tools with accurate geo-data and capability to jointly optimize the access and backhaul layer can be appropriately applied to design a dense high-frequency FWA network. Radio planning at those frequencies is a critical and complex task, therefore such a tool is thought to be mandatory for future sub-THz operators.

ACKNOWLEDGMENT

This work received funding from the French National Research Agency within the frame of the BRAVE project (ANR-17-CE25-0013).

REFERENCES

- [1] Y. Corre et al., "Sub-THz spectrum as enabler for 6G wireless communications up to 1 Tbit/s," BRAVE white paper, 2019.
- [2] N. Rajatheva et al., "White paper on broadband connectivity in 6G," arXiv preprint arXiv:2004.14247, 2020.
- [3] M. Z. Aslam and Y. Corre, "Simulated propagation properties for future outdoor sub-THz networks," in IEEE Personal, Indoor and Mobile Radio Communications (PIMRC), 2020
- [4] S. Bicaïs, J.-B. Doré, G. Gougeon, and Y. Corre, "Optimized single carrier transceiver for future sub-terahertz applications," in IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2020, pp. 5095–5099.
- [5] B. Marques, M. Sousa, P. Vieira, M. P. Queluz, and A. Rodrigues, "Automated joint access and backhaul planning for 5G millimeter-wave small cell networks," in 2020 23rd International Symposium on Wireless Personal Multimedia Communications (WPMC), 2020,
- [6] F. F. Manzano, A. Clemente, and J. L. González-Jiménez, "High-gain D-Band transmitarrays in standard PCB technology for beyond-5G communications," IEEE Transactions on Antennas and Propagation, vol. 68, no. 1, Art. no. 1, 2019.
- [7] S. Bicaïs and J.-B. Doré, "Design of digital communications for strong phase noise channels," IEEE Open Journal of Vehicular Technology, vol. 1, pp. 227–243, 2020.
- [8] V. Petrov, T. Kurner and I. Hosako, "IEEE 802.15.3d: first standardization efforts for sub-Terahertz band communications toward 6G," in IEEE Communications Magazine, vol. 58, no. 11, pp. 28-33, November 2020
- [9] J. C. Ikuno, M. Wrulich, and M. Rupp, "System level simulation of LTE networks," in IEEE Vehicular Technology Conference, 2010
- [10] NGMN Alliance, "Guidelines for LTE backhaul traffic estimation", July 2011
- [11] G. Gougeon, Y. Corre, and M. Z. Aslam, "Sub-THz channel characterization from ray-based deterministic simulations," ITU Journal: ICT Discoveries, vol. 2, no. 1, Art. no. 1, 2019.