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Performance Analysis of Multi-Hop Networks at Terahertz Frequencies

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***Abstract*—The emergence of Terahertz (THz) frequency wireless networks holds great potential for enabling various high-demand services, including Industrial Internet of Things (IIoT) applications. These applications benefit significantly from the ultra-high data rates, low latency, and high spatial resolution offered by THz frequencies. However, a primary well-known challenge of THz networks is their limited coverage range due to high path loss and vulnerability to obstructions. This paper addresses this limitation by proposing two novel multi-hop protocols, Table-Less (TL) and Table-Based (TB), respectively, both avoiding centralized control and/or control plane transmissions. Indeed, both solutions are distributed, simple, and rapidly adaptable to network changes. Simulation results demonstrate the effectiveness of our approaches, as well as revealing interesting trade-offs between TL and TB routing protocols, both in a real IIoT THz network and under static and dynamic conditions.**

***Index Terms*—Terahertz (THz), Industrial Internet of Things (IIoT), Medium Access Control (MAC), Table-Less Multi-Hopping, Table-Based Multi-Hopping.**

I. Introduction

The advent of mobile radio networks operating in the Terahertz (THz) band, which spans frequencies from 0.1 to 10 THz, promises to unleash the development of innovative applications [1], [2]. The vast bandwidth available in these networks can offer ultra-high data rates, low latency, device miniaturization, and high spatial resolution [3], [4]. These capabilities are particularly beneficial in challenging scenarios such as Extended Reality (XR), digital twins, and Industrial Internet of Things (IIoT) applications [5]. For instance, establishing wireless interconnections between virtualized Programmable Logic Controllers (PLCs) and sensors/actuators on industrial machines necessitates per-user data rates of up to 100 Mbps [6], resulting in network throughputs of tens of Gbps even for a relatively small number of devices, along with latencies below 0.1 ms [2], highlighting the need for advancements in current wireless technologies.

However, one of the primary limitations of THz wireless networks is their restricted coverage range due to high path loss and susceptibility to obstacles [7], [8]. A viable option to overcome this limitation is the use of multi-hop communication to extend the coverage area and ensure reliable connectivity. This approach is particularly important in environments with numerous obstructions and distances spanning several tens of meters, such as industrial plants. In particular, multi-hop networks leverage intermediate devices to relay data from the source to the destination, thereby overcoming the distance limitations imposed by the high path loss of THz frequencies.

The concept of multi-hop communication has been extensively studied in the context of wireless mesh networks [9], [10]. Several approaches have been proposed to address the challenges of routing in THz networks, including methods to optimize path selection, relay distribution, enhance reliability, and reduce latency [11]–[13]. However, traditional routing protocols often involve complex algorithms and require significant overhead for maintaining routing tables and network state information [14]. In addition, there exist many works dealing with energy-efficient routing metric, aiming at minimizing the packet forwarding energy consumption, without accounting for the lifetime of routers, that is assuming they are always on and ready for forwarding data (see, e,g., [15]).

Given the dynamic evolution of the THz channel, which is highly susceptible to environmental changes due to the millimeter-scale wavelength, current approaches may encounter practical issues in real-world scenarios. This is primarily due to the higher control plane overhead required to find a relay, making it difficult to quickly adapt routing decisions.

This paper proposes two multi-hop approaches for THz mobile radio networks, that distinguish themselves from existing solutions through its simplicity and fast adaptability to dynamic conditions. Unlike conventional multi-hop schemes that rely on centralized control and/or control plane transmissions, we consider two fully distributed approaches that depend solely on ongoing user plane data transmissions to enable multi-hopping. In addition, in contrast to existing works, we account for the possibility that routers cannot forward data generated by neighbors, because of not being in reception state during data transmission.

Specifically, we propose Table-Less (TL) and Table-Based (TB) multi-hop network protocols: in the former, devices leverage reception phases for data collection and forwarding, while in the latter, users exploit neighbor tables to select the next hop based on the ongoing data transmission flow.

The proposed analysis considers an Unslotted-Aloha protocol [16] at the Medium Access Control (MAC) layer, motivated by the following main characteristics of THz frequencies: (i) the small coverage range of each device, which spatially limits collisions, and (ii) the long propagation delays compared to transmission times, which vary from link to link

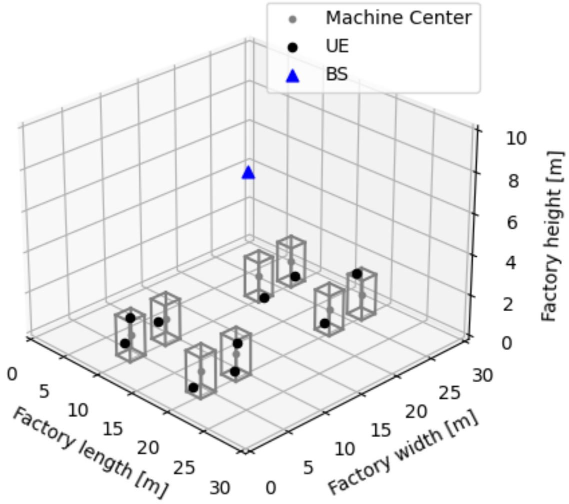

Fig. 1. The considered IIoT scenario.

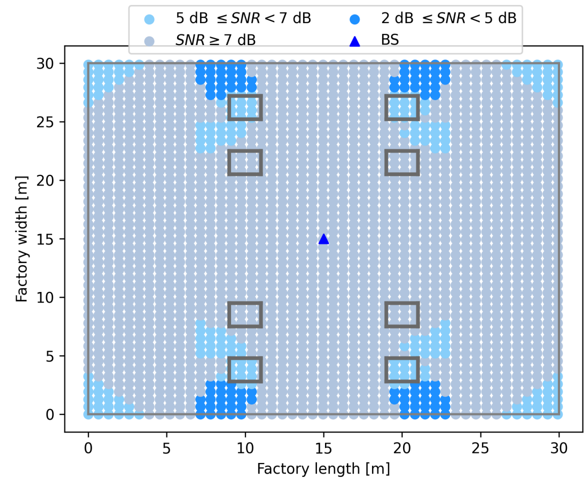

Fig. 2. 2D map illustrating the uplink SNR distribution in the considered industrial plant.

and reduce the probability of simultaneous reception of data at the receiver side.

After demonstrating the need for multi-hop solutions over single-hop Unslotted Aloha, the simulation campaign analyzes the trade-offs between TL and TB routing, evaluating their performance in a real IIoT environment under both static and dynamic conditions, and demonstrating that the stringent requirements of IIoT applications can be achieved.

The paper is thus structured as follows. Sec. II introduces the system model, covering the scenario, traffic, and channel model. Sec. III details the MAC layer, with a brief recap of the basic Unslotted Aloha working principle. Then, the proposed TL and TB multi-hop approaches are explained in Sec. IV. The metrics used to assess our proposal are listed in Sec. V, and Sec. VI presents the simulation results. Finally, in Sec. VII, we summarize the main findings of our paper.

II. System Model

A. Scenario

Among the possible applications of THz frequencies, we focus on an IIoT scenario involving the remotization of PLCs, which represents one of the most challenging use cases [6]. In particular, the simulated environment emulates an industrial plant measuring 30 x 30 x 10 meters. Within this plant, $O = 8$ packing machines are positioned in fixed locations. For simplicity, these industrial machines are modeled as cubes with sides of 2 meters.

We then consider N User Equipments (UEs) (i.e., microcontroller boards embedding sensors) that are randomly distributed within the O machines. These UEs need to communicate in real-time with a remote PLC. To reach the latter, a Base Station (BS) is located at the center of the top base of the factory, as shown in Fig. 1.

B. Traffic Model

This paper aims to analyze the achievable network performance in a worst-case scenario in terms of offered traffic. This scenario arises when the buffers of the UEs are consistently full, meaning the UEs always have a new DATA packet ready for transmission to the BS immediately after receiving the Acknowledgment (ACK) for the previous transmission. This analysis is crucial for evaluating the maximum network throughput of a THz network (with queue always full), as this metric depends on the type of traffic. Therefore, in the following sections, we will assume that all UEs generate traffic with a fixed DATA packet size P.

C. Channel Model

The channel propagation conditions considered in this work follow the Indoor Factory (InF) scenario of 3GPP TR 38.901 [17]. In particular, the channel is modeled with a narrowband description where the path loss PL in dB can be formulated as follows:

$$PL[dB] = \beta + \alpha \log_{10}(d[m]) + \gamma \log_{10}(f_c[GHz]), \quad (1)$$

where d is the Tx-Rx Euclidean distance, f_c represents the carrier frequency, whereas α, β, and γ are real-values that depend on:

1) Line-of-Sight (LOS)/Non-Line-of-Sight (NLOS) conditions that are computed deterministically based on the reciprocal positions of UEs and BS, where an intra-machine link is assumed to be in NLOS;
2) the clutter density of the scenario, either sparse (S) or dense (D). Specifically, the clutter density is defined as the ratio between the sum of the area occupied by the O machines, and the area of the industrial plant. For the considered IIoT scenario, this results in a sparse clutter density;

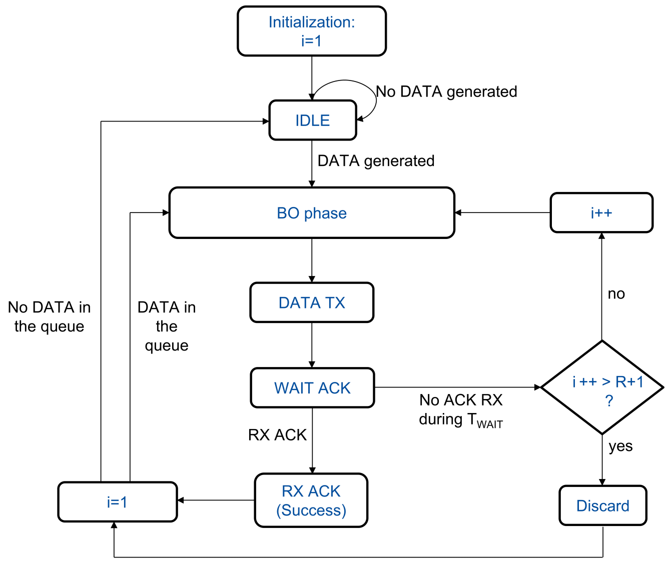

Fig. 3. Flowchart of the MAC layer protocol from the UE side.

3) the height of the transmitter and receiver, either low (L), if both of them are below the height of the machines, or high (H), otherwise.

The Signal-to-Noise Ratio (SNR) can be then expressed as:

$$SNR\,[dB] = P_{\mathrm{TX}}\,[dBW] + \eta_{\mathrm{TX}}\,[dB] + \eta_{\mathrm{RX}}\,[dB] + G_{\mathrm{TX}}\,[dB] + G_{\mathrm{RX}}\,[dB] - PL\,[dB] - P_{\mathrm{N}}\,[dBW], \quad (2)$$

where P_{TX} is the transmitted power, η_{TX}, η_{RX} are the transmitter and receiver antenna efficiencies, respectively, G_{TX}, G_{RX} are the transmitter and receiver gains, PL is the path loss, and $P_{\mathrm{N}} = 10\log_{10}(kT_0F_{\mathrm{RX}}B)$ is the noise power assuming the antenna temperature equal to the reference temperature T_0, with k being the Boltzmann constant, F_{RX} is the receiver noise figure, and B the bandwidth. In particular, successful decoding occurs when SNR overcomes a given threshold SNR_{TH}, that is, $SNR \geq SNR_{\mathrm{TH}}$.

To provide a quantitative analysis, Fig. 2 presents the 2D coverage map of the industrial plant, illustrating uplink SNR values based on the parameters in Table I. A typical threshold of $SNR_{\mathrm{TH}} \geq 7$ dB does not ensure full coverage, particularly under NLOS conditions, such as when UEs are deployed within O machines. This underscores the necessity of multi-hop transmissions for THz communications in IIoT scenarios, which is the focus of this paper.

III. MAC Layer

A. MAC protocol

As a trade-off between simplicity and performance [18], and given the unique characteristics of THz communications that help mitigate collisions, we consider a simple MAC protocol based on Unslotted Aloha [16], incorporating a random Back-Off (BO) even in the first transmission to further reduce collisions.

In particular, the MAC protocol works as follows. Each UE is initially in IDLE mode. When new DATA has to be transmitted, the UE initiates a BO for $T_{\mathrm{B}} = T_{\mathrm{BO}}\,\xi$, where T_{BO} is the minimum BO duration; ξ is a uniform random number in the range $[1; 2^iC]$, with C being an integer defining the maximum duration of the contention window; and i being an integer counting the number of transmission attempts (starting at 1 for the first attempt). At the end of the BO period, the UE sends the DATA and enters reception mode for a maximum period, T_{WAIT}. Specifically, we set $T_{\mathrm{WAIT}} = T_{\mathrm{ACK}} + 2\,\tau_{\mathrm{p_{max}}}$, since it is the time needed to transmit the DATA and receive the corresponding ACK, where $T_{\mathrm{ACK}} = \frac{8\,P_{\mathrm{A}}}{R_{\mathrm{b}}}$, P_{A} is the number of bytes forming an ACK, $R_{\mathrm{b}} = B\log_2(M)$ is the bit rate, M is the modulation order, and $\tau_{\mathrm{p_{max}}}$ is the maximum possible propagation delay in the considered IIoT scenario.

If an ACK is received during T_{WAIT}, the UE either goes back to BO, if a new DATA packet is in the MAC layer queue, or returns to IDLE if no DATA is queued. Conversely, if no ACK is received during T_{WAIT}, the UE retries the transmission up to a maximum number of attempts, R. The flowchart of the MAC layer protocol from the UE side is shown in Fig. 3.

B. Interference modeling

Collisions are computed at the receiver side, taking into account the actual propagation delays from the transmitter(s). If two or more transmissions are received partially or completely overlapping in time, they are all considered lost, that is, we assume the worst-case scenario with no capture effect. Additionally, we assume a half-duplex mode of operation, meaning that if a device is busy transmitting an ACK and receives DATA simultaneously, the reception is discarded.

Note that we account for propagation delays, which vary for each BS-UE and UE-UE link, as they can be longer than transmission times at THz frequencies and thus impact the overall performance. Indeed, this peculiarity may actually reduce collision probability, since simultaneous transmissions (either DATA or ACK) may not lead to collisions if they are received at different times by the receiver.

IV. Multi-hop Approach

In this section, we describe our proposal, that is, a TL and TB multi-hop algorithm at the network layer.

The key innovation of both approaches is that UEs switch to reception mode during the BO period, ensuring they can potentially receive DATA. Consequently, after BO, UEs transmit both their own DATA and any DATA received from other UEs.

To realize the above approach, we set the BO duration equal to $T_{\mathrm{B}} = T_{\mathrm{DATA}} + \tau_{\mathrm{p_{max}}} + T_{\mathrm{BO}}\,\xi$, where $T_{\mathrm{DATA}} = \frac{8\,P}{R_{\mathrm{b}}}$ is the time needed to transmit a DATA, and P is the number of bytes forming the DATA. If during BO the UEs correctly receive DATA, and the number of DATA in the MAC layer queue is below its capacity Q, they will enqueue it. In this case, UEs will immediately acknowledge successful reception with an ACK. Note that, during the WAIT phase, each UE remains in reception mode to receive the ACK for all transmitted DATA. This also allows a UE to receive DATA from other UEs during T_{WAIT} and forward them accordingly.

A. Table-less multi-hopping

In the TL solution, after the BO period, each UE always sends its own DATA with a broadcast address, thereby producing the well-known broadcast storm problem [9] but, at the same time, increasing the likelihood that at least one UE within its transmission range is listening to the channel (i.e., is in reception mode during the BO or WAIT phase) and can subsequently forward the DATA to the BS. Then, UEs enter the reception mode either (i) for a maximum duration of T_{WAIT} or (ii) until they correctly receive the ACK before T_{WAIT} expires. It is important to note that the non-negligible propagation delays, which contribute to reducing collisions and packet loss, allow us to account for ACK transmissions from UEs that have successfully received packets for forwarding. This approach contrasts with conventional flooding methods in the literature, where such delays are often overlooked.

B. Table-based multi-hopping

In the TB approach, UEs create a neighbor table containing for each other UE: (i) an indication of whether it has the BS in its own table, (ii) the number of ACKs received from it; and (iii) the corresponding SNRs. Hence, after the BO phase, each UE transmits its own DATA with a unicast address to the optimal receiver selected based on the neighbor table. Specifically, the optimal receiver is always the BS if it is present in the neighbor table; otherwise, it is the UE that has the BS in its table and/or from which the highest number of ACKs has been received at the highest SNR.

When the neighbor table is empty, after BO, the UEs initiate a discovery phase without adding any control plane overhead. Indeed, UEs simply transmit its own DATA in broadcast and then enter reception mode for T_{WAIT}. During this time, they populate the neighbor table based on the ACKs received from all receivers that have correctly collected the broadcast transmission. Once the neighbor table contains at least one entry, the discovery phase concludes. This means that, in the next BO phase, DATA are sent in unicast to the optimal receiver and the WAIT phase ends before T_{WAIT} if the correct ACK is received (as in the TL case).

Note that each UE removes an entry from the table after a Time To Live, TTL, expires, which is defined as the number of consecutive missed receptions of an ACK from a specific neighbor.

C. Final remarks

For both TB and TL approaches, it is important to note that:

1) During T_{WAIT}, UEs can also receive DATA from other UEs. In this case, they will transmit the corresponding ACK(s) at the end of the WAIT phase;
2) The BS discards any duplicate DATA generated by the same UE but forwarded by different UEs;
3) UEs discard any received DATA that (i) is already present in their queue, (ii) originates from themselves (to prevent loops), or (iii) exceeds the predefined hop count limit H (i.e., the maximum number of relays to be traversed before reaching the BS);
4) The UEs discard any ACK received during BO or WAIT but not intended for them.

V. Key Performance Indicators

In this section, we present the Key Performance Indicators (KPIs) that have been utilized to validate the proposed multi-hop approaches (see Sec. IV) within our THz-based system model (see Sec. II).

A. Success probability

The success probability, p_{s}, is defined as the ratio between the average number of DATA successfully received at the BS, and the total number of DATA transmitted by the UEs, that is,

$$p_{\mathrm{s}} = \frac{1}{N}\sum_{j=1}^{N}\frac{N_{\mathrm{RX_j}}}{N_{\mathrm{TX_j}}}, \tag{3}$$

where N is the total number of UEs, $N_{\mathrm{RX_j}}$ is the number of DATA successfully received at the BS by the j-th UE, and $N_{\mathrm{TX_j}}$ is the number of DATA transmitted by the j-th UE. We then recall that a DATA packet is deemed successfully received at the BS when its $SNR \geq SNR_{\mathrm{TH}}$ and it has not collided with any other transmission.

B. Network Throughput

The network throughput, S, is defined as the number of information bits per second successfully received at the MAC layer of the BS, that is,

$$S = \frac{PN_{\mathrm{R}}}{T_{\mathrm{S}}}, \tag{4}$$

where P is the DATA size, N_{R} is the number of DATA successfully received at the BS, and T_{S} is the simulation time.

C. Latency

The average latency, $\overline{L}$, is defined as the average time needed by UEs to transmit DATA with success, that is,

$$\overline{L} = \frac{1}{N}\sum_{j=1}^{N}\frac{1}{N_{\mathrm{P_j}}}\sum_{i=1}^{N_{\mathrm{P_i}}} L_{j,i} \tag{5}$$

where $N_{\mathrm{P_j}}$ is the number of DATA generated by the j-th UE and not discarded, and $L_{j,i}$ is the time interval from the generation of the i-th DATA by the j-th UE to the reception of the corresponding ACK[1]. When the BS successfully receives the DATA from the first relay, we calculate the latency for

[1]Note that UEs can receive ACKs from other UEs acting as relays to the BS.

TABLE I
SIMULATION PARAMETERS.

Symbol	Description	Value
f_c	Carrier frequency	100 GHz
B	Bandwidth	25 GHz
$P_{\mathrm{TX,UE}}$	Power transmitted from a UE	25 dBm
$P_{\mathrm{TX,BS}}$	Power transmitted from the BS	30 dBm
η_{UE}	Antenna efficiency of a UE	0 dB
η_{BS}	Antenna efficiency of the BS	0 dB
G_{UE}	Antenna gain of a UE	8 dB
G_{BS}	Antenna gain of the BS	10 dB
F_{UE}	Noise figure of a UE	9 dB
F_{BS}	Noise figure of the BS	8 dB
T_0	Reference temperature	290 K
M	Modulation order	4
SNR_{TH}	SNR threshold	7 dB
C	Integer value defining the BO period	5
R	Maximum number of retransmissions	3
H	Maximum number of hops of a single DATA	4
P_{A}	Size of an ACK	10 B
P	Size of a DATA	20 B
Q	Length of the UEs' queue	{5, 9}
TTL	Time To Live for an entry in the neighbor table	3
T_{BO}	BO minimum time slot duration	1.6 ns
N_{S}	Number of simulations	20
T_{S}	Simulation time	0.5 ms

that packet, denoted as $L_{j,i}$, by summing T_{ACK} and the propagation delay of the ACK. It is important to note that the ACK from the BS may not be received by the originating UE, as it is not in reception mode after already receiving confirmation from the first relay.

VI. PERFORMANCE EVALUATION

A. Simulation setup

Simulations parameters, if not otherwise specified, are reported in Table I. In particular, all results have been obtained by averaging over N_{S} simulations of duration T_{S}, where each simulation mainly differs for the spatial distribution of UEs. It is worth noting that UEs are distributed randomly within the O machines so that half of them are connected to the BS (i.e., $SNR \geq SNR_{\mathrm{TH}}$), and the others are not.

Based on the system model described in Sec. II, we first consider the single-hop Unslotted Aloha-based MAC layer protocol (UALOHA), as described in Sec. III-A with no movements of the UEs. This serves as a baseline to illustrate the limitations of single-hop communication and highlight the necessity of multi-hop approaches.

Beyond this first analysis, our simulation campaign has considered four cases:

1) *TL, Static*: This is the proposed TL multi-hop approach described in Sec. IV-A, where UEs do not change positions during a single simulation run;
2) *TL, Dynamic*: This is similar to case 1 but with UEs changing positions during a single simulation run. Specifically, the UEs are moved to modify their potential neighbor(s);
3) *TB, Static*: This is the proposed TB multi-hop approach described in Sec. IV-B, where UEs occupy fixed positions during a single simulation run;
4) *TB, Dynamic*: This is similar to case 3 but with UEs changing positions during a single simulation run, as in case 2.

TABLE II
SUCCESS PROBABILITY COMPARISON BETWEEN SINGLE-HOP UALOHA, TB AND TL, WHEN CONSIDERING STATIC CONDITIONS.

N	UALOHA	TB	TL
4	0.5	0.999	0.997
6	0.5	0.999	0.989
8	0.499	0.998	0.979
10	0.499	0.991	0.970
12	0.498	0.988	0.961

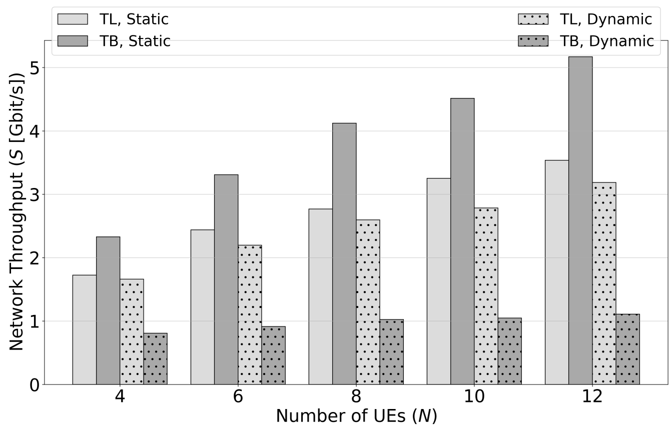

Fig. 4. Network Throughput, S, as a function of the number of UEs, N, and the four simulation cases.

B. Numerical results

We start our analysis with Table II, which evaluates the success probability, p_{s}, as a function of the number of UEs, N, for the single-hop UALOHA protocol, and our proposals, namely TB, and TL routing protocols. In this case, we consider only static conditions. As expected, p_{s} decreases with increasing N, due to higher collision rates, and UALOHA exhibits the worst performance, justifying the need for multi-hopping. This is because half of the UEs remain disconnected from the BS due to spatial constraints in the considered IIoT scenario. In contrast, the proposed multi-hop extensions (TL and TB) enable full connectivity by allowing all UEs to communicate with the BS, even being outside its coverage range. This is achieved through broadcast or unicast transmissions characterizing the TL and TB versions, respectively. Additionally, TB outperforms TL due to its reduced overhead from unicast transmissions, which lowers the collision probability.

After demonstrating the need for multi-hop communications, Figure 4 presents the network throughput, S, as a function of the number of UEs, N, across the four simulation cases. As observed, S increases with N since the total number

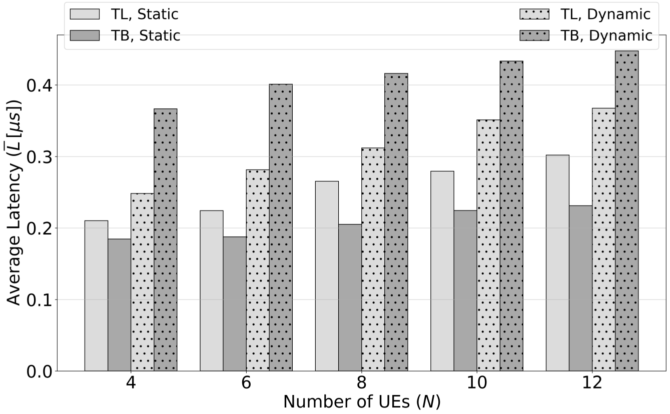

Fig. 5. Average latency, $\overline{L}$, as a function of the number of UEs, N, and the four simulation cases.

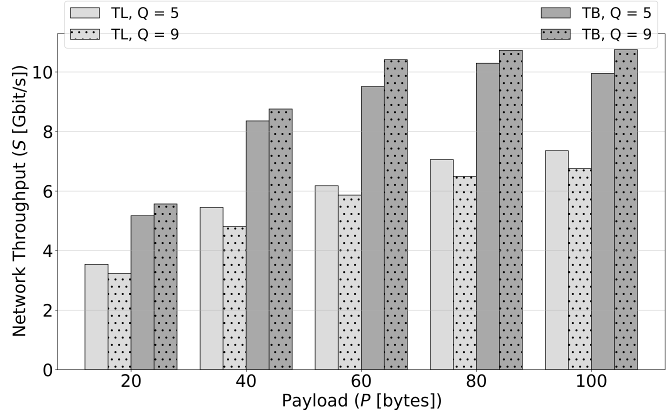

Fig. 6. Network Throughput S, as a function of DATA size P, the length of the UEs' MAC layer queue Q, and TB and TL in the static case for a fixed number of $N = 12$ UEs.

of packets successfully received at the BS, N_{R}, also grows with N, despite a higher collision rate. This results in a network throughput in the order of few Gbit/s, which satisfies the requirements of IIoT applications [6]. Furthermore, as previously shown, TB outperforms TL under static conditions due to a higher number of successfully received packets at the BS. This improvement stems from the next-hop selection mechanism, which significantly reduces collisions and improves p_{s}. The reader can also note that TL and TB approaches behave differently under static and dynamic conditions. In fact, TL is robust to changes in network topology due to UEs broadcasting their DATA without selecting a specific next hop, thereby leveraging spatial redundancy at the expense of the known drawbacks caused by the broadcast storm problem [9]. In contrast, TB requires UEs to update their neighbor tables for next-hop selection, which can lead to missed transmissions when the selected neighbor moves out of range, significantly lowering N_{R} and, consequently, network throughput S in dynamic conditions.

Then, Figure 5, shows the Average Latency, $\overline{L}$, as a function of the number of UEs, N, and again the four simulation cases. As expected, $\overline{L}$ increases with N due to the higher number of collisions and retransmissions caused by the greater number of UEs competing for the channel, while still remaining below 0.5 μs. These results further confirm the better performance of TB under static conditions because of the higher reliability given by the choice of the next hop and the advantage of TL in dynamic scenarios thanks to the broadcast transmission of packets.

Finally, Figure 6 illustrates the network throughput, S, as a function of the DATA size P, the MAC layer queue length Q, for a fixed number of $N = 12$ UEs. The simulation cases analyzed are TB and TL under static conditions and it can be noted that, for both solutions, S increases as P grows from 20 to 100 bytes. Despite a lower success probability due to a higher number of collisions, these results confirm the robustness of the proposed solutions, demonstrating that throughput in the order of several Gbit/s can be achieved even with larger payloads. In particular, the traffic offered from each UE increases with P (ranging from 0.35 Gbit/s to 1.5 Gbit/s) and with that also the number of packets successfully received at BS, N_{R}. However, the increasing trend of S tends to saturate as P increases, as the interference effect starts to become dominant w.r.t the higher offered traffic.

It can also be observed that TL and TB have opposite behaviors when modifying the buffer length. This trend can be attributed to the robustness of TB in the static scenario, where it maintains a high success rate, particularly with large queues. Although collisions occur, their impact remains limited, allowing a larger buffer to accomodate more successfully received packets at the BS. In contrast, in TL, setting $Q = 9$ leads to performance degradation due to excessive collisions, since all data are transmitted in broadcast. However, reducing $Q = 5$ mitigates these collisions, resulting in improved performance. Nevertheless, the best performance of TB with respect to TL in the static scenario is still confirmed.

VII. Conclusions

In this paper, we proposed two TL and TB multi-hop approaches for THz wireless networks, based on the well-known Unslotted Aloha MAC layer protocol. We consider the unique properties of THz frequencies, such as small coverage range and link-by-link propagation delays, and we emulate a real IIoT environment under static and dynamic conditions. Through extensive simulations, we demonstrated the necessity of multi-hop approaches and showed that the proposed solutions significantly enhance network throughput – reaching several Gbit/s – while reducing the average latency to below 0.5 μs. These promising results indicate the potential to meet the demanding requirements of IIoT applications. Moreover, we show that under static conditions, the considered TB network protocol provides better performance. In contrast, the lower overhead of the TL algorithms is more advantageous in dynamic conditions, as maintaining routing tables can be costly. Future works will focus on leveraging artificial intelligence to optimize the identified trade-offs between TL and TB network algorithms.

Acknowledgments

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