Integrated Access and Backhaul in Millimeter-Wave Cellular: Benefits and Challenges

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Abstract

The recently proposed NR-ready integrated access and backhaul (IAB) architecture promises to bring a cost-efficient deployment solution for both coverage extension and capacity boosting in the emerging 5G/5G+ systems. While its impact on the coverage extension was thoroughly addressed in the literature, the effect of advanced functionalities such as multihop, multi-connectivity, and multi-beam operations on the throughput remained unclear. We review and characterize the system-level impact of these capabilities on the performance of self-backhauled IAB systems operating in half-duplex mode and utilizing millimeter-wave (mmWave) technology across both access and backhaul. Our results indicate that the throughput gain of multihopping and multi-beaming is significant even without multi-connectivity operation. Another important lesson is that in all-mmWave systems with link blockage, multi-connectivity with link switching allows achieving self-load balancing. Finally, we outline future research directions.

Introduction

While the first wave of 5G New Radio (NR) deployments utilizing microwave bands is already underway, the attention of operators and vendors is now set on millimeter-wave (mmWave) band NR that allows benefiting from larger bandwidth. According to the 3rd Generation Partnership Project (3GPP) Release 17, frequencies of up to 71 GHz are supported. However, severe path loss along with link blockage require extremely dense deployments to provide ubiquitous coverage [1, 2]. Exploring the ways to reduce capital expenditures when deploying mmWave 5G NR systems, 3GPP has recently proposed integrated access and backhaul (IAB) architecture [3].

By utilizing relays, named IAB nodes, 3GPP incorporates inherently multihop architecture into future 5G/5G+ cellular system design with backhaul links connecting IAB nodes to each other and to the donor gNB (DgNB). The user equipment (UE) that is outside of the coverage of the DgNB may associate with the nearest available IAB node, thus benefiting from coverage extension provided by the emerging IAB architecture [4]. The performance of an IAB network with respect to coverage extension has been extensively investigated in the literature [4]. Resource partitioning is addressed in [6], while the topology formation problem is solved in [7, 8].

The throughput of 3GPP IAB multihop systems is limited by the constraints of modern wireless principles, such as half-duplex operation [9]. To improve the capacity while utilizing the IAB architecture, 3GPP included support for multi-connectivity and multi-beam functionalities as well as dynamic slot formatting. These capabilities are aimed at throughput boosting and are crucial for all-mmWave IAB deployments, where the mmWave band is utilized for both access and backhaul [10].

Multi-beam operation is expected to enhance the volume of available radio resources at the expense of increased interference, while multi-connectivity may potentially allow higher connection reliability and enhanced data rates at the air interface. However, the impact of all these mechanisms depends on multiple factors including the scenario of interest, constraints imposed by multihop operation and half-duplex IAB radio design, specific implementations of these functionalities, as well as the utilized resource allocation (RA) scheme. Therefore, the ultimate effect of these mechanisms on the system throughput in all-mmWave 3GPP IAB architecture still remains unclear.

In this article, we study the effects of advanced IAB functionalities primarily on per-user throughput in all-mmWave 5G NR deployments. By gradually adding multihopping, multi-beaming, and multi-connectivity, we isolate and thoroughly characterize the impact of each individual mechanism as well as their joint utilization under static and dynamic slot formatting schemes. Then we discuss several challenges for implementing these features in real-world systems. The results help outline a set of recommendations on the use of these capabilities in practical all-mmWave IAB deployments.

The rest of this text is organized as follows. First, we review the state-of-the-art IAB architecture and introduce the considered advanced functions with their various design options. The numerical results and their interpretation are then provided. We further highlight the main challenges associated with the implementation of the advanced functionalities for future deployments of the IAB technology. Conclusions are drawn in the last section.

IAB Architecture and Enhancements

In this section, we start with a brief review of the IAB system architecture. Then we introduce the considered functionalities individually.
3GPP IAB Architecture for In-Band Backhauling

The architecture of the NR-ready IAB system is based on the central/distributed unit (CU/DU) split, which was proposed in 3GPP TR 38.874 Release 16. It is facilitated by new entities named IAB nodes. The details on higher-layer protocols and architecture were later specified in TS 38.401, while radio transmission and reception for IAB were documented in TS 38.174. The current work in Release 17 related to IAB enhancements includes improved topology robustness, resource multiplexing, and network management. The possible extensions of IAB in Release 18 may include self-interference mitigation methods to improve the full-duplex operational mode, enhanced mobility support, and reduced multihop latency.

The gNB is connected to the core network via the NG interface and provides the user plane (UP) and control plane (CP) protocols termination toward the UEs. The gNB can be a single logical node or it can comprise a CU and a DU connected to each other via the F1 interface. Each IAB node handles MT and DU, where the MT function is responsible for communication with a parent node, while the DU function arbitrates communication with a child. According to TR 38.874, in-band operations are inherently limited by the half-duplex constraint. In this case, an IAB node cannot receive and transmit simultaneously.

The concept of IAB assumes the reuse of 5G NR access links for backhauling. It utilizes the functions of mobile-termination (MT), gNB-DUs, gNB-CU, user plane function (UPF), core access and mobility management function (AMF), session management function (SMF), and the corresponding interfaces (i.e., NR Uu, F1, NG, X2, and N4). Each IAB node connects to its parent using the MT functionality over the NR Uu link. The protocol stack for the CU/DU split architecture is specified in TS 38.401.

Multihop Operation

IAB nodes enable multihop backhauling, which allows for flexible coverage extension in 5G NR deployments. An example of the IAB architecture with multihop functionality is offered in Fig. 1. In this setup, each IAB node and DgNB holds zero or more child nodes, which are located below it in the tree. A node that has a child is known as a parent node.

To establish an IAB network, the so-called integration procedure is accomplished. According to TS 38.401, a parent node is discovered initially. After that, the IAB node requests a remote radio call (RRC) connection with the CU via the parent node, while the backhaul link is created via the radio link control (RLC). IAB-specific features include backhaul adaptation protocol (BAP), which is defined in TS 38.340. It is employed on the backhaul links to enable efficient multihop forwarding.

The access and backhaul links at the IAB nodes can be multiplexed using time-division (TDM), frequency division (FDM), or space-division multiplexing (SDM). However, as stated in TS 38.174, IAB is especially beneficial in the mmWave spectrum; hence, TDM is the most common approach due to the large available bandwidth.

Following TR 38.874, RLC between IAB nodes can be hop-by-hop or end-to-end. End-to-end automatic repeat request (ARQ) can be beneficial as packets do not traverse through all RLC states at the intermediate IAB nodes. On the other hand, hop-by-hop ARQ guarantees more efficient retransmissions.

According to TR 38.874, directed acyclic graph (DAG) and tree multihop topologies are supported. The procedure of the intra-CU backhaul radio link failure (RLF) recovery is then described in TS 38.401, which is required to be performed by IAB nodes to switch from one to another parent node under the same IAB donor CU.

Multi-Beam Functionality

Another advanced system feature is multi-beam functionality that can be utilized in IAB deployments at both DgNB and IAB nodes. Multi-beam communications imply simultaneous operation of independent directional beams, which enables efficient frequency reuse and significantly higher system capacity. However, the transmit power of an individual beam is reduced as compared to a single-beam scenario due to the fact that it is split among the beams. 3GPP provides more details regarding the beam management in Release 14 TR 38.912, while alternative strategies are proposed in, for example, [11]. The multi-beam capabilities can be utilized at both DgNB and IAB nodes. However, this functionality may significantly compromise the cost efficiency of practical NR deployments as it requires digital or hybrid beamforming [12].

Multi-Connectivity Capabilities

Multi-connectivity improves network reliability via simultaneous support of several links from source to destination. The maximum number of links that can be utilized simultaneously is named the degree of multi-connectivity. Dual-connectivity is ratified in TS 37.340, wherein it implies that a UE utilizes radio resources of two eNB/gNB within the same band. In 5G NR, the dual connectivity notion is generalized; that is, the UE may exploit the resources provided by E-UTRA access and NR access simultaneously.

In the context of IAB networks, multi-connectivity can be implemented in different ways. For
example, an additional connection might serve as a backup link, or both can be utilized simultaneously. Potentially, other solutions are also feasible, and they are addressed in what follows. In our target deployment, a given UE utilizes the resources of several nodes simultaneously.

By enabling multi-connectivity, advanced functionalities to combat link blockage can be employed. These refer, for example, to fast switching (FS), which is changing the association point if the current one becomes unavailable. In this setup, UE does not perform re-switching to the initial state even if the blockage period on that link has expired. An improved version of FS corresponds to the situation where re-switching is allowed even when the links are not blocked. Moreover, regular scanning is utilized for a continuous awareness of links with the highest reference signal received power (RSRP).

**Dynamic Slot Formatting**

5G NR offers six different waveform configurations, which are known as numerologies. Depending on the numerology, the symbol length and the number of slots within a frame can be controlled to satisfy various throughput and latency requirements. The general frame structure for the third numerology is provided in Fig. 2.

Slot formatting for 5G NR systems was introduced in TS 38.213. It indicates how each orthogonal FDM (OFDM) symbol in a single slot can be utilized. This allows making the scheduling more adjustable as compared to LTE. The NR specifications offer 61 predefined symbol combinations, which can be assigned while designing the network. In addition, dynamic slot configuration can be enabled, which is essential for capacity improvement.

We consider three different methods of slot division, as shown in Fig. 2. The first one is a baseline, wherein the same amount of resources is allocated for uplink (UL) and downlink (DL) directions. On one hand, the implementation of such a division is straightforward. However, asymmetric load in the UL and DL directions is not accounted for. To implement proportional fair (PF) slot formatting, the number of active UEs in UL and DL should be available. UE is considered active if it has buffered traffic in the UL or DL directions. After this information is provided, the slot division coefficient in the DL can be computed as a fraction of the number of active UEs in the DL to the total number of active UEs in both UL and DL. The slot division coefficient in the UL is calculated similarly.

The weighted PF (WPF) approach aims to improve the PF method by enhancing fairness. For example, C_{UL1} and C_{DL1} in Fig. 2 are computed as a fraction of the number of active UEs in the UL connected to the IAB-node to the total number of active UEs in both UL and DL connected to this IAB node. Then C_{UL2} and C_{DL2} (Fig. 2) are averaged to account for the asymmetry of the traffic demands with the aim to equalize the slot weights in the logical directions.

**Performance Evaluation Results**

In this section, we report the results of our evaluation campaign by focusing on the impact of each of the considered functionalities in detail.

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**TABLE 1**

| Numerology | Frame structure |
|------------|-----------------|
| 1          | 1 frame = 10 subframes = 10 ms |
| 2          | 1 subframe = 8 slots = 1 ms |
| 3          | 1 slot = 14 symbols = 0.125 ms |

**FIGURE 2.** Considered slot formats.
tributions (e.g., R1-1808692 and R1-1811514).

The scheme based on the maximum RSRP value is chosen according to the maximum RSRP value of the worst link over all the available routes. The second strategy refers to the case where the path is selected based on the minimum number of hops between the UE and the DgNB. The first method reflects the situation where all the UEs attempt to connect to the DgNB if it is available. The scheme based on the maximum RSRP criterion has been proposed in several 3GPP contributions (e.g., R1-1808692 and R1-1811514).

The explanation here is twofold. First, static slot formatting in the UL and DL directions is not optimal under dynamic traffic conditions. On top of this, several UEs are forced to connect to the DgNB despite poor channel conditions. Increasing the number of IAB nodes from 3 to 7 at first decreases the throughput because of a larger delay. However, for higher values of session intensities, the same schemes with 7 IAB nodes provide larger throughput than with 3 IAB nodes due to the load balancing effect.

The explanation for the obtained results further, one may notice that WPF converges to the 50/50 ratio in the considered scenario; that is, the slot division coefficient equals 0.5 most of the time. Notably different behavior is exhibited by the PF approach because the PF scheme allocates more resources in the more loaded direction. In addition, this effect lowers the backlog in the overloaded direction.

Moreover, the use of dynamic slot formatting in the multihop regime improves the UE throughput by 10–30 percent even when other advanced capabilities including multi-connectivity and multi-beaming are not utilized. In practice, it implies that cost-efficient 3GPP IAB solutions using simple single-beam antenna arrays and CUs not supporting multi-connectivity capabilities may still significantly benefit from optimized dynamic slot formatting.

We also address different multi-beam options to quantify their effect on the UE throughput. First, a fully multi-beam scenario is considered, where all IAB nodes and the DgNB have separate beams for backhauling and an additional access beam. Further, a scenario where only the DgNB has multi-beam functionality is addressed. Finally, an all-single-beam scenario is considered, where all IAB nodes and the DgNB utilize a single beam configuration. In all the simulations, the statistical data are obtained in the steady-state regime.

**TABLE 1. Parameters utilized in numerical assessment.**

| Parameter                        | Value                      |
|----------------------------------|----------------------------|
| Carrier frequency               | 30 GHz                     |
| Bandwidth                       | 400 MHz                    |
| Number of UEs                   | 60                         |
| Cell radius                      | 500 m                      |
| Tx power of DgNB                | 40 dBm                     |
| Tx power of IAB node            | 33 dBm                     |
| Tx power of UE                  | 23 dBm                     |
| Number of IAB nodes             | 3, 7                       |
| Number of DgNBs                 | 1                          |
| Noise figure of DgNB and IAB node| 7 dB                      |
| Noise figure of UE              | 13 dB                      |
| Power spectral density of noise  | –173.93 dBm/Hz             |
| Antenna array of UE             | 4×4                        |
| Antenna array of DgNB and IAB node | 16×16                   |
| Velocity of UE                  | 3 km/h                     |
| Height of DgNB                  | 25 m                       |
| Height of IAB node              | 10 m                       |
| Height of UE                    | 1.5 m                      |
| Height of blocker               | 1.5 m                      |
| Radius of blocker               | 0.2 m                      |
| Degree of multi-connectivity     | 2                          |
| Scheduler                       | Round-robin                |
| File size                       | 2 MB                       |

**FIGURE 3.** Mean throughput per UE as a function of session intensity for multihopping schemes based on the minimum number of hops and the highest RSRP value.

The total gain of an array is obtained as a superposition of its elements. The procedure of pattern generation is described in detail in TR 37.840.

In multihop scenarios, we consider two topology formation strategies. The first one corresponds to the situation where the path is selected based on the minimum number of hops between the UE and the DgNB. The second strategy refers to the case where the path is selected based on the maximum RSRP. It implies that the backhaul route is chosen according to the maximum RSRP value of the worst link over all the available routes. The first method reflects the situation where all the UEs attempt to connect to the DgNB if it is available. The scheme based on the maximum RSRP criterion has been proposed in several 3GPP contributions (e.g., R1-1808692 and R1-1811514).
main reason is that the former allows exploiting more resources available at the IAB nodes and the DgNB. However, with the FS capabilities, single-connectivity mode outperforms the conventional multi-connectivity scheme.

The rationale behind the obtained results is that the use of FS capabilities not only allows efficiently combating the effect of blockage but also helps evenly distribute the network load across the IAB nodes and the DgNB. By utilizing regular scanning, one may improve the load distribution even further. This conclusion is important for the UE energy conservation as single-connectivity with FS and regular scanning does not require the support of two active links. At the same time, this configuration displays higher UE throughput across the considered range of parameters.

The reported behavior also emphasizes the importance of balanced traffic distribution in the IAB deployments. In particular, the choice of an uncongested route to the DgNB becomes more essential than the choice of a link having slightly better channel conditions. In this context, we specifically emphasize the aforementioned “self-balancing” behavior of the considered mmWave IAB system, where one may not require any further mechanisms to ensure even load distribution.

**Multi-Beam Am at DgNB and/or IAB Nodes**

Another functionality that we address is multi-beam DgNB and IAB node operation as illustrated in Fig. 5. The latter demonstrates the mean UE throughput as a function of blocker density with and without multi-connectivity capabilities. We consider the single-connectivity option with FS and regular scanning capabilities that showed the best results previously. Multi-beaming at the DgNB improves the UE performance by around 50–70 percent depending on the blocker density. However, introducing multi-beam support at the IAB nodes improves it further by only 10–15 percent. The reason is that changing the DgNB configuration to multi-beam allows overcoming the backhaul-limited regime that occurs in the single-beam mode.

By comparing the performance of route selection schemes also indicated in Fig. 5, one may observe that the throughput attained by the best RSRP option is higher compared to the minimum hops. The throughput initially increases. The rationale is that as the blocker density grows, blockage of direct links with the DgNB leads to choosing other routes that have multiple hops, which benefits the system performance. That is, increased blocker density leads to better topology under the minimum number of hops strategy. The higher number of IAB nodes provides an additional pool of resources. For the latter, the throughput increases. The rationale is that as the blocker density grows, blockage of direct links with the DgNB leads to choosing other routes that have multiple hops, which benefits the system performance. That is, increased blocker density leads to better topology under the minimum number of hops strategy. The higher number of IAB nodes provides an additional pool of resources. For the latter, the throughput increases.

**Challenges and Future Work**

The introduction of multihop functionality in IAB architecture naturally requires semi-distributed operation in cellular systems that historically relied on fully centralized control. This opens up several unique research questions that need to be carefully addressed.

**RA and Topology Organization:** The reliance on multihop communications brings challenges related to efficient RA. Centralized RA incurs additional latency related to the delivery of decisions to remote IAB nodes. Hence, the overall RA in IAB systems needs to be performed in a semi-distributed manner. The matter of RA in IAB systems cannot be considered separately from topology optimization. Therefore, RA needs to account for multiple available paths and may include traffic splitting functionality. Operating in a full-duplex mode, this can be formalized as a conventional network flow problem [15]. However, the half-duplex regime adds further constraints to the network connectivity patterns.

**Distributed Packet Scheduling:** MAC scheduling algorithms pose another challenge to the IAB systems. In our setup, an equal time-sharing scheduler is utilized as the focus is to demonstrate the potential of dynamic slot formatting. However, the use of another scheduler may provide different quantitative results. Moreover, the related overheads cannot be disregarded. For example, RRC signaling is needed to configure a slot format as discussed below. In addition, a guard interval is required for a transceiver to switch between the UL and the DL modes. It is worth noting that the slot format should be configured mindful of the half-duplex constraint.

**Multihop and Multi-Connectivity:** In real-world deployments, the density of blockers varies with, for example, the time of day; hence, it may be beneficial to enable adaptability of the system. In addition, multi-connectivity solutions require synchronization of the scheduling and ARQ mechanisms. While the utilization of differ-
ent paths offers channel diversity, it also aggravates packet delay variability. Therefore, packets arriving out of order may create bufferboils if no reordering algorithm is applied. When switching between the available links, one should take into account the delays due to the data collecting and beam sweeping procedures.

**Multi-Beam Operation:** This functionality raises research questions related to the optimal number of beams required to achieve the balance between access and backhaul limited regimes. Moreover, the use of digital beamforming at the IAB nodes depends on the cost-efficiency trade-off that has not been deeply addressed so far. On one hand, it allows enhancing the backhaul capacity at the IAB interfaces. However, it lowers the power of each beam and may also create additional interference for individual UEs. Similar to the use of this functionality at the DgNB, one needs to determine the optimal number of beams required to fully utilize the available resources.

**Signaling Overheads:** Operating in a semi-decentralized regime, IAB systems face challenges related to signaling. On the other hand, beam management signaling overheads are planned to be reduced in 3GPP Release 17. The type of information that needs to be exchanged between UE/IAB nodes and DgNB to make decisions on the RA and topology maintenance is not specified in the 3GPP documents. Potentially, the information provided to the DgNB by the IAB nodes may include buffer states of the UEs, their capabilities, quality of service, current resource utilization of backhaul and access links, etc. However, due to the limited capacity of control channels, propagation, and buffering delays along multihop routes, this information has to be constrained.

**Conclusions**

3GPP IAB architecture promises to offer a cost-efficient means of densifying the 5G/5G+ cellular deployments by providing both coverage extension and capacity boost at the air interface. Our results demonstrated that for a cost-efficient deployment of 3GPP IAB systems, where multi-beam and multi-connectivity functionalities are not utilized, the throughput gain from enabling dynamic slot formatting over multihop topologies is notable and reaches 10–30 percent. By employing multi-connectivity operation with advanced link switching mechanisms, the system can reach further capacity gains of 10–40 percent depending on the density of blockers. Furthermore, the use of dynamic link selection strategies not only efficiently mitigates the impact of dynamic blockage but also equalizes the load across the IAB nodes and the DgNB, thus resulting in a more efficient use of the available resources. Finally, multi-beam operation yields better performance irrespective of the choice of other system parameters. However, most of these gains stem from enabling this advanced functionality at the DgNB side.

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