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Assessing Latency of Packet Delivery in the 5G 3GPP Integrated Access and Backhaul Architecture with Half-Duplex Constraints

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Abstract: Integrated Access and Backhaul (IAB) is an enabling technology for efficient 5G millimeter wave (mmWave) New Radio (NR) deployment. The key feature of IAB is multi-hop wireless backhauling, allowing utilizing relaying IAB-nodes to provide cost-efficient access network densification and alleviate the problem of blockages. One of the critical performance measures in such systems is the latency of packet delivery over the multi-hop paths. The paper aims at assessing the impact of multi-hop transmission on the end-to-end delay in an IAB radio access network, taking into account the half-duplex constraint. We build a detailed queuing theory model for latency assessment in time-division-multiplexing (TDM)-based IAB deployments and evaluate the delay due to queuing in the network nodes for several cell topologies and under different time allocation strategies between access and backhaul. The paper considers a practical Manhattan-style urban deployment, which is characteristically impaired by the blockage of buildings. The numerical results show that balancing the access and backhaul micro phases is crucial for reducing the end-to-end packet delay, at least in the uplink, while increasing the number of network hops yields a linear increase in the total packet delay for both the uplink and downlink. The numerical results were obtained via simulation using the open-source software OMNeT++.

Keywords: 5G; New Radio; millimeter wave; Integrated Access and Backhaul; latency

1. Introduction

The bandwidth and delay requirements in the Fifth-Generation (5G) cellular networks are an order of magnitude stricter than in the currently deployed systems [1–3]. Furthermore, the microwave frequency bands utilized for mobile communications today are close to exhaustion and become less efficient with respect to increasing quality of service (QoS) needs [4]. As a result, the 3rd Generation Partnership Project (3GPP) standards organization has recently specified millimeter wave communication (mmWave) New Radio (NR) technology capable of operating in the band from 24 to 100 GHz.

Although the mmWave band allows for much higher transmission rates, its use is challenging due to a short propagation range and a strong susceptibility to blockage [5,6]. For this reason, 5G mmWave NR base stations (BS) must be located more densely, leading to high network deployment costs. To alleviate this problem, self-backhauled networks have been proposed as a solution to this problem. 3GPP calls the corresponding technology Integrated Access and Backhaul (IAB) and specifies it in TR 38.874 [7] and TS 38.401 [8].

The key feature of IAB is multi-hop wireless backhauling. In an IAB deployment, only some BSs (called IAB-donors) have a wired backhaul to the core network, whereas others (IAB-nodes) are wirelessly backhauled to IAB-donors, directly or hop-by-hop via multiple IAB-nodes. In such a setup, the end-to-end packet delay may greatly increase due to multi-hop transmission and the related queuing [9]. The problem is made even more difficult by the half-duplex communication requirements for the current wireless...
Accordingly, the IAB-nodes and IAB-donor cannot simultaneously transmit and receive information over multiple antennas they are associated with. The IAB-donor must carefully plan and schedule the uplink and downlink, as well as access and backhaul transmissions in the whole network.

Separation of uplink and downlink transmission (half-duplex IAB) can be performed via time, frequency, or spatial division multiplexing (TDM [11], FDM [12], SDM [13]). According to 3GPP TR 38.874 [7], TDM should be considered as the preferred option. The use of TDM means that each IAB-node, at each time instant, must either receive traffic or transmit. Moreover, in accordance with 3GPP TS 38.174 [14], each antenna, at each time instant, can work either for access or for backhaul.

3GPP IAB is the first architecture for commercial cellular networks to use multi-hop radio transmission. It must satisfy the quality of service requirements set by the ITU-R and 3GPP standards, one of which is the end-to-end delay. In multi-hop systems, the end-to-end delay requirement presents the main design challenge, especially given the constraints of half-duplex transmission.

The arising time allocation problem between access and backhaul was tackled, for instance, via convex programming [15,16] and heuristics [17]; however, these solutions are suitable for special cases only. In [18], the authors conducted demo end-to-end simulations using ns-3, concentrating on the upper layers of the protocol stack. The performance measures such as the average delay to retrieve an HTTP web page and network bandwidth were compared for deployments consisting of only IAB-donors, of only IAB-donors fully connected by a wired connection, and for typical IAB. The study demonstrated a significant reduction in latency when IAB-nodes are present in the network, close to the values that are collected from a fully meshed wired network consisting of IAB-donors. The authors noted the influence of the network topology and route selection schemes on its performance indicators, but did not take this into account when modeling and using abstract deployments. The work in [19] was devoted to the cross-layer modeling of routing and resource allocation. When solving these problems, the authors addressed the transmission delay, taking it into account when formulating the optimization problem. The proposed solution was evaluated based on deep reinforcement learning using the latency metric.

Thus, the study of the influence of the number of hops on end-to-end delay in IAB systems, in addition to solving the general problems of route selection and network topology, has its own relevance. However, to date, most of the research has been devoted to meeting the requirements for network reliability and throughput, as can be seen from the detailed review in Section 2.

This paper aims at assessing the impact of multi-hop transmission on the end-to-end delay in an IAB radio access network (RAN) by explicitly accounting for the half-duplex constraint. We evaluate the delay due to queuing in IAB-nodes for several IAB network topologies and different time allocation strategies between access and backhaul. The numerical results were obtained via computer simulations by utilizing the open-source software OMNeT++.

The main contributions of our work are:

- The detailed queuing-based model for delay assessment in TDM-based IAB deployments with multiple network configurations and various time allocation strategies between access and backhaul;
- Numerical results showing a linear increase in the total packet delay on the uplink and downlink as the maximum number of network tiers (hops) increases, as well as a noticeable influence of the resource allocation scheme between access and backhaul, which requires further study;
- The impact of increasing the maximum number of IAB-nodes on the end-to-end delay strongly depends on the choice of the topology and requires maintaining the optimal ratio between the maximum number of hops and the average network load. Determining this ratio is subject to further research.
The rest of the paper is organized as follows. Section 2 provides an overview of the IAB technology and its main features and also reviews the recent research on the topic. In Section 3, we describe the adopted system model and related assumptions. Further, in Section 4, we parameterize the model and outline the implementation specifics. Numerical results are then provided and discussed in Section 5. Section 6 concludes the paper.

2. Background and Related Work

In this section, we first provide a brief account of IAB technology focusing on the main features introduced by 3GPP. Then, we overview the recent studies in the field and provide their exhaustive classifications.

2.1. IAB Features and Standardization

IAB is characterized by 3GPP as a flexible technology that should reuse the features and interfaces of 5G NR as much as possible to reduce the impact on the core network. To achieve this, the IAB architecture relies on the concept of network virtualization and, particularly, on the base station functional split, which was proposed in Release 15 TR 38.816 and consists of dividing the base station into logical parts: one central unit (CU) and one or more distributed units (DUs).

The CU/DU split architecture proposed for IAB in TR 38.874 [7] is depicted in Figure 1. The IAB network consists of an IAB-donor and IAB-nodes. The IAB-donor is a logical node that provides the NR-based wireless backhaul to IAB-nodes and holds a CU and one or more wired donor DUs. The CU hosts the Packet Data Convergence Protocol (PDCP), Service Data Adaptation Protocol (SDAP), or Radio Resource Control (RRC) and terminates the control and user plane interfaces to the core network. The IAB-node, which may have multiple radio antennas, is wirelessly backhauled to the IAB-donor and consists of a DU and a mobile-termination (MT) function. The DU includes the Radio Link Control (RLC), Medium Access Control (MAC), and Physical Layer (PHY) protocols. The CU controls the DU nodes over the F1 interface(s), whereas the DU node hosts the lower layers for the NR Uu interface to the user equipment (UE). The MT allows the IAB-node to connect to an uplink node or donor, while via the DU the IAB-node, it connects to the UEs and to the MTs of downlink IAB-nodes.

The only IAB-specific protocol—Backhaul Adaptation Protocol (BAP)—was introduced in 3GPP TS 38.401 [8] and is responsible for forwarding IP data across connected IAB-nodes. The BAP data are carried by backhaul RLC channels on each link. For QoS enforcement, multiple channels can be configured for traffic prioritization. The BAP entity in nodes maps data to the appropriate backhaul RLC channel. Hop-by-hop packet forwarding is provided by the BAP routing identity, which is assigned by the IAB-donor.

Following [7], all IAB-nodes exactly one hop downlink from a given IAB-node (or the IAB-donor) are called its “child” nodes and exactly one hop uplink “parent” nodes.
Each IAB-node and the IAB-donor can have zero or more child nodes. The different link types present in an IAB network are illustrated in Figure 2. Here, the access links are the links between an IAB-node/donor and a UE, whereas the backhaul links are between two IAB-nodes or between an IAB-node and the IAB-donor.

![Figure 2. IAB link types (adapted from [7]).](image)

IAB is supposed to support out-of-band and in-band backhauling (the use of different or the same spectrum for backhaul and access, respectively). In-band backhauling involves half-duplex restrictions, implying that the MT part of an IAB-node cannot receive while its collocated DU is transmitting and vice versa to avoid intra-site interference.

The first 3GPP technical report on the IAB technology, TR 38.874, was published in January 2018. Its current version, v16.0.0 [7], addresses single-hop/multi-hop topology management, route selection, dynamic resource allocation between the access and backhaul links, and spectral efficiency. A detailed description of the IAB RAN deployment is provided in 3GPP technical specification TS 38.401 v17.0.0 [8]. 3GPP suggests the following IAB features for research and evaluation:

- Multi-hop backhauling;
- Multiplexing of the access and backhaul links;
- Multi-beaming;
- Multi-connectivity.

Multi-connectivity in the context of IAB can be interpreted in different ways, but the most interesting is the ability to connect a UE to several IAB-nodes to enable fast switching in case of channel blocking during traffic transmission.

2.2. Overview of Related Studies

The 3GPP TR 38.874 [7] identified a number of challenges that need to be investigated:

- **Topology management**: Emphasis is placed on designing the network protocols and architecture, as well as the description of traffic control procedures.
- **Route selection**: When adopting multi-hop access technology, the classic problem of traffic routing and resource allocation in the RAN is complicated by the half-duplex constraint and the need to take into account the spectral efficiency due to wireless backhauling.
- **Resource allocation between backhaul and access**: Channel multiplexing and cross-link interference are proposed for study. Resource management in the context of interference avoidance is required because 5G NR can operate at relatively low frequencies, for which antenna arrays do not have such a high directivity as for mmWave. In the case of mmWave, the problem is largely solved by spacing the IAB-node antennas at a short distance away from each other [10].
- **Spectral efficiency**: The need for improving the existing mechanisms, such as modulation and coding schemes, is expressed. However, the report also emphasizes the importance of reusing standard NR solutions as much as possible.
As can be seen in Table 1, the above-mentioned challenges have been addressed in the recent literature; however, the way to tackle any of them highly depends on whether half-duplex or full-duplex transmission is assumed. We note that the classification in Table 1 is somewhat subjective because the challenges are often related to each other. For example, it is hardly possible to study route selection and resource allocation separately, so the studies are classified according to the problem that received more emphasis. In the remainder of the section, we briefly review the literature dealing with the identified problems.

| Challenge               | Sub-Problem                                                                 | Related Papers                                      |
|-------------------------|-----------------------------------------------------------------------------|----------------------------------------------------|
| Topology management     | Protocols and architecture design                                           | [20–25] [26–31]                                    |
|                         | Control and user plane procedures for multi-hop traffic forwarding and QoS handling | [32–36] [37,38]                                    |
| Route selection         | Management of backhaul links and dynamic route selection and benefit evaluation | [9,39–46]                                         |
| Resource allocation     | Multiplexing                                                                | [11,12,47] [10,15–17,51] [48–50] [52–56]          |
|                        | Cross-link interference                                                     |                                                    |
| Spectral efficiency     | Physical Layer solutions or enhancements                                    | N/A [57–61]                                       |

2.2.1. Topology Management

The literature offers a wide variety of solutions for modifying the IAB network architecture and protocol stack: mesh-based topologies [20], user-provided networks [21], the use of mmWave unlicensed spectrum [25], moving relays [22,23,29,30], using caching storages [24], novel schemes of network coding [26], a backhaul topology to sustain bursty traffic [27], UAV-based IAB-nodes [28,31], reconfigurable intelligent surfaces (RISs) [31]. In the context of multi-hop traffic forwarding and QoS management [38], researchers address such issues as autonomous IAB-node activation and dynamic sleeping [32,33], alternative access control policies [34,35,37], and novel beam management strategies [36]. It should also be noted that case studies of IAB cell architectures with mobile IAB-nodes are already under development in Release 18 of the 3GPP specifications.

Only a few of the studies mentioned above address the packet level performance of IAB systems. Specifically, in [43], the authors investigated how the density of IAB-nodes in a cell affects the mean number of hops that a packet has to make, provided that a minimum access throughput is provisioned by the network. The IAB cell was compared with a conventional macro-cell deployment having multiple BSs. The authors also assessed the effect of the IAB-donor-to-nodes ratio on the network throughput. It was shown that a dense IAB network outperforms a macro-cell deployment in terms of throughput and also that the number of relaying points is reduced when the network is further densified by IAB-donors.

2.2.2. Route Selection

The route selection problem is mainly investigated in the context of half-duplex operation (see, e.g., [9,39–46]). Specifically, the authors of [39] conducted an extensive simulation of an IAB network with a two-hop backhaul. The cell was divided into three sectors, each having two IAB-nodes. The IAB-donor is placed in the center and has three physical antennas. The proposed resource allocation algorithms uses information on the nominal position of the IAB-nodes and determines their real position to further maximize the metric of interest, which is the spectral efficiency.

The study in [40] also considered the question of maximizing the spectral efficiency, but at the expense of forming an adaptive network topology. A related graph optimization problem was formulated and solved by combining machine learning and graph embedding methods. The works in [41,42] studied the coverage probability in single-hop IAB networks.
Specifically, the authors of [41] explored the impact of environmental factors and compared the IAB architecture with the wired backhauling option.

The authors in [44] focused on measuring the end-to-end throughput and delay at the application layer. Resources were allocated so as to maximize the first metric and to minimize the second by using a tree maximum weight matching algorithm. The studies [45,46] were devoted to the design of fair scheduling and flow control algorithms. However, the authors did not explicitly capture packet delays caused by buffering at IAB-nodes. The system model in [9] was based on the assumption that the number of hops is limited to just two network steps and the IAB-nodes are located in the best line-of-sight positions. The work aimed at developing a scheduling policy for the backhaul network.

2.2.3. Resource Allocation

The articles devoted specifically to resource allocation are fewer in number. The paper [12] briefly discussed possible improvements to resource multiplexing in an IAB network for the 3GPP Release 17. In [11], the authors considered two schemes for multiplexing access and backhaul to optimize the average packet delay and network throughput, as well as spectral efficiency. The study in [47] compared the OFDM and single-carrier quadrature amplitude modulation (SC-QAM) schemes and concluded that SC-QAM might be a better alternative. In [49,50], a single-hop backhaul IAB network was assumed. Specifically, the authors in [49] proposed an auction-based mechanism for distributing network resources among users. The problem of resource allocation was then solved by utilizing deep reinforcement learning (DRL) without taking into account IAB specifics.

The work [48] was focused on reducing network congestion and increasing the average access bit rate in full-duplex conditions. This was achieved by using a DRL-derived neural network, which receives the values of the average latency and load on the IAB-nodes as its input. However, the performance was evaluated without a benchmark; only the proposed solution was quantified under different system and environmental conditions.

The studies [10,15–17,51] considered cross-link interference (CLI) by explicitly taking into account half-duplex constraints. In [15], the authors proposed a beamformer design with the weighted queue minimization objective and resource allocation to manage the resulting CLI and to allocate wireless backhaul and access resources jointly. The study [51] considered several options for MIMO antenna arrays and investigated time slot allocation. These studies differed from [52–56], which considered CLI for full duplex. In the latter studies, the authors mainly advocated dealing with self-interference first and then proceeded to CLI management. As a measure to avoid self-interference caused by simultaneous reception, physical antenna separation and smart scheduling strategies were proposed in [10].

Finally, the studies [57–61] were devoted to technical issues related to signal precoding and beamforming.

2.2.4. Spectral Efficiency

Improving spectral efficient is a generic task that requires mechanisms from different layers. In [42], the authors considered the problem of IAB network deployment. The work focused on minimizing the blockage of the propagation paths by trees (foliage) using the multi-connectivity feature specified by 3GPP [62], namely by switching the user to another IAB-node or the IAB-donor. It was concluded that a planned node deployment provides benefits compared to a random deployment, especially in specific cases where environmental factors must be taken into account.

The authors in [63] investigated the impact of scheduling strategies, multi-beam antennas, and multi-connectivity strategies on the throughput of IAB systems operating in half-duplex mode. They showed that the use of multi-beam antennas for throughput improvement is only warranted at IAB-nodes, whereas multi-connectivity may not only improve system performance, but also induce self-load balancing in IAB systems.
2.2.5. Summary

To summarize, several points stand out. First, numerous authors considered an IAB network with the number of hops restricted to one or two for simplicity. Second, only a few studies considered the end-to-end latency as the main metric of interest; UE throughput and spectral efficiency were often optimized instead. Third, limited results were available for in-band half-duplex transmission, which must be supported by IAB systems. Furthermore, to the best of our knowledge, there have been no studies proposing an efficient general TDM pattern for IAB-node operation in this regime. Finally, we note that, due to the complexity of the problem, many authors resort to machine learning techniques, namely DRL. However, the state space of the systems is often extremely large, resulting in high solution complexity and limited tractability.

3. System Model

In this section, we introduce the system model by specifying its components. We start with assumptions on IAB system operation, then proceed to specify the topology and the packet transmission process and complement the model with a detailed TDM parametrization. Finally, the metrics of interest are introduced.

3.1. IAB System Specifics

In this study, we considered an IAB system operating in the in-band half-duplex mode. The former implies that the bandwidth $B$ is utilized at both the access and backhaul links. Relying on the results of [10], we assume that the IAB-node and IAB-donor can simultaneously either transmit or receive on all their physical antennas. However, simultaneous transmission and reception are not feasible due to excessive interference. Semi-centralized coordination of resources was assumed, where the CU makes a decision on long-term resource allocation according to TDM operation to avoid violating half-duplex constraints.

We assumed mmWave operation of the IAB system. The capacity of the access and backhaul links can be abstracted by utilizing Shannon’s law:

$$ C = B \log_2 \left(1 + \frac{P_T G_T G_R}{P_L N_0 B_{PRB} M_{SF} L} \right), \quad (1) $$

where $P_T$ is the emitted power, $G_T$ and $G_R$ are, respectively, the transmitter’s and the receiver’s antenna gains, $N_0$ is the thermal noise power spectral density, $B_{PRB}$ is the size of the physical resource block (PRB), $M_{SF[dB]} \sim \text{Norm}(0, \sigma_{SF\text{LoS/SF\text{fLoS}}})$ is the slow fading, and $L$ represents aggregated losses given, in decibels, by

$$ L_{[dB]} = M_I + F_N + L_C \quad (2) $$

with $M_I$ being the interference margin, $F_N$ the noise figure, and $L_C$ the cable losses.

3.2. Topology Description

We considered an IAB network having one IAB-donor and $N - 1$ IAB-nodes numbered from 2 to $N$. We say that the network consists of $N$ network nodes and refer to the IAB-donor as Node 1. We further assumed that network node $n = 1, \ldots, N$ has $A_n$ antenna sectors numbered from 1 to $A_n$. Each antenna sector provides uplink and downlink communication to UEs and can support one wireless backhaul connection to another network node.

The network topology was assumed fixed and tree-shaped with the IAB-donor, i.e., Node 1, at its root. In other words, a single specific route exists between the IAB-donor and each IAB-node. Such a topology can be represented by a matrix $M = (M_{ij})_{i,j=1,\ldots,N}$, where entry $M_{ij} \in \{0,1,\ldots,A_i\}$ is either the antenna sector in node $i$ through which it communicates with node $j \neq i$ or 0 if there is no link between these nodes. Note that if $M_{ij} = 0$, then $M_{ji} = 0$, and conversely, if $M_{ij} > 0$, then $M_{ji} > 0$. We let $M_{ij} = 0$ for all $i = 1, \ldots, N$. 

An example of an IAB RAN with $N = 3$, $A_1 = 4$, and $A_n = 3$ for $n = 2, 3$ is depicted in Figure 3. We say that a network node belongs to tier $k$ if its distance (the number of links) from Node 1 is $k - 1$. Node 1 is hence always the only node in Tier 1. Node 2 in Figure 3 belongs to Tier 2. It is connected to Node 1, which corresponds to the IAB-donor, through its Sector 1 and to Node 3 through Sector 2. The backhaul topology of the network in Figure 3 is given by

$$
M = \begin{bmatrix}
0 & 3 & 0 \\
1 & 0 & 2 \\
0 & 3 & 0
\end{bmatrix}.
$$

(3)

Figure 3. Example of an IAB RAN.

3.3. Packet Transmission

Any sector at any network node can have associated UEs. The IAB network transfers packets between the UEs and the core network, to which the IAB-donor is fiber-backhauled. Because mmWave NR is capable of extremely high data rates and this work is specifically focused on the TDM-induced delay, we assumed that the radio transmission of a packet between nodes or between a node and a UE occurs instantaneously. However, since not all the links can be active at the same time due to TDM, packets have to be buffered and wait for the link to be activated.

As is shown in Figure 4, we let each sector of each node have one backhaul (BH) and two access buffers, one outbound (or downlink, $AC_{DL}$) and one inbound (or uplink, $AC_{UL}$). The inbound access buffer is an abstraction representing the packets waiting for uplink transmission at all UEs associated with the sector. The outbound access buffer contains the packets destined to the UEs associated with the sector. The backhaul buffer contains the packets waiting for transmission via the backhaul link supported by the sector antenna. It can correspond to either the downlink or uplink direction depending on whether the connected node is, respectively, farther from or closer to Node 1.

Consider a packet traveling from a UE (uplink) associated with sector $i$ of node $n$ (denoted as $(n, i)$). Let node $n$ belong to tier $k$. First, the packet arrives at the inbound (uplink) access buffer of sector $(n, i)$. Then, upon activation of the uplink access link in sector $(n, i)$, the packet reaches the node. If $n = 1$ (the node is the IAB-donor), then the packet leaves the system right away. If $n > 1$, then the packet instantaneously moves to the backhaul buffer of a sector $(n, j)$ facing tier $k - 1$, i.e., of a sector linking node $n$ to a node belonging to tier $k - 1$ (it is possible that $j = i$). For the packet to move the next hop towards the IAB-donor, the link between node $n$ and node $m$ such that $M_{n,m} = j$ must be activated. As soon as this happens, the packet arrives at node $m$. Then again, if $m = 1$, the
packet leaves the system, and if \( m > 1 \), then the packet joins the backhaul buffer in the sector facing tier \( k - 2 \). The process continues until the packet reaches Node 1 and leaves the system. By the total packet delay in the uplink, we understand the time from the instant the packet joins the inbound access buffer in its sector to the instant it leaves the system.

**Figure 4.** Queuing network representation of an IAB-node.

Next, consider a packet traveling downlink, from the core network to a UE in sector \((n, i)\), with node \( n \) belonging to tier \( k \). If \( n = 1 \), then the packet enters the system by joining the outbound access buffer in sector \((1, i)\) and leaves as soon as the corresponding access link is activated. If \( n > 1 \), then the packet first joins the backhaul buffer in a sector \((1, j)\) linked to node \( n \) if \( k = 2 \) or to a Tier 2 node through which node \( n \) can be reached. Once the backhaul link is activated, the packet arrives at node \( m \) such that \( M_{1,m} = j \). If \( m = n \), then the packet joins the outbound access buffer in the destination sector \((n, i)\) and waits for the outbound access link to be activated, upon which it leaves the system. If \( m \neq n \), the packet is put into the backhaul buffer in a sector linking node \( m \) with node \( n \) or a Tier 3 node through which node \( n \) can be reached, etc. The process continues until the packet leaves the outbound access buffer in node \( n \). By the total packet delay in the downlink, we understand the time from the instant the packet joins a buffer in Node 1 to the instant it leaves the system via an access link.

### 3.4. Time Division Duplexing and Multiplexing

As was stated previously, due to the utilized TDM scheme, not all the links can be activated simultaneously. We assumed that, at each time instant, each network antenna sector can be in one of the following states:

1. Transmitting to a network node (transmit backhaul);
2. Receiving from a network node (receive backhaul);
3. Transmitting to associated UEs (transmit access);
4. Receiving from associated UEs (receive access).

Furthermore, in order to limit self-interference, we assumed that, at each time instant, all sectors of the same node can either all transmit or receive. For example, at a time \( t = t_1 \)
in a node \( n \), Sector 1 can be receiving backhaul and Sectors 2 and 3 receiving access, while at a time \( t = t_2 \), all sectors can be transmitting access.

In order to activate access links and transmit packets from the access buffers, it suffices that the corresponding sector goes into states transmit access or receive access. Thus, e.g., as soon as a sector \((n, i)\) enters state receive access, all the content of the sector’s inbound access buffer reaches node \( n \), and furthermore, any packet joining this buffer while the sector is in the receive access state goes straight to node \( n \).

To activate a backhaul link, however, coordinated actions of two connected sectors are required: one has to transmit backhaul and the other to receive backhaul. Going back to Figure 3, the backhaul link between Nodes 1 and 2 is activated for downlink transmission (from Node 1 to Node 2) whenever Sector \((1, 3)\) is transmitting backhaul and Sector \((2, 1)\) is receiving backhaul. During this time, all packets from the backhaul buffer in Sector \((1, 3)\) instantaneously move to Node 2. Similarly, the backhaul link between Nodes 2 and 3 is activated uplink if Sector \((3, 2)\) is transmitting backhaul and Sector \((2, 2)\) is receiving backhaul. If in a given topology, a sector is not used for backhaul, its feasible states are transmit access and receive access, since being in states transmit backhaul and receive backhaul would not result in any link activation.

### 3.5. Performance Metrics

In this work, we aimed at evaluating the TDM-induced end-to-end packet delay in the IAB access network. Thus, we are interested in the following metrics:

- The total packet delay in the uplink defined as the time from the instant the packet joins the inbound access buffer in its sector to the instant it leaves the system;
- The total packet delay in the downlink defined as the time from the instant the packet joins a buffer in Node 1 to the instant it leaves the system via an access link.

### 4. Scenario and Parameterization

In this section, we first introduce the considered Manhattan-like deployment scenario. Then, we parameterize and specify the usage of TDM patterns. Finally, we briefly describe the simulation setup and data collection techniques.

#### 4.1. Considered Scenario

5G IAB NR network deployments are generally targeted at urban environments, where the signal propagation is heavily obstructed by large obstacles such as buildings. Specifically, the signal propagates mainly through the streets, blocked by buildings, preventing it from penetrating and reaching areas around their corners. As an example, for the numerical evaluation, we considered a Manhattan grid environment typical for city centers. Here, the natural deployment points of the BSs were street intersections, and their density was the main scenario parameter.

The average size of a Manhattan block is 76 by 183 m [64], and the average avenue/street width is 30 m. We assumed that the nodes’ antenna coverage radius is 210 m or less [5]. The nodes were installed according to the topologies depicted in Figure 5. An example of deploying Topology # 2 is shown in Figure 6. It was assumed that \( A_1 = 4 \) and \( A_n = 3 \) for \( n = 2, \ldots, N \).

Let the UEs be evenly distributed across the streets’ area. We modeled packet arrivals from all UEs associated with sector \((n, i)\) as a single Poisson process with parameter \( \lambda_{n,i} = L_{n,i} \lambda \), where \( L_{n,i} \) is the average number of UEs in sector \((n, i)\) and \( \lambda \) is the average packet arrival rate from one UE. Downlink packet arrivals destined to UEs in sector \((n, i)\) are represented as a Poisson process with parameter \( a \lambda_{n,i} \), where \( a \) is a coefficient that specifies the load ratio between downlink and uplink.

The first hop in a multi-hop network is the “bottleneck” and must provide throughput for all IAB-nodes down the hop chain. This is one of the main limitations of IAB network scaling.
4.2. Parameterized TDM Pattern

In this work, for a tractable delay estimation, we considered the following fixed parameterized TDM pattern. The pattern was repeated every $2T$ ms and consisted of two equal macro-phases. During the first macro-phase of length $T$ ms, i.e., in time intervals $[2nT, (2n + 1)T)$, $n \in \mathbb{N}$, all the network nodes in odd tiers (Tiers 1, 3, etc.) transmit, while all the network nodes in even tiers (Tiers 2, 4, etc.) receive. During the second half of the pattern, i.e., in time intervals $[(2n + 1)T, 2(n + 1)T)$, $n \in \mathbb{N}$, the opposite happens: all the network nodes in odd tiers receive, while all the network nodes in even tiers transmit.

Each macro-phase is divided into the backhaul and access micro-phases. For the sake of synchronization, the backhaul micro-phase comes first, followed by the access micro-phase. While the macro-phases are common for the whole network, the ratio between micro-
phases, i.e., between backhaul and access, can be set individually for each pair of connected sectors or network tiers. It is convenient to specify the backhaul/access micro-phase durations by an \( N \times N \) matrix, say \( \mathbf{D} = (D_{ij})_{i,j=1,...,N} \), where entry \( D_{ij} \in [0,1] \) indicates the portion of the macro-phase the backhaul link from node \( i \) to node \( j \) is activated.

To illustrate the above notation, let us go back to Figure 3 and consider an example. Here, Sectors 1, 2, and 4 of Node 1 do not support backhaul links, and Node 1 belongs to Tier 1 (odd); therefore, the TDM patterns for these sectors will be:

1. \( 0 \leq t < T \): transmit access;
2. \( T \leq t < 2T \): receive access.

Exactly the same pattern will be followed by Sectors 1 and 3 of Node 3, since it also belongs to an odd tier (Tier 3) and these sectors have no backhaul links. Sector (2,3) has no backhaul link, but the node belongs to an even tier (Tier 2); hence, it follows the symmetrical pattern:

1. \( 0 \leq t < T \): receive access;
2. \( T \leq t < 2T \): transmit access.

Now, Sectors (1,3) and (2,1) are linked to each other (\( M_{1,2} = 3 \) and \( M_{2,1} = 1 \)). To activate the link between them in either direction, the TDM pattern of these sectors must contain a non-zero backhaul micro-phase. To specify the lengths of these micro-phases, we used parameters \( D_{1,2} \) and \( D_{2,1} \). Transmission from Node 1 to Node 2 is possible only when Node 1 is transmitting and Node 2 is receiving, i.e., during the first macro-phase of the pattern. This macro-phase lasts \( T \) ms and is divided into the backhaul and access micro-phases by the parameter \( D_{1,2} \): the backhaul lasts \( D_{1,2}T \) ms and the access \((1 - D_{1,2})T \) ms. Parameter \( D_{2,1} \) characterizes the transmission from Node 2 to Node 1 and, hence, specifies the subdivision of the second macro-phase into a backhaul micro-phase of length \( D_{2,1}T \) and an access micro-phase of length \((1 - D_{2,1})T \). Thus, Sectors (1,3) and (2,1) follow symmetrical patterns of the form:

1. \( 0 \leq t < D_{1,2}T \): (1,3) transmits backhaul, (2,1) receives backhaul;
2. \( D_{1,2}T \leq t < T \): (1,3) transmits access, (2,1) receives access;
3. \( T \leq t < T + D_{2,1}T \): (1,3) receives backhaul, (2,1) transmits backhaul;
4. \( T + D_{2,1}T \leq t < 2T \): (1,3) receive access, (2,1) transmits access.

Table 2 gives the TDM patterns for sectors \((i, M_{ij})\) and \((j, M_{ji})\) for any \( i \) and \( j \) such that \( M_{ij} > 0 \) in the general case. The application of non-synchronized TDM patterns in the network of Figure 3 is illustrated in Figure 7. Here, \( T = 6 \) transmission time intervals (TTIs), and the durations of the backhaul micro-phase in different backhaul-supporting sectors were set \( \frac{T}{2}, \frac{T}{2}, \frac{T}{2} \). Non-synchronized micro-phases in linked sectors lead to channel downtime and the waste of resources. For example, the backhaul micro-phase in Sector (1,3) is \( \frac{T}{2} \), while in the linked Sector (2,1), it is \( \frac{T}{2} \), which results in a downtime of \( \frac{T}{6} \) TTIs for both antennas in each pattern run.

**Table 2.** The TDM pattern specified by matrix \( \mathbf{D} \) for any linked sectors \((i, M_{ij})\) and \((j, M_{ji})\); node \( i \) belongs to an odd tier, \( n \in \mathbb{N} \).

| Start Time | End Time | Sector \((i, M_{ij})\) | Sector \((j, M_{ji})\) |
|------------|----------|------------------------|------------------------|
| \(2nT\)    | \(D_{ij}T + 2nT\) | transmit backhaul        | receive backhaul        |
| \(D_{ij}T + 2nT\) | \((2n + 1)T\) | transmit access          | receive access          |
| \((2n + 1)T\) | \(D_{ij}T + (2n + 1)T\) | receive backhaul         | transmit backhaul       |
| \(D_{ji}T + (2n + 1)T\) | \((2n + 1)T\) | receive access           | transmit access         |
4.3. Implementation Specifics and Data Collection

The considered IAB system model was implemented in the OMNeT++ simulation environment. OMNeT++ is a general-purpose discrete-event simulator (DES), supporting main networking functions and allowing for flexible extensions. To implement the considered scenario, we extended the library "queuinglib" with the classes presented in Figure 8. The Sink, Queue, and Source classes correspond to the standard components of queuing theory models.

![Figure 7. The considered non-synchronized TDM patterns.](image)

![Figure 8. Simulator classes diagram.](image)
Network initialization begins with the link manager interpreted by the \text{LinkManager} class. It receives the model’s input parameters and configures the links between nodes according to the given topology. This module implements link scheduling following the TDM pattern and coordinates the operation of the entire network. Due to the peculiarities of the chosen topologies, upstream routing is a simple task, because there is always only one parent node. In the case of downstream, each packet is assigned a header with information about the destination node and the sector in which the service takes place. After the initialization of the network, based on matrix $M$, route tables are compiled and sent to each node. Thus, knowing the destination node number and self number, each node uniquely determines the next recipient. The route table consists of pairs of directly linked nodes, i.e., for the network in Figure 3, we have routes:

\begin{align*}
1: & () \\
2: & (1,2) \\
3: & (1,2), (2,3)
\end{align*}

Here, the destination node is specified before the colon, and the first value (key) in the pairs is the number of the node where the packet is currently located. Using the packet header, the line in the route table is determined, and using the number of the current node, the number of the next one (the second value in the pair) is found. The packet is directed to the antenna sector maintaining the backhaul link with this node. When the packet arrives at the destination node, the previous node of the route is determined from the same route table (now the second value is used as a key). Knowing this, we determine the sector of the antenna on which reception will be carried out.

We extended the standard \text{Queue} class to \text{QueueWithGate} by adding an abstract gate that prevents packets from leaving the queue if the link to another node is not active. The \text{CoreNetwork} class consists of a sink for upstream packets and a set of packet sources whose number equals the total number of antennas in the network. The \text{Antenna} class consists of a number of queues (buffers) with gates according to Figure 3 and includes \text{UE}s, which describe associated groups of users. \text{IABNode} contains an array of antennas and some variable parameters that are needed to capture the node state.

To obtain the simulation data reliably, the method of replications with sampling was utilized [65]. Specifically, for each considered set of system parameters, the simulation was performed 30 times with different random seeds. The overall duration of each experiment was set to 600 s. To get rid of the residual correlation in obtained data, each 10th packet was sampled. Data were collected during the steady-state period only. To detect the beginning of the steady-state period, the exponentially weighted moving average (EWMA) was utilized. Then, the obtained latency values in each experiment were averaged and then utilized to form an independent and identically distributed (iid) sample for further statistical analysis.

5. Numerical Results

In this section, we report our numerical results for the IAB model specified in Section 3 and parameterized in Section 4. The main metrics of interest are the uplink and downlink packet delivery latencies as functions of the system parameters.

To calculate the packet arrival rates, 1000 UEs were distributed over an area of size $1260 \times 1260$ m. The coverage radius was set to 105 m for the IAB-nodes and to 210 m for the IAB-donor. We set $TTI = 1$ ms, $T = 6$ TTIs, $\lambda = 200$ s$^{-1}$, and $\alpha = 4$.

Finally, the ratios between micro-phases for each network tier were set as follows:

- Topology #1: Tier 1: $2/3$ T, Tier 2: $1/3$ T.
- Topology #2: Tier 1: $5/6$ T, Tier 2: $1/2$ T, Tier 3: $1/3$ T.
- Topology #3: Tier 1: $2/3$ T, Tier 2: $1/2$ T, Tier 3: $1/3$ T.
- Topology #4: Tier 1: $5/6$ T, Tier 2: $2/3$ T, Tier 3: $1/2$ T, tier 4: $1/6$ T.

Note that, to cover the area under consideration, we need:
• 9 networks of Topology # 0 (only IAB-donor),
• 7 networks of Topology # 1 (IAB-donor + 3 IAB-nodes),
• 6 networks of Topology # 2 (IAB-donor + 5 IAB-nodes),
• 4 networks of Topology # 3 (IAB-donor + 7 IAB-nodes) or
• 2 networks of Topology # 4 (IAB-donor + 14 IAB-nodes).

Figure 9 shows the end-to-end delay as a function of the number of nodes in the network. Adjusting the micro-phases on the tiers can reduce packet latency by approximately 5 ms in the upstream. As a baseline, we utilized the latency observed in a network with one IAB-donor and no IAB-nodes (Topology #0, \( N = 1 \) in Figure 9). In this case, the deployment is significantly more expensive, although the delay is minimal.

![Figure 9. Delay vs. number of nodes.](image)

Figure 10 depicts the end-to-end delay vs. the number of hops. It can be observed that the trend is close to linear, and the delay increases by about 4–6 ms with each network hop (node tier).
6. Conclusions

In this work, we propose a detailed queuing-based model for delay assessment in TDM-based IAB deployments with multiple network configurations and parameterized time allocation strategies between access and backhaul. The numerical results showed that balancing the access and backhaul micro-phases reduces the total packet delay, at least for the uplink, for our configuration. Increasing the maximum number of network hops yields a linear increase in the total packet delay for both uplink and downlink. Our further research will be aimed at obtaining a more detailed picture of the impact of network parameters on the end-to-end packet delay.

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