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Research

Delay reduction and interference mitigation by resource management for IAB networks

Chourouk Ghodhbane^{1,2} · Patrick Savelli¹ · Cedric Gueguen² · Xavier Lagrange³

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Abstract

To overcome the increasing demand for high-throughput data services, the 3rd Generation Partnership Project (3GPP) has proposed Integrated Access and Backhaul (IAB) in Release 16 as a scalable and cost-effective alternative to traditional fiber backhaul for 5 G systems. A key feature of IAB is the shared use of the same spectrum band for both access and backhaul communications, which introduces challenges related to interference, delays, capacity sharing, and additional complexity due to the half-duplex constraint. In this paper, we provide an overview of the 3GPP guidelines for IAB resource management and introduce a semi-centralized, heuristic-based resource management policy aimed at jointly enhancing end-to-end delay and minimizing interference in IAB networks, in compliance with 3GPP standards. We conduct a comparative study of our proposed policy against several policies, including the baseline proposed by 3GPP. The evaluation is performed through discrete-event simulations under two types of traffic and varying network loads. The simulation results underline that our semi-centralized resource management policy effectively controls interference, leading to improved network Key Performance indicators (KPIs) like system throughput and end-to-end delay. Specifically, our solution achieves up to an 11% increase in system throughput and a 30% reduction in end-to-end delay compared to the baseline for constant traffic, while for variable traffic, it results in a 16% increase in system throughput and a 26% reduction in end-to-end delay.

Article Highlights

- The algorithm complies with 3GPP standards, providing practical insights for real-world IAB networks.
- The Proposal strikes a balance between interference management and resource sharing.
- The policy reduces network delay by up to 30% and increases system throughput by up to 16%.

Keywords Delays · Integrated access and backhaul (IAB) · Interference · Resource management

✉ Chourouk Ghodhbane, chourouk.GHODHBANE@b-com.com; Patrick Savelli, Patrick.SAVELLI@b-com.com; Cedric Gueguen, cedric.gueguen@irisa.fr; Xavier Lagrange, xavier.lagrange@imt-atlantique.fr | ¹Advanced Connectivity Lab, Institute of Research and Technology b-com, 35510 Rennes, France. ²IRISA UMR CNRS 6074, University of Rennes, 35042 Rennes, France. ³IRISA UMR CNRS 6074, IMT Atlantique, 35510 Rennes, France.



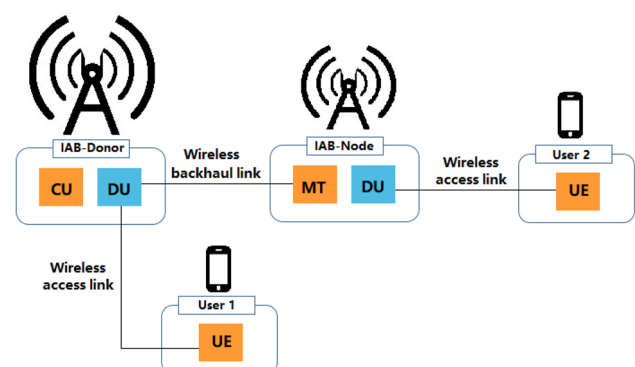
1 Introduction

With the significant increase in the number of users and their demands for services, operators are challenged to densify their networks to ensure adequate coverage and capacity. However, traditional densification methods can be costly and often involve prolonged deployment times. This is where the Integrated Access and Backhaul (IAB) architecture, proposed by the 3rd Generation Partnership Project (3GPP) in Release 16 [1, 2] of 5 G systems, comes into play to address these issues. IAB offers a promising approach by combining access and backhaul functionalities within the same frequency bands, thus optimizing the use of spectrum and enhancing network efficiency. One of the key advantages of IAB is its remarkable flexibility. Unlike conventional networks that rely heavily on extensive fiber optic backhaul infrastructure, IAB can dynamically reconfigure and extend the network using wireless links. This wireless backhaul capability is particularly beneficial in scenarios where deploying physical cables is impractical or cost-prohibitive. As a result, IAB enables mobile operators to swiftly deploy additional capacity exactly where and when it is needed: for instance, during major public events or in urban hotspots experiencing unexpected surges in traffic. IAB addresses this challenge by allowing rapid deployment of wirelessly connected next Generation Node Bs (gNBs) called IAB nodes acting as relays. They can offload traffic from a congested gNB called IAB donor which is generally connected with fiber to the Core Network (CN). These IAB nodes can be seamlessly integrated into the existing network infrastructure, ensuring consistent and high-quality service. Moreover, the deployment of IAB nodes does not require extensive planning and civil works typically associated with laying fiber. This significantly reduces the time and cost involved in network expansion. Operators can quickly respond to traffic demands, whether in densely populated urban areas or remote rural locations, enhancing overall network agility and resilience.

As shown in the example of Fig. 1, We have an IAB network composed of a main gNB, the IAB-donor, and an IAB-node that is wirelessly connected to the IAB-donor. In this example, the IAB topology offers the possibility for the User Equipment (UE) to connect to the core network either directly through the IAB donor as the User 1, or indirectly by multi-hop relaying connections through IAB nodes as the User 2. The direct connection is represented via an access link between the UE and the IAB donor. The indirect connection is represented via an access link between the UE and a IAB-node and one or more backhaul links between a IAB-node and the IAB donor depending on the number of hops. Even though we can assume better propagation conditions on the backhauling links with respect to the access link, the extra resource cost of transmitting backhaul data in IAB is significant. Consequently, if the data flow is routed through an IAB-node, the throughput depends on two links. Thus, several strategies for cell selection are proposed in the literature [3–5], but until now there is no standardized policy.

In IAB networks, the fact that the frequency band used for the backhaul link is the same as for the access link is referred to as “in-band backhauling”. The in-band operation allows the operator to avoid paying for a new frequency. However, it presents specific technical challenges. Notably, an IAB node cannot receive and transmit simultaneously on the same frequency, necessitating careful scheduling to avoid self-interference. Due to this half-duplex constraint, a semi-static configuration is defined by the 3GPP [1, 2], that can authorize or deny transmission by an IAB node or a UE to manage transmission permissions. The risk of significant interference is heightened when two proximate gNBs IAB transmit at the same time on the same frequency. Such scenarios are particularly problematic in densely populated urban environments, where physical proximity of IAB nodes can lead to severe signal interference, degrading network performance through reduced throughput, increased latency, and potential connection drops.

Fig. 1 Different IAB link types



The 3GPP recommendations do not provide specific policy for resource management and interference mitigation, leaving these critical tasks to network operators and IAB solution providers. In this context, we propose in this paper a new resource management policy specific to IAB networks. Our proposed policy enables time resource repartition for delay reduction and interference mitigation.

The rest of the paper is organized as follows. In sect. 2, the state of the art is presented. Sects. 3 and 4 include the description of the IAB resource management problem and our contribution, respectively. Sects. 5 and 6 illustrate our system model and performance evaluation results, respectively. Finally, Sect. 7 concludes the paper and discusses possible extensions of this work.

2 Related work

The allocation of shared bandwidth resource between backhaul and access is a hot topic that has been the subject of several research studies with different approaches over the last few years.

In [6], the authors address the IAB resource allocation problem by formulating it as a linear program. They aim to enhance network performance and reliability. To solve this, they propose an iterative approximate algorithm and a Graph Neural Network (GNN) based algorithm. Simulations show that combining these algorithms improves spectral efficiency and overall network performance. In [7], The authors address routing and resource allocation challenges in fifth generation (5 G) IAB multi-hop networks, where mutual interference can limit capacity. They formulate an optimal routing problem to minimize latency while meeting reliability requirements. To solve this, they propose a Deep Reinforcement Learning (DRL) framework that operates with perfect knowledge of network topology and channel conditions. ns-3 simulation results show their algorithm outperforms existing state-of-the-art algorithms in terms of latency and reliability. In [8], authors address access and backhaul band partitioning in IAB networks with a semi-centralized resource allocation approach. They introduce an optimal scheme based on the Maximum Weight Matching (MWM) problem on graphs. Managed by a central controller, typically located at the IAB-donor, this approach assumes timely feedback exchange between IAB-nodes and the donor regarding Channel State Information (CSI) and buffer status. The framework aims to optimize a utility function, such as maximizing throughput, with linear complexity relative to network size. Their system-level simulations demonstrate superior performance in throughput and end-to-end delay compared to state-of-the-art distributed approaches.

In [9], the authors compare static and dynamic bandwidth allocation strategies for millimeter-wave (mmWave) IAB in 5 G networks. They propose two approaches: Integrated Resource Allocation (IRA), dynamically dividing bandwidth between access and backhaul based on load, and Orthogonal Resource Allocation (ORA), statically dividing bandwidth between the two. IRA employs round-robin scheduling to divide bandwidth among users, while ORA reserves a portion for access and allocates the rest to backhaul. Monte Carlo simulations demonstrate IRA's superiority over ORA in handling varying backhaul loads effectively. In [10], the authors propose a novel scheduler for IAB networks designed to meet Quality-of-Service (QoS) requirements across various service types. Their approach considers the multi-hop relay topology, backhaul constraints, and specific QoS demands. The scheduler operates in two stages: the first stage schedules access and backhaul flows, while the second stage distributes allocated traffic volumes to downstream flows under backhaul flows. Each flow type (Guaranteed Bit Rate (GBR), Non-GBR, Delay-critical GBR) is managed using tailored state-of-the-art scheduling algorithms that match its QoS needs. System-level simulations demonstrate the scheduler's ability to maintain QoS requirements even under heavy network load. In [11], the authors address the challenge of delay-aware scheduling in IAB networks, which are prone to delays and performance issues due to uneven traffic distribution across multi-hop relays. They model the scheduling problem as a Markov Decision Process (MDP) and propose a strategy that jointly optimizes user traffic routing and the multiplexing of access and backhaul links under half-duplex and interference constraints. To solve the MDP's complexity, they explore several approximation methods, including Q-learning, Monte Carlo Tree Search (MCTS), and genetic algorithms (GAs).

The studies mentioned above introduce various techniques for sharing bandwidth between backhaul and access in IAB networks, each employing distinct methodologies and goals. However, none of these works explicitly explore the semi-static configuration defined the 3GPP to provide efficient resource allocation policies.

In [12], the 3GPP introduced an IAB-donor coordinated policy for resource management. To prevent interference between IAB-nodes, the same soft slot will not be allocated to two IAB-nodes that could potentially conflict with each other. However, this proposal lacks a specific algorithm for managing hard resources.

In [13], authors propose Coordinated Parallel Resource allocation scheme (CPReal), a novel resource allocation scheme for IAB networks that integrates the semi-static configuration. CPReal involves coordinated parallel resource allocation to optimize network performance, hard resources are allocated by the IAB-donor for GBR traffic, while soft resources are allocated by the IAB-nodes for bursty traffic, with assistance from the IAB-donor, addressing the challenges of interference and efficient use of the spectrum. Event-driven simulations demonstrate CPReal's superior performance in terms of end-to-end delay and throughput compared to the baseline proposed by the 3GPP [12].

In [13], first, the resource allocation in terms of Resource Blocks (RBs) deviates from the 3GPP standard, which specifies resource multiplexing at slot or symbol levels, not at the RB level. This discrepancy could impact interoperability and compliance with industry standards. Second, the authors of this paper suppose that the IAB-donor knows the modulation and coding scheme (MCS) of each network link, which is not a realistic hypothesis. Based on this unrealistic hypothesis, the IAB-donor can allocate the required hard resources precisely. Third, the proposed policy allocates a portion of the hard resources for control messages to ensure coordination between nodes and to resolve allocation conflicts. This approach may limit the resources available for data transmission, particularly in dense networks with many IAB-nodes.

3 IAB resource management problem formulation

The IAB donor handles two units: a Central Unit (CU) in charge of the IAB topology and routing management, and a Distributed Unit (DU) that provides radio access to a user and maintains the backhaul radio connection. The IAB node also handles two units: a DU like the donor and a Mobile Termination (MT) to set up a backhaul connection via a parent node (IAB donor/ IAB node). The IAB shared resource band between MT and DU sides of the IAB node, is a time-frequency resource grid. In the frequency domain, one RB corresponds to 12 subcarriers, and in the time domain one slot corresponds to 14 consecutive symbols. Symbols in a slot can be classified as [1, 2]:

- Uplink (UL): The resource will be used for transmission in the Uplink (UL) direction and reception in the Downlink (DL) direction.
- Downlink (DL): The resource will be used for reception in the UL direction and transmission in the DL direction.
- Flexible (F): The resource can will be used either for UL or for DL.

Due to the half-duplex constraint, a semi-static configuration is defined for the configuration of the DU resource part, in order to coordinate the MT and DU parts. According to the 3GPP [1, 2], each of the DL, UL, and Flexible (F) time resource types of the DU resource are further configured as:

- Hard (H): The time resource is always available for the DU part.
- Soft (S): The time resource can only be used if that does not impact the MT's ability to receive and/or transmit and the availability of the corresponding time resource for the DU part is explicitly and/or implicitly controlled by the parent gNB.
- Not Available (NA): The time resource is always not available for the DU part.

In the case of a soft configuration, the DU party can use the time resource if the IAB node concludes that this does not affect the MT's ability to transmit/receive because, for example, there is no data available for MT transmission [14], referred as implicit indication of availability of soft DU resource, or the parent node provides an explicit indication of the availability of the soft DU time resource via a Downlink Control Information (DCI) message [15].

IAB support both slot and symbol-level multiplexing of access and backhaul links [14], for this work, we consider slot-level multiplexing.

The resource allocation of the different time resource types mentioned above in IAB networks is managed by the Media Access Control (MAC) layer and according to 3GPP [12], can be defined in a semi-centralized way by two complementary stages. The first stage is controlled by the MAC layer of the IAB donor to ensure time slot resource repartition between the different gNBs (donor and nodes) operating in the network. In the second stage, each gNB, in each of their allocated time resource, performs a classical scheduling algorithm such as round robin scheduling to select the appropriate RBs for its children.

The main challenge is to share the different types of radio resource mentioned above efficiently between the network gNBs, in the case of a simple star topology.

4 Description of the JODI policy for IAB networks

JOint enhancement of Delay and Interference (JODI) is our proposed resource management policy for IAB networks. JODI aims to determine the resource allocation scheme that jointly reduces interference and delays in IAB single-hop context defined in 3GPP standards, where IAB nodes are associated with the donor directly. This policy allows the IAB donor to determine the efficient time slot resource repartition that reduces interference and delay by applying the algorithm summarized by the flow chart presented on Fig. 2. JODI manages 5 types of resource: hard, soft, and not available resource, as defended by the 3GPP, combined with Soft+ (S+) and Soft- (S-) resource. The two additional resource types introduce soft resource priority management, where soft+ represents the highest priority soft resource, and soft- represents the lowest priority soft resource. To manage these 5 types of resource, at each new Repartition Period (RP) JODI allocates hard, soft, soft+, and soft- slots in that order, and at each Scheduling Period (SP), each gNB will start occupying its allocated slots in the following order hard, soft+, soft, and soft-. The resource allocation process, as explained in Sect. 1 is divided into several fixed-length RPs (stage 1), each of which in turn consists of several fixed-length SPs (stage 2) as shown in Fig. 3.

4.1 Hard resource repartition

The allocation of hard resource is based on a calculation of the number of slots required on each (access or backhaul) link, depending on traffic load and link quality. Traffic load is perfectly known to the donor in case of DL traffic, or determined on the basis of Scheduling Request (SR) [16], Buffer Status Report (BSR) [16], and pre-emptive BSR [16, 17] messages received by IAB nodes in case of UL traffic. These MAC signaling messages SR, BSR, and pre-emptive BSR, are made to inform the donor that it needs resource for UL transmission without indicating the volume of data to be sent, the volume of UL buffered data to be sent, the expected volume of UL data (rather than buffered data) that will arrive at an IAB node from its children, respectively. Link quality is determined on the basis of the donor's Signal-to-interference-plus-noise

Fig. 2 JODI flow chart

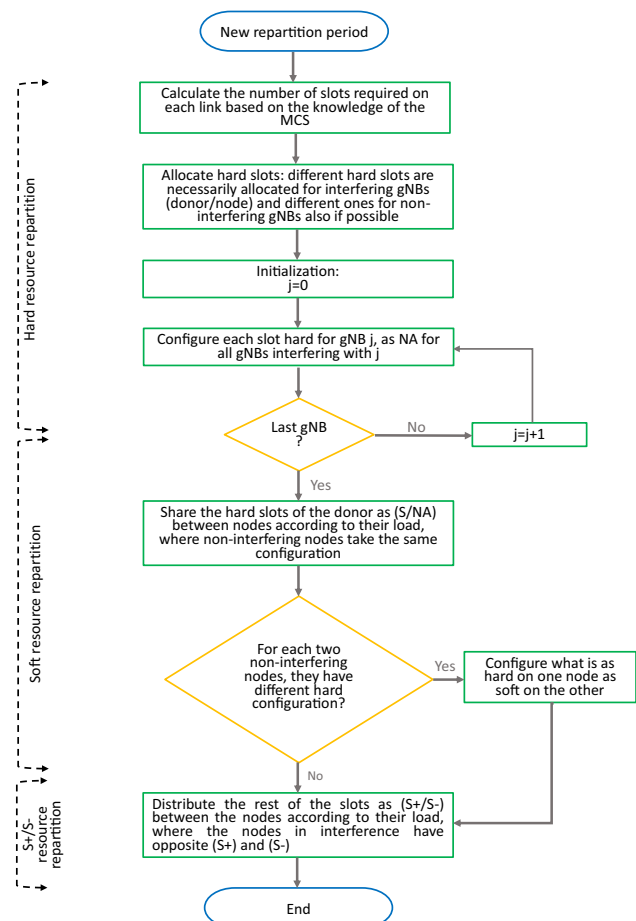
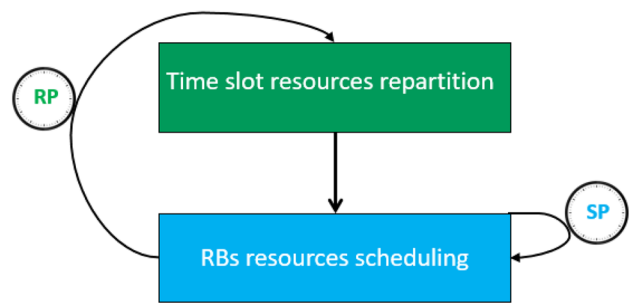


Fig. 3 Repartition and scheduling periods



ratio (SINR) knowledge on each link, where we assume that the donor has knowledge of the SINR value on access links with its directly associated users and on backhaul links with its associated IAB nodes. Donor’s knowledge of SINR is based on the Channel Quality Indicator (CQI) information periodically reported by UEs [18] and IAB nodes [19] for access and backhaul, respectively. The donor uses these reports to determine SINR on the basis of CQI-SINR mapping table proposed in [20, 21].

The CQI represents the quality of the channel between the IAB donor and the UE or IAB node for transmitting down-link data and allows IAB donor to make decisions about resource allocation, scheduling, and link adaptation to optimize network performance. We assume also that the donor has knowledge of the average SINR value between each node and its associated users. The average SINR information is transmitted by each IAB node to its parent IAB donor. This information and feedbacks are periodically reported to the IAB donor at the beginning of each RP to avoid simultaneous DL and UL transmissions.

The knowledge of the link quality in terms of SINR will enable the determination of the appropriate Modulation and Coding Scheme (MCS) index corresponding to this SINR value [22]. Let γ be the SINR on the reception side of a given link. Each MCS should be used within a given SINR range. We define $f(\gamma)$ the step function that gives the MCS that should be used for SINR γ . Furthermore, based on the MCS index, a modulation order Q_m and a code rate C can be determined [18]. These two values permit the calculation of the number of user bits that constitute the transport block. We define $g(\gamma)$ the function that gives the number of user bits in one RB as follows:

$$g(\gamma) = N_{sub-carriers} N_{symbols} Q_m(\gamma) C(\gamma) \tag{1}$$

where $N_{symbols}$ is the number of symbols during a slot and $N_{sub-carriers}$ is the number of sub-carriers within a RB.

Let R_i be the application bit rate for user i . Thus, $\frac{R_i T_f}{g(\gamma)}$ RBs are required in each frame of T_f [s] duration for user i . Users with the same parent gNB can occupy different RBs in the same slot, so the total number of slots required for each gNB k depends on its load $|I_k|$ in terms of number of directly associated users (where I_k defines the list of users directly associated with the gNB k) and can be calculated as follows:

The number of required slots S_{donor} for access between the donor and its directly associated users is given by:

$$S_{donor} = \left\lceil \frac{\sum_{i \in I_{donor}} \frac{R_i T_f}{g(\gamma_i)}}{N_{rb}} \right\rceil \tag{2}$$

The number of required slots S_j for access between the node j and its directly associated users is given by:

$$S_j = \left\lceil \frac{\sum_{i \in I_j} \frac{R_i T_f}{g(\gamma_{ij})}}{N_{rb}} \right\rceil \tag{3}$$

The number of required slots $S_{donor,j}$ for backhaul between the donor and node j is given by:

$$S_{donor,j} = \left\lceil \frac{\sum_{i \in I_j} R_i T_f}{\frac{g(\gamma_j) |I|}{N_{rb}}} \right\rceil \tag{4}$$

where γ_i is the SINR γ on the link between the donor and user or node i , γ_{ij} is the SINR γ on the link between the node j and user i and N_{rb} is the maximum transmission bandwidth configuration [RBs].

At this point, JODI assigns to each node S hard slots based on (2), (3), and (4). Note that, to avoid overestimating the number of hard slots required and to ensure that all hard slots are consumed, we define JODI+ as a variant in which a more aggressive strategy is used: the MCS used for the next transmissions is $f(\gamma) + a$ where a is an integer parameter within [1,4] (for Jodi, $a=0$).

To respect the half-duplex constraint, different hard resource are allocated to IAB nodes rather to IAB donor. To prohibit intense interference, the donor allocates different hard time slots to each two interfering gNBs and the donor configures the hard slots of each gNB as not available for its interfering gNBs, to avoid resource conflicts. If possible, to prevent weak interference, the donor allocates different hard time slots to each two non-interfering gNBs. This prevention of interference on hard resource is called as the JODI "H-inter" property. All pairs of interfering gNBs are detected by the IAB donor on the basis of the network topology and knowledge of the SINR. In more details, two gNB's are considered to be interfering if the interference generated between one of these gNB's and at least one user in the other gNB's cell increases the noise power by 3 dB or more.

4.2 Soft resource repartition

In this step, the donor will mark each of its assigned hard time slots as soft or not available time slots for the IAB nodes that are in a state of non-interference with the donor, where, each pair of interfering IAB nodes will have opposite Soft/Not available allocation. The sharing is based on IAB nodes loads (number of users directly associated with each node). Secondly, for each pair of non-interfering IAB nodes, the hard resource of one will be configured as soft for the other. This soft resource configuration ensures that a time slot resource cannot be configured as soft for both interfering IAB nodes, and called as the JODI "S-inter" property.

4.3 Soft+ and soft- resource repartition

After hard and soft resource have been allocated, the remaining unallocated slots during the frame will be shared as Soft+/Soft- between the IAB nodes, where each pair of interfering IAB nodes will have an opposite Soft+/Soft- allocation. The sharing is based on IAB nodes loads (number of users directly associated with each node) and called as the JODI "S+/S-" property.

This will lead to a priority system for the utilization of different types of soft resource (soft+, soft, and soft-), where soft+ represents the highest priority soft resource, and soft- represents the lowest priority soft resource. Contrary to soft slots, which are always controlled by the parent gNB, soft+ and soft- slots can be used without restriction. The key advantage of Soft+/Soft- is to increase resource sharing between the IAB nodes, with a reduced risk of interference based on priorities.

5 System model

In this section, we provide the necessary details on the system model used for performance evaluation.

As a simulation scenario, we consider an IAB network with 4 cell sites for one IAB-donor and 3 IAB nodes shown in Fig. 4. The IAB donor maintains a wired connection with the CN, while the IAB nodes are in a single hop wireless communication with the CN through the IAB donor with a maximum distance of 400 m between the IAB donor and each IAB node. There are N UEs dropped uniformly and randomly in each cell within a 200 m radius without consideration of mobility. Each UE is assumed to have a downlink traffic where the data packets are generated from the IAB-donor to UEs taking into account possible interference between the different gNBs and without consideration of retransmission. The entire network operates in a half-duplex context. As summarized in Table 1, the assumed bandwidth is 100 MHz, the central frequency used by the system of 2600 MHz, and the transmit power is set to 44 dBm for the donor and 30 dBm for the node. The antenna configuration is specified as SISO (Single Input Single Output), with a half power beam width of 65 degrees. We implement the Urban Macrocell (Uma) line-of-sight (LOS) path loss model [23] for backhaul links and access links between the IAB donor and users, assuming clear line-of-sight conditions between elevated infrastructure points. For the access links between IAB nodes and users, we apply the Urban Microcell (Umi) Non-line-of-sight (NLOS) path loss model [24], which accounts for signal degradation due to obstacles such as buildings. Additionally, the log-normal shadow fading standard deviation is set at 10 dB, capturing the variability in signal strength caused by environmental

Fig. 4 Network topology

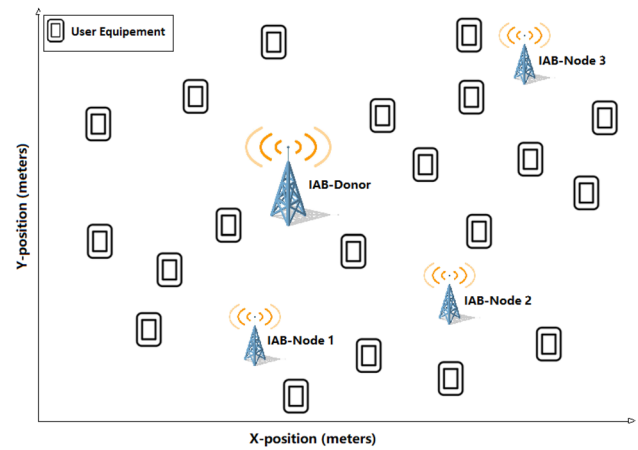


Table 1 Scenario parameters

Parameter	Value
Frequency [MHz]	2600
Bandwidth [MHz]	100
subcarrier spacing (SCS) [kHz]	30
Antenna configuration	SISO (Single Input Single Output)
Half power beam width [°]	65
Donor emission power [dBm]	44
Node emission power [dBm]	33
Path loss model for donor	Uma-LOS [23]
Path loss model for nodes	Umi-NLOS [24]
Log normal shadow fading standard deviation [dB]	10
Minimum Coupling Loss (MCL) [dB]	70
Height of donor [m]	25
Height of node [m]	10
Height of UE [m]	1.5
Maximum donor-node distance [m]	400
Cell radius [m]	200
Donor antenna gain (G_{ant}) [dBi]	15
Node antenna gain (G_{RX}) [dBi]	8
Thermal noise floor [dBm/Hz]	-174
gNB noise figure [dB]	5
UE noise figure [dB]	9
UEs mobility	None
Mode	TDD (Time Division Duplex)
Frame duration (T_f) [ms]	10
Direction of data transfer	Downlink (DL)

Table 2 Traffic models parameters

Parameter	Constant traffic	Variable traffic
Packet size [bytes]	1500	Weibull distribution
Inter-packet time [ms]	20	20
Maximum packet size [bytes]	-	15000

factors. Two models of traffic have been evaluated as described in Table 2. Constant traffic is modeled by generating packets of 1500 bytes every 20 ms, and variable traffic is modeled by the video conference application traffic pattern based on IEEE 802.11ax [25] evaluation methodology to generate video conference traffic packets of different sizes every 20 ms, where packet size is determined by a Weibull distribution (with a maximum packet size of 15,000 bytes). Although our simulation scenario involves only three IAB nodes and a single traffic model (either constant or variable), our proposed policy has no restrictions regarding the number of IAB nodes or the traffic model. It can be applied without any modifications required to larger scenarios, in terms of the number of nodes and traffic models; however, it does not currently ensure QoS differentiation, while still operating within the context of a single-hop IAB network in half-duplex mode. Our choice of context is justified as we propose a policy that complies with 3GPP standards, aiming to provide practical insights for real-world IAB networks. First, to our knowledge, currently deployed 5G networks primarily operate in half-duplex mode. Second, our goal is to reduce latency, which represents a crucial challenge for IAB networks. We are convinced that increasing the number of hops negatively impacts latency [26]. Therefore, we have chosen a single-hop context in half-duplex mode, making our assessment of the performance and applicability of our proposed policy relevant for real-world IAB networks.

We perform MATLAB simulations with 20,000 time frames of 10 ms. For the purposes of this study, we focus on an in-band communication configuration, where the access and backhaul links share the same spectrum band. Following our channel model, the power received (expressed in dBm) at each node can be expressed as follows (see in [27]-section 4.5):

$$RX_{PWR} = TX_{PWR} - \max(L - G_{TX} - G_{RX}, MCL) \quad (5)$$

where TX_{PWR} is the transmitted signal power, L is the path loss, G_{TX} is the transmitter antenna gain, G_{RX} is the receiver antenna gain and MCL refers to the minimum coupling loss, which is the parameter describing the minimum loss in signal between gNB and UE or between two UEs in the worst case. MCL is defined by the 3GPP in [27] as the minimum distance loss including antenna gains measured between antenna connectors.

6 Performance evaluation

To evaluate the performance of JODI and JODI+ policies, several alternative policies were also implemented as shown in Table 3, with the aim of determining the profit made by each of the properties explained in Sect. 4. The S0 policy represents the simplest solution that ignores all properties and allocates the hard slots without taking into account possible interferences, then places the rest of slots as soft. The baseline policy is the IAB donor-coordinated scheme proposed by the 3GPP [12]. Same soft slot will not be allocated to IAB nodes, which may cause conflicts between them. As there is no specific policy for hard resource, the IAB-donor allocates hard resource at slot level in the same way as JODI with "H-interf" and respecting the half-duplex constraint. This section presents the main results of the performance evaluation under the two traffic models explained in Sect. 5.

6.1 JODI+'s MCS property evaluation

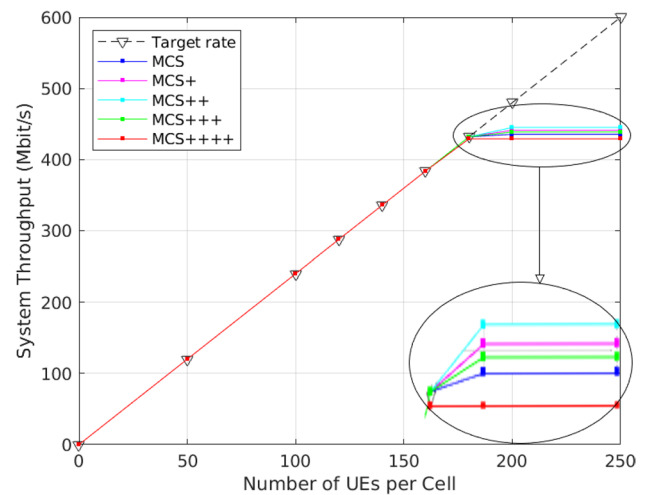
Before evaluating the performance of the JODI+ policy, we began the simulations by testing different variants of the MCS calculation explained in Sub-Sect. 4.1.

Figure 5 shows the system throughput as a function of the network load under a constant traffic. This metric gives the amount of data in Mbit that each policy guarantees to deliver per second. The target rate plot represents the theoretical throughput desired. The results show that the MCS value to be used for calculating the number of required resource has a significant impact on the system throughput with a slight gain between the different variants and that "MCS+"

Table 3 Evaluation policies

Property	S0	S1	Baseline	JODI	JODI+
MCS++	-	-	-	-	✓
S+/S-	-	-	-	✓	✓
S-interf	-	-	✓	✓	✓
H-interf	-	✓	✓	✓	✓

Fig. 5 JODI+'s MCS property impact on the system throughput



where $a = 1$ offers a better throughput than "MCS" where $a = 0$ and even better if taking $a = 2$ by "MCS++", but if further increasing the value $a = 3$ and $a = 4$ by "MCS+++" and "MCS++++" respectively, the throughput degrades. In fact, taking values above the average MCS will enable us to avoid overestimating the number of hard resource and therefore we'll have more soft+ and soft- resource, which will enable us to increase the sharing and reuse of resource and therefore increase throughput, but of course we have to choose the best variant of increase to avoid large interferences linked to high reuse of resource. On the basis of these results, $a = 2$ was used for JODI+ for the rest of the evaluations and this property is called "MCS+".

6.2 Constant traffic evaluation

Figure 6 shows the system throughput as a function of the network load. The results show that, hard resource protection via "H-interf" will allow S1 to achieve a throughput higher than S0, the introduction of "S-interf" will similarly allow the baseline to generate an even better rate than S1, soft resource priority management via "S+/S-" will allow JODI to generate a better throughput than the baseline and finally the addition of "MCS++" will also enable JODI+ to reach the best system throughput compared to other policies and to be closest to the target rate.

Figure 7 shows the percentage of packet loss due to capacity as a function of the network load. This metric gives the percentage of packet stored on buffers at the end of simulation. The results show that, S0 is the first policy that reaches its maximum capacity and start buffering at 140 users compared with other policies, and JODI+ always offers a lower sum of buffered packets than the other policies. What it means, more attention the policy pays to interference thanks to "H-interf", "S-interf", "S+/S-"; "MCS++", a larger amount of traffic can be handled, while guaranteeing better resource quality.

Fig. 6 System throughput as a function of network load (constant traffic)

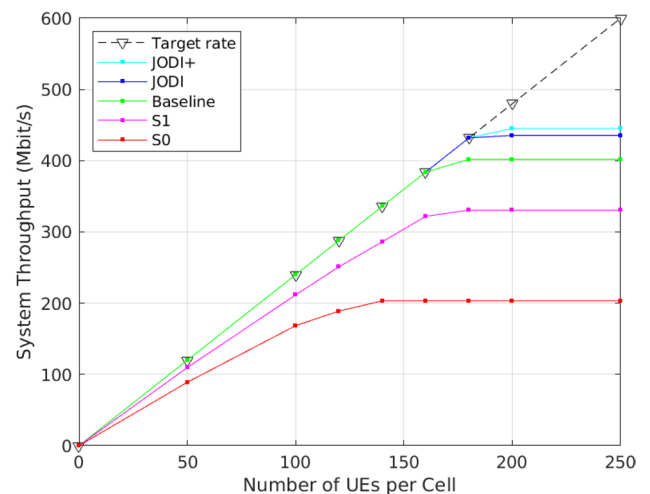


Fig. 7 Percentage of packet loss due to capacity as a function of network load

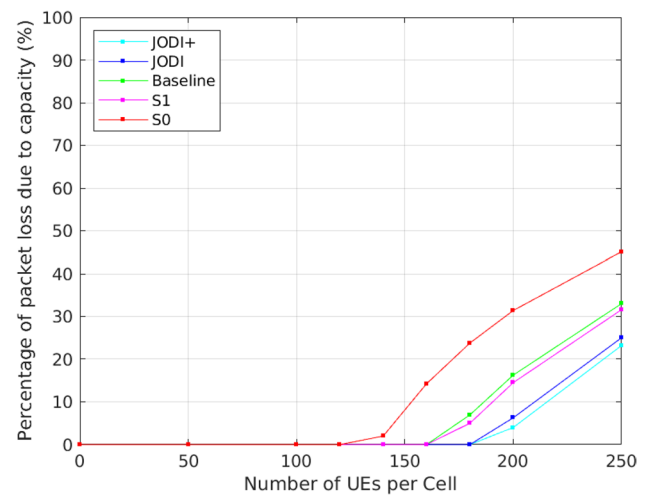


Fig. 8 Percentage of packet loss due to interference as a function of network load

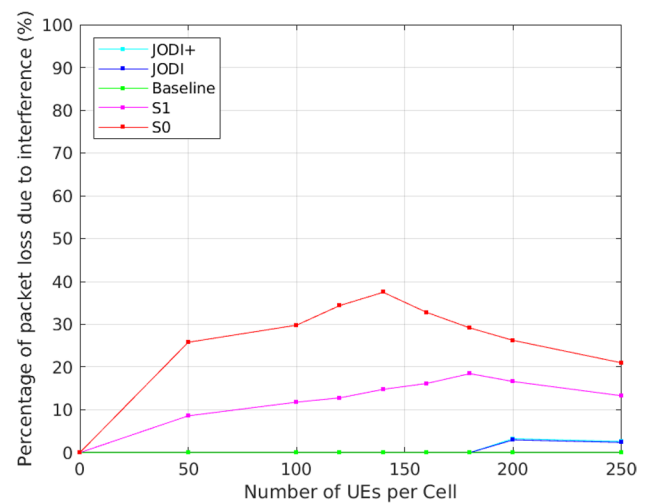


Figure 8 shows percentage of packet loss due to interference as a function of the network load. This metric gives the percentage of packet dropped due to interference (knowing that retransmission is not considered). The results show that, S0 is the most vulnerable policy to interference and starts to lose packets even at low loads, as resource are shared between the various interfering gNBs, resulting in data loss and degradation of resource quality. The baseline is the most interference-resistant policy, thanks to "H-interf" and "S-interf" who are on hand to eliminate interference. Up to 180 users per cell, JODI+ guarantees zero data loss due to interference, and even at higher loads, it offers lower loss. Also, JODI+ losses a few more packets due to interference compared to JODI at the cost of a significant gain in terms of buffered packets as shown in Fig. 7.

Figure 9 shows the percentage of undelivered packets as a function of the network load. This measure indicates the percentage of the sum of undelivered packets over the total number of packets generated by the donor. The results show that, for each policy, the percentage of undelivered packets obtained represents the sum of the percentage of packet loss due to capacity and the total of packet loss due to interference shown in Figs. 7 and 8 respectively, which validates the obtained results.

Figure 10 shows the end-to-end delay as a function of the network load. This metric gives the average time taken for a packet to be transmitted across a network from source to destination. The results show that, the faster the policy is able to defile what is on its buffer as shown in Fig. 7, the more it offers low packet delays thanks to good resource quality in terms of spectral efficiency. At a low load of 60 UEs per cell, JODI+ achieves a delay reduction of 11% compared to the baseline. This gain increases with the load, reaching a 30% improvement relative to the baseline at 160 UEs per cell.

Fig. 9 Percentage of undelivered packets as a function of network load

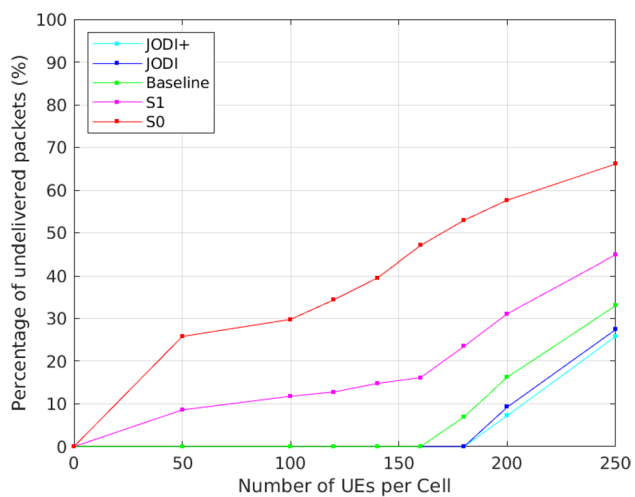


Fig. 10 End-to-end delay as a function of network load (constant traffic)

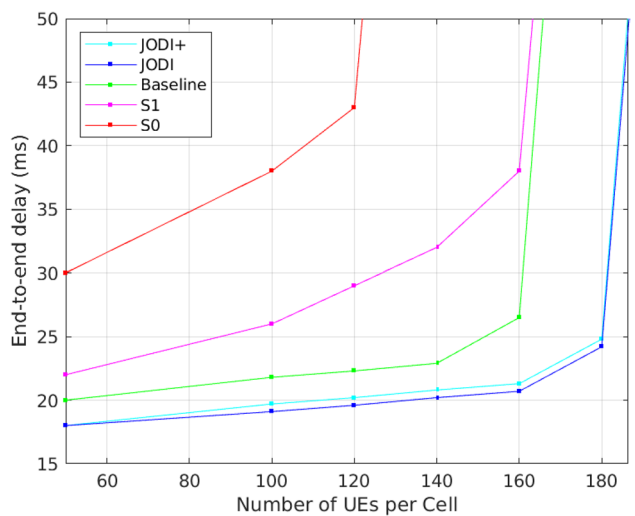


Fig. 11 System throughput as a function of network load (variable traffic)

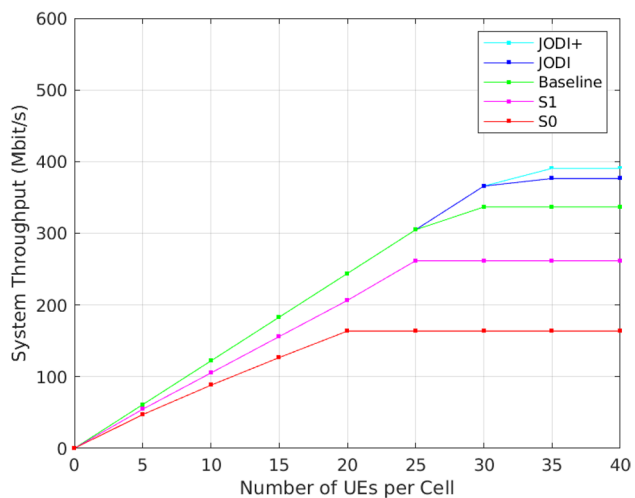
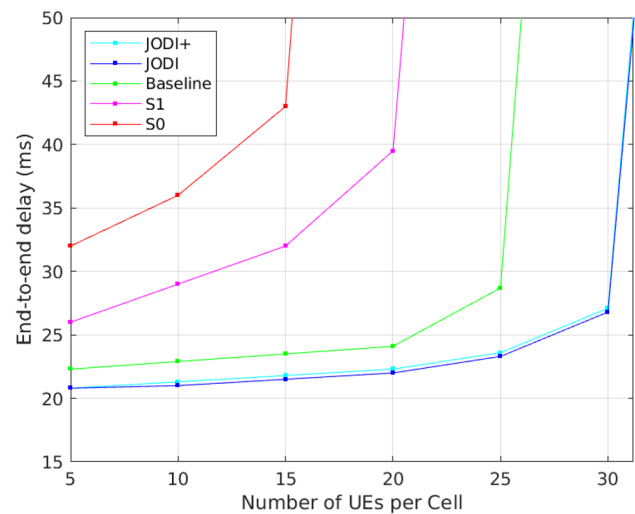


Fig. 12 End-to-end delay as a function of network load (variable traffic)



6.3 Variable traffic evaluation

Figure 11 shows the system throughput as a function of the network load. The results show that, in the case of variable traffic, all policies guarantee a lower peak throughput than in the case of constant traffic and traffic variation accentuates the utility of the various soft resource that will handle the additional resource requirement, so the more the policy enhances soft resource management through "S-interf", "MCS++" and "S+/S-", the greater the gain in system throughput over other policies.

Figure 12 shows the end-to-end delay as a function of the network load. The results show that, in the case of variable traffic, all policies start to generate high delays at lower loads than in the case of constant traffic. As the size of packets is variable in the case of variable traffic, large packets require segmentation to be transmitted, which introduces delays. At a low load of 5 UEs per cell, JODI+ achieves a delay reduction of 10% compared to the baseline. This gain increases with the load, reaching a 26% improvement relative to the baseline at 25 UEs per cell.

7 Conclusion

In this work, a new resource management policy JODI+, for IAB networks was proposed. JODI+ aims to determine the efficient management of resource that jointly reduces interference and delays. In order to validate the performance of JODI+, a comparative study with various policies using different metrics was performed. The results show, the significant impact of each JODI+ property to reduce interference and delay and to efficiently manage resource across a combination of these properties. This ultimately leads to a substantial improvement in network performance regarding metrics such as system throughput and end-to-end delay which represent two crucial challenges for IAB during major public events, urban hotspots, or natural disasters. We achieve up to an 11% increase in system throughput and a 30% reduction in end-to-end delay compared to the baseline for constant traffic, while for variable traffic, it results in a 16% increase in system throughput and a 26% reduction in end-to-end delay. In addition, the significant impact of "MCS++" property which considerably improves system capacity in terms of peak system throughput, at the cost of a slight increase in delays and interference. As a future work we are looking to extend JODI+ to resource management for UL traffic, exploiting the information collected by the measurement reports, as well as introducing QoS management for different types of traffic class.

Author contributions This work is part of C.GH's ongoing thesis, which explores . The research and manuscript were developed under the supervision of P.S, C.G, and X.L.C.GH conducted the research, performed the simulations, and wrote the manuscript. P.S, C.G, and X.L provided substantial guidance throughout the research process, including the design of the study, analysis of results, and critical revisions of the manuscript. They were involved in detailed correction, verification, and improvement of the paper, ensuring the accuracy and quality of the final submission.

Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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References

1. 3GPP. Technical Specification Group Radio Access Network; NR; Study on Integrated Access and Backhaul (Release 16). 3GPP TR 38.874 V16.0.0. (2018).
2. Madapatha C, et al. On integrated access and backhaul networks: current status and potentials. *IEEE Open J Commun Soc.* 2020;1:1374–89.
3. Polese M, Giordani M, Roy A, Castor D, Zorzi M. Distributed path selection strategies for integrated access and backhaul at mmWaves. 2018 IEEE Global Communications Conference (GLOBECOM). 2018;1–7.
4. Khan MF. An approach for optimal base station selection in 5g hetnets for smart factories. *IEEE 21st International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM).* 2020;64–65.
5. Ghodhbane C, Manini M, Savelli P, Gueguen C, Lagrange X. Load-efficiency-balance cell selection policy for IAB networks. 2023 IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC). 2023;1–6.
6. Harris D, Raz D, Sagiv P. Bandwidth resource allocation in integrated access and backhaul networks. *Proceedings of the ACM SIGCOMM Workshop on 5G and Beyond Network Measurements, Modeling, and Use Cases.* 2022;1–7.
7. Yin H, Roy S, Cao L. Routing and resource allocation for iab multi-hop network in 5g advanced. *IEEE Trans Commun.* 2022;70:6704–17.
8. Pagin M, Zugno T, Polese M, Zorzi M. Resource management for 5G NR integrated access and backhaul: a semi-centralized approach. *IEEE Trans Wirel Commun.* 2021;21:753–67.
9. Saha C, Dhillon HS. Millimeter wave integrated access and backhaul in 5G: performance analysis and design insights. *IEEE J Sel Areas Commun.* 2019;37:2669–84.
10. Ranjan S, Jha P, Karandikar A, Chaporkar P. Two stage downlink scheduling for balancing QoS in multihop IAB networks. *Comput Netw.* 2022;218: 109395.
11. Sadovaya Y, et al. Delay-aware link scheduling in IAB networks with dynamic user demands. *IEEE Trans Veh Technol.* 2024;73:15125.
12. 3GPP TDoc R1-1902992. IAB Resource Management Framework. Qualcomm, 3GPP RAN WG1 Meeting #96. (2019).
13. Yu M, Pi Y, Tang A, Wang X. Coordinated parallel resource allocation for integrated access and backhaul networks. *Comput Netw.* 2023;222: 109533.
14. 3GPP TDoc R1-1913600. RAN1 Agreements for Rel-16 IAB. Qualcomm, 3GPP RAN WG1 Meeting #99. (2019).
15. 3GPP. NR; Physical layer procedures for control (Release 16). 3GPP TS 38.213, V16.12.0. (2022).
16. 3GPP. NR; Medium Access Control (MAC) protocol specification. 3GPP TS 38.321, V16.11.0. (2022).
17. 3GPP. NR; NR and NG-RAN Overall description; Stage-2. 3GPP TS 38.300, V16.2.0. (2020).
18. 3GPP. 5G; NR; Physical Layer procedures for data (Release 16). 3GPP TS 38.214, V16.14.0. (2023).
19. 3GPP. 5G; NR; Integrated Access and Backhaul (IAB) conformance testing; Part 1: Conducted conformance testing. 3GPP TS 38.176-1, V16.1.0. (2021).
20. Khayrov E, Koucheryavy Y. Packet level performance of 5G NR system under blockage and micromobility impairments. *IEEE Access.* 2023;11:90383.
21. Kovalchukov R, Moltchanov D, Gaidamaka Y, Bobrikova E. An accurate approximation of resource request distributions in millimeter wave 3GPP new radio systems. *International Conference on Next Generation Wired/Wireless Networking.* 2019;572–585.
22. Ramos AR, Silva BC, Lourenço MS, Teixeira EB, Velez FJ. Mapping between average sinr and supported throughput in 5g new radio small cell networks. 2019 22nd International Symposium on Wireless Personal Multimedia Communications (WPMC). 2019;1–6.
23. 3GPP. Study on channel model for frequencies from 0.5 to 100 GHz (Release 16). 3GPP TR 38.901, V16.0.0. (2019).
24. ITU M Series. Guidelines for evaluation of radio interface technologies for IMT-Advanced. Report ITU-R M.2135-1. 2009;1–72.
25. Porat R, Fischer M. et al. IEEE 802.11 ax Evaluation methodology. *IEEE802.11-14/0571r2.* (2014).
26. Ronkainen H, Edstam J, Ericsson A, Östberg C. Integrated access and backhaul a new type of wireless backhaul in 5G. *Ericsson Technol Rev.* 2020;2020:2–11.
27. 3GPP. Evolved Universal Terrestrial Radio Access (E-UTRA) radio frequency (rf) system scenarios. 3GPP TR 36.942, V16.0.0. (2020).

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