

Integrated Access and Backhaul for 5G and Beyond (6G)

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To my parents

Abstract

Enabling network densification to support coverage-limited millimeter wave (mmWave) frequencies is one of the main requirements for 5G and beyond. It is challenging to connect a high number of base stations (BSs) to the core network via a transport network. Although fiber provides high-rate reliable backhaul links, it requires a noteworthy investment for trenching and installation, and could also take a considerable deployment time. Wireless backhaul, on the other hand, enables fast installation and flexibility, at the cost of data rate and sensitivity to environmental effects. For these reasons, fiber and wireless backhaul have been the dominant backhaul technologies for decades. Integrated access and backhaul (IAB), where along with cellular access services a part of the spectrum available is used to backhaul, is a promising wireless solution for backhauling in 5G and beyond. To this end, in this thesis we evaluate, analyze and optimize IAB networks from various perspectives.

Specifically, we analyze IAB networks and develop effective algorithms to improve service coverage probability. In contrast to fiber-connected setups, an IAB network may be affected by, e.g., blockage, tree foliage, and rain loss. Thus, a variety of aspects such as the effects of tree foliage, rain loss, and blocking are evaluated and the network performance when part of the network being non-IAB backhauled is analysed. Furthermore, we evaluate the effect of deployment optimization on the performance of IAB networks.

First, in Paper A, we introduce and analyze IAB as an enabler for network densification. Then, we study the IAB network from different aspects of mmWave-based communications: We study the network performance for both urban and rural areas considering the impacts of blockage, tree foliage, and rain. Furthermore, performance comparisons are made between IAB and networks of which all or part of small BSs are fiber-connected. Following the analysis, it is observed that IAB may be a good backhauling solution with high flexibility and low time-to-market.

The second part of the thesis focuses on improving the service coverage probability by carrying out topology optimization in IAB networks focusing on mmWave communication for different parameters, such as blockage, tree foliage, and antenna gain. In Paper B, we study topology optimization and routing in IAB networks in different perspectives. Thereby, we design efficient Genetic algorithm (GA)-based methods for IAB node distribution and non-IAB backhaul link placement. Furthermore, we study the effect of routing in the cases with temporal blockages. Finally, we briefly study the recent standardization developments, i.e., 3GPP Rel-16 as well as the

Rel-17 discussions on routing. As the results show, with a proper planning on network deployment, IAB is an attractive solution to densify the networks for 5G and beyond.

Finally, we focus on improving the performance of IAB networks with constrained deployment optimization. In Paper C, we consider various IAB network models while presenting different algorithms for constrained deployment optimization. Here, the constraints are coming from either inter-IAB distance limitations or geographical restrictions. As we show, proper network planning can considerably improve service coverage probability of IAB networks with deployment constraints.

Keywords: Backhaul, Beyond 5G, Blockage, Constrained deployment, Coverage probability, Densification, Genetic algorithm (GA), Integrated access and backhaul (IAB), Millimeter wave (mmWave) communications, Node selection, Poisson point process (PPP), Relay, Routing, Stochastic geometry, Topology optimization, Tree foliage, Wireless backhaul, 3GPP, 5G new radio (NR), 6G

List of Publications

This thesis is based on the following publications:

[A] **C. Madapatha**, B. Makki, C. Fang, O. Teyeb, E. Dahlman, M-S. Alouni, and T. Svensson, “On integrated access and backhaul networks: current status and potentials”. *IEEE Open Journal of the Communications Society*, vol. 1, pp. 1374-1389, Sept. 2020.

[B] **C. Madapatha**, B. Makki, A. Muhammad, E. Dahlman, M. -S. Alouini, and T. Svensson, “On topology optimization and routing in integrated access and backhaul networks: a genetic algorithm-based approach”. *IEEE Open Journal of the Communications Society*, vol. 2, pp. 2273-2291, Sep. 2021.

[C] **C. Madapatha**, B. Makki, H. Guo, and T. Svensson, “Constrained Deployment Optimization in Integrated Access and Backhaul Networks”. Submitted to *IEEE Wireless Communications and Networking Conference(WCNC)*’ 2023, Glasgow, United Kingdom.

Other publications by the author, **not included** in this thesis, are:

[D] C. Fang, **C. Madapatha**, B. Makki, and T. Svensson, “Joint scheduling and throughput maximization in self-backhauled millimeter wave cellular networks”. in *Proc. IEEE ISWCS*, Berlin, Germany, Sept. 2021, pp. 1-6.

[E] O. P. Adare, H. Babbili, **C. Madapatha**, B. Makki, and T. Svensson, “Uplink power control in integrated access and backhaul networks”. in *Proc. IEEE DySPAN*, Los Angeles, CA, USA, Dec. 2021, pp. 163-168.

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Göteborg, October 2022

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Acronyms

BAP	Backhaul Adaptation Protocol
BS	Base Stations
CP	Coverage Probability
CSI	Channel State Information
CU	Centralized Unit
DU	Distributed Unit
FHPPP	Finite Homogeneous Poisson Point Process
gNB	gNodeB
HetNet	Heterogeneous Network
IAB	Integrated Access and Backhaul
LoS	Line-of-sight
LTE	Long-Term Evolution
MBSs	Macro Base Station
MAC	Medium Access Control
mmWave	Millimeter Wave
MT	Mobile Termination
mIAB	Mobile Integrated Access and Backhaul
MIMO	Multiple-Input-Multiple-Output
NLoS	Non-line-of-sight
PtP	Point-to-Point
RLC	Radio Link Control
RAN	Random Access Network
RIS	Re-configurable Intelligent Surface
SBS	Small Base Station
SINR	Signal-to-Interference-plus-Noise Ratio
TDD	Time Division Duplex
UAV	Unmanned Aerial Vehicle
UMa	Urban Macro
UE	User Equipment
UMTS	The Universal Mobile Telecommunications System
3GPP	3rd Generation Partnership Project
5G NR	5G New Radio

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Part I

Overview

CHAPTER 1

Introduction

1.1 Background

Wireless network traffic usage is predicted to skyrocket and thus, in order to tackle this massive increase in data traffic, the 5G and beyond networks have moved the transmissions into the until then non-traditional millimeter wave (mmWave) spectrum. Thus, network densification [1], [2] is a key enabler in the road map to 5G and beyond, driven by the high frequencies with limited coverage in mmWave. This is an important part in ensuring massive increment of user data throughput, and a large number of small base stations (SBSs) need to be connected to support the densification. Fiber offers reliable connections with high data rates, however, one main challenge which may hinder its deployment is the noteworthy initial investment required for trenching and installation of the fiber links [3]. Moreover, it can take long installation time and in some cases, may not be allowed, especially in historical sites and metropolitan areas.

Wireless backhauling is a feasible option compared to wired alternatives in ultra dens networks. The trend to use microwave backhaul links by the mobile operators world wide is likely to continue [4]–[6]. This is triggered by its scalability and the ability to meet increasing requirements in beyond 5G and 6G networks. Currently, microwave backhaul links mainly operate in the high-frequency wireless backhaul bands (e.g., 10-80 GHz), and lower microwave frequencies (e.g., 6 GHz) range in licensed point-to-point (PtP) spectrum [7], [8].

Regardless of having limited coverage, mmWaves are inherent with wide bandwidth, high transmission quality, strong detection ability, narrow beam, and thus

can significantly improve the rising wireless communication demands [9], [10]. Meanwhile, mmWave transmissions are highly directional and thus may render fairly noise-limited networks rather than being interference-limited in most cases [11]–[13]. However, since these signals are easy to be blocked by the buildings/obstacles and have short coverage as noted earlier, it is important to have densified networks as well to compensate. Thus, due to the introduction of 5G with the access to wide bandwidth in mmWave spectrum, integrated access and backhaul (IAB) networks, where along with cellular access communications part of the radio resources can be utilized for backhauling in a more integrated manner, has received a significant attention [14], [15], [16], [17]. IAB is promising mainly thanks to its flexibility, ease of maintenance, and low time-to-market [18], [19], [20]. Figure. 1.1 illustrates an example of 5G expansion for dense networks using IAB.

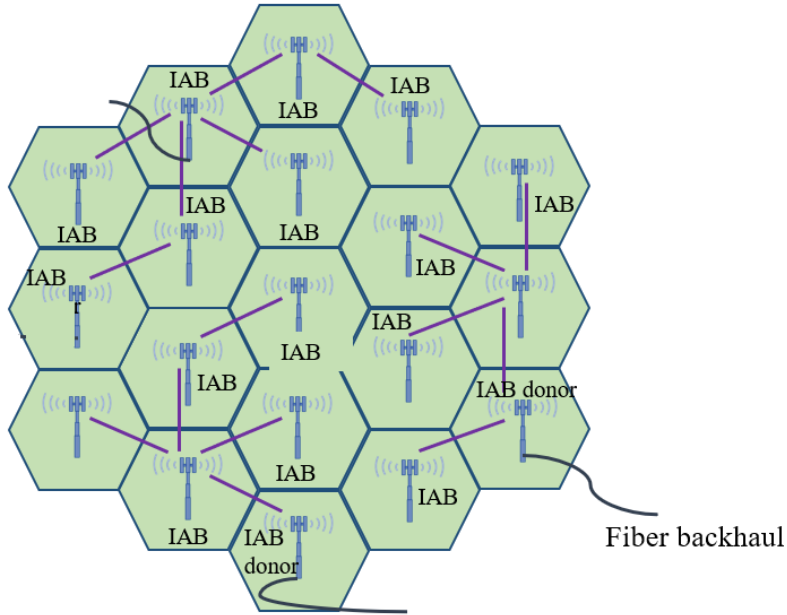


Figure 1.1: 5G NR coverage expansion with IAB.

Relayed backhaul links have been specified in long-term evolution (LTE) Release-10, as LTE-relaying [21]–[23], however, the commercial deployment cases were limited due to the unavailability of massive bandwidth and because the spectrum in sub-6 GHz band is expensive to be used for backhauling. The limitations of LTE relaying include, 1) the limitation on number of supported hops, i.e., designed to support only a single hop; 2) the inflexible static bandwidth allocation between access and

backhaul; 3) static parent node to child node architecture [24]–[26]. However, in 5G and beyond networks IAB may be more successful because of the availability of massive bandwidth and the need for densified deployments due to the short propagation range of mmWave. Also, in contrast to the LTE relaying, IAB allows greater flexibility due to its multi-hop architecture and dynamic resource sharing between access and backhaul. Moreover, new radio (NR) inherits highly directional beamforming capabilities and multiple-input-multiple-output (MIMO) which can help to mitigate the cross-link interference between the access and backhaul links.

Although it is not the focus of this thesis, IAB also permits deployment of mobile cells, called mIAB in par with the previously studied moving relay/mobile relay, which is supposed to be standardized after 3GPP Rel-18. In general, such IAB nodes could be placed in buses, trains and unmanned aerial vehicles (UAVs)¹ [26]–[29]. Along with frequent handovers and interference management, one of the main challenges for mIAB is the fast-outdated channel state information (CSI) caused by mobility. One promising solution is to use predictor antenna [30], [31], [32], such that additional antennas are deployed in the front of the main antenna(s) and are used for CSI acquisition.

Various system design and resource allocation methods for mIAB have been studied in, e.g., in [26], [30], [32]–[39].

1.1.1 Topology Optimization and Related Work

Routing has been studied for multi-hop IAB networks in [40]–[47]. Also, [48] designs cost-optimal node placement schemes while [49] evaluates joint resource allocation and node placement strategy to maximize the sum rate of downlink in IAB networks. Moreover, various network topology optimizations for non-IAB networks using machine-learning based solutions have been studied [50]–[62]. Still, in contrast to our work, these studies have not considered non-IAB backhaul distribution optimization nor joint optimization of non-IAB node placement and non-IAB backhaul link placement. Also, in our work, we study the effect of different deployment constraints on the performance of IAB networks.

1.1.2 Topology Optimization in IAB Networks

Well planned and optimized networks can achieve better performance while saving costs to the mobile network operators as well. This is resulted from the ability to avoid, e.g., static blockages like buildings and trees [63], [64]. For moving blockages, one way is to use routing to compensate for temporal blockages. Alternatively, context-information based dynamic blockage avoidance could be realized with cooperative base stations (BSs) [65]. Still, when the network size increases in urban dense areas, the derivation of closed-form solutions for network topology/routing/cooperative

¹Note that 3GPP Rel-18 work-item does not support UAV-based mIAB.

blockage avoidance becomes infeasible to achieve. It is worth noting that the network topology optimization can be performed offline and be recalculated whenever there are considerable changes in blocking conditions, addition of new BSs and different service coverage requirements. However, in all such cases, the optimization problem rapidly becomes very large, which motivates the efforts to go for a sub-optimal machine learning-based approach, as searching over all possible options via exhaustive search is infeasible. In this way, machine learning techniques give effective (sub)optimal solutions with reasonable implementation complexity.

1.2 Scope of the Thesis

The main focus of this thesis is evaluating IAB networks and designing effective techniques to improve the network performance. Specifically, we evaluate the network performance in the cases with tree foliage, rain loss and blockages. Furthermore, we carry out analysis on the network performance when part of the network is non-IAB backhauled. Thereby, we optimize the network not only for IAB node placement but also for dedicated non-IAB backhaul connection distribution. Moreover, we take into account spatial constraints when placing IAB nodes and develop efficient algorithms to optimize such constrained networks. We consider a dense urban area with a two-tier heterogeneous network (HetNet) [66], [67], i.e., a two-hop IAB network, where multiple MBSs (M: macro) and SBSs serve the user equipment (UE). In this way, following the 3GPP definitions (see Chapter 2), the MBSs and the SBSs represent the IAB donor and the child IABs, respectively.

1.3 Organization of the Thesis

In Chapter 2, the HetNet model, 3GPP concepts and protocols are discussed. The details of the channel model are also presented. Thereby, in Chapter 3, different topology optimization and routing schemes are presented, specifically, GA-based methods to improve the network's service coverage probability (CP). Furthermore, discussion is carried out on optimization of node placement in spatially-constrained networks [68]. Finally, Chapter 4 provides a brief overview of our contributions in the attached papers, and discusses possible future research directions.

Network Model and 3GPP Concepts

2.1 Overview on Standardization

Since many years, wireless backhaul links have been around and 3GPP has already taken actions to standardize this matter in LTE Release 10 context [69]–[71]. The work on IAB has started in 5G NR. Particularly, IAB could operate in all spectrum in principle, however, 3GPP standardization work has been concentrated on mmWave spectrum. This has become the norm because the low spectrum is very expensive due to the limited bandwidth and given the fact that access to wider bandwidth is available in mmWave, in contrast to low bands.

The standardization process of IAB commenced in 2017 within 3GPP Rel-15 with IAB architectures, and radio protocols [72]. Later, Release 16 was endorsed in July 2020 with protocol layers and IAB architectures [73], [74]. Standardization continued in Rel-17 to enhance the performance of IAB networks. Due to this reason, IAB has a significant potential and also a lot of open areas to be researched. In particular, IAB specifies two different types of network nodes [75],

- The IAB-Donor node is the node consisting of Centralized Unit (CU) and Distributed Unit (DU) functionalities, and connects to the core network via non-IAB, e.g., fiber, microwave backhaul.
- The IAB node includes two modules, i.e., DU and mobile termination (MT). IAB-DU serves the UEs and, potentially, downstream IAB nodes in case of multi-hop wireless backhauling. At its other side, an IAB-MT is the unit that connects an IAB node with the DU of the parent/upstream node.

When it comes to the connectivity with the parent node, the IAB-MT connects to the DU of its parent node essentially as a normal UE. On one hand, from the UE point-of-view, the DU of an IAB node appears as a normal DU. This is necessary to preserve backward compatibility so that legacy (pre Rel-16) NR UEs could also access the network via an IAB node. Figure 2.1 shows the types of connections in IAB networks.

2.1.1 IAB-DU classes

The requirements of the below specifications apply only to Wide Area IAB-DU, Medium Range IAB-DU and Local Area IAB-DU unless otherwise stated. The associated deployment scenarios for each class are exactly the same for IAB-DU with and without connectors.

For IAB type 1-O and 2-O, IAB-DU classes are defined as indicated follows, [76, Section 4.4.1], [77].

- Wide Area IAB-DU are characterised by requirements derived from Macro Cell scenarios with a BS to UE minimum distance along the ground equal to 35 m.
- Medium Range IAB-DU are characterised by requirements derived from Micro Cell scenarios with a BS to UE minimum distance along the ground equal to 5 m.
- Local Area IAB-DU are characterised by requirements derived from Pico Cell scenarios with a BS to UE minimum distance along the ground equal to 2 m.

Meanwhile, for IAB type 1-H, the IAB-DU classes are defined as indicated follows, [76, Section 4.4.1],[77]:

- Wide Area IAB-DU are characterised by requirements derived from Macro Cell scenarios with a BS to UE minimum coupling loss equal to 70 dB.
- Medium Range IAB-DU are characterised by requirements derived from Micro Cell scenarios with a BS to UE minimum coupling loss equals to 53 dB.
- Local Area IAB-DU are characterised by requirements derived from Pico Cell scenarios with a BS to UE minimum coupling loss equal to 45 dB.

2.1.2 IAB-MT classes

The requirements in this specification apply to Wide Area IAB-MT and Local Area IAB-MT classes unless otherwise stated. For IAB type 1-H, 1-O, and 2-O, IAB-MT classes are defined as indicated follows, [76, Section 4.4.2]:

- Wide Area IAB-MT are characterised by requirements derived from Macro Cell and/or Micro Cell scenarios.

- Local Area IAB-MT are characterised by requirements derived from Pico Cell and /or Micro Cell scenarios.

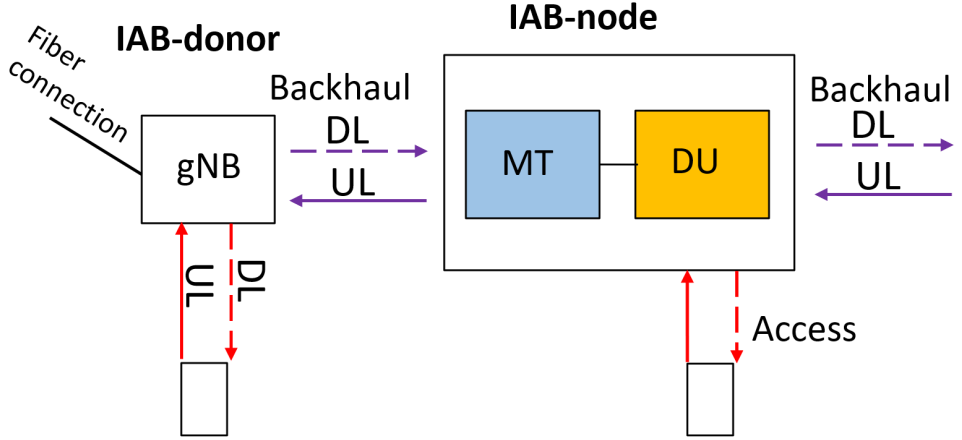


Figure 2.1: Types of connections in IAB networks.

2.1.3 Backhaul Adaptation Protocol

A new IAB-specific protocol for routing and bearer mapping in data packets of IAB network is introduced as backhaul adaptation protocol (BAP). This BAP is taking care of packet forwarding in intermediate hops lying between IAB-donor-DU and access IAB node. In the downlink traffic, the BAP layer of IAB-Donor-DU adds a BAP header to the received packets from the upper layer. Similarly, BAP layer of access IAB-node appends a BAP header to the upper layer packets in the uplink traffic.

Topology Optimization with Constraints in IAB Deployments

3.1 System model

The IAB network is modeled using finite homogeneous Poisson point processes (FHPPP), with implementation details described below (See paper A for further reading).

3.1.1 Spatial Distribution

In general, we consider a two-tier heterogeneous (HetNet) IAB network with multiple IAB-donor nodes and IAB-child nodes serving UEs, of which only the IAB-donors are fiber-connected while the SBSs use wireless connections for both access and backhaul links. The MBSs, SBSs and UEs are distributed using FHPPP distributions with their respective densities, λ_M , λ_S and λ_U where, $\lambda_M < \lambda_S < \lambda_U$.

We let the network area be a circular disk, where the FHPPPs are distributed on. For simplicity and without loss of generality, we let A be a circular disk with radius D . However, the study is generic and can be applied on arbitrary regions A . The SBSs and the UEs are also located on the same A in accordance with two other FHPPPs ϕ_S and ϕ_U having the densities λ_S and λ_U , respectively, which are all mutually independent.

The blockages are modeled using the well-known germ grain model, [78], which performs well for environments with larger obstacles than the stochastic models, under the assumption that the blocking is independent in different links. The distribution model is an FHPPP, distributed within the same circular disk area with a blockage density of λ_B . The blockages are given a length of l_B and orientation

of θ . The blockages with these specified characteristics are distributed in random locations uniformly as of the FHPPP.

3.1.2 Channel Model

We consider an inband communication setup, where both the access and backhaul links operate in the same mmWave spectrum band. Following the state-of-the-art mmWave channel model, the received power at each node can be expressed as

$$P_r = P_t h_{t,r} G_{t,r} L_{(1m)} L_{t,r} (||x_t - x_r||)^{-1} F_{t,r} \gamma_{t,r}. \quad (3.1)$$

Here, P_t denotes the transmit power in each link, and $h_{t,r}$ represents the independent small-scale fading of each link. The small-scale fading is modelled as a normalized Rayleigh random variable in our analysis. Then, $G_{t,r}$ represents the combined antenna gain of the transmitter and the receiver of the link, $L_{t,r}(\cdot)$ denotes the path loss due to propagation, and $L_{(1m)}$ is the reference path loss at 1 meter distance. The tree foliage loss is denoted by $F_{t,r}$ while $\gamma_{t,r}$ represents the rain loss between the transmitter and the receiver of the link in linear scale. The total path loss, in dB, is characterized according to the 5GCM UMa close-in model described in [79].

In 5G, large antenna arrays with directional beamforming are used to mitigate the propagation losses. We model the beam pattern as a sectorized-pattern antenna array and thus the antenna gain between two nodes can be expressed by

$$G_{i,\varphi} = \begin{cases} G_0 & -\frac{\theta_{\text{HPBW}}}{2} \leq \varphi \leq \frac{\theta_{\text{HPBW}}}{2} \\ g(\varphi) & \text{otherwise.} \end{cases} \quad (3.2)$$

Here, i, j are the indices of the considered transmit and receive nodes, and φ is the angle between them in the considered link. Also, θ_{HPBW} is the half power beamwidth of the antenna, and G_0 is the directional antenna's maximum gain while $g(\varphi)$ is the side lobe gain.

The inter-UE interferences are neglected due to the low power of the devices and with the assumption of sufficient isolation. The interference model focuses on the aggregated interference on the access links, due to the neighbouring interferers, which for UE u is given by

$$I_u = \sum_{i,j \in \phi_{i,j} \setminus \{\mathbf{x}_c\}} P_j h_{i,j} G_{i,j} L_{(1m)} L_{x_i, x_j} (||\mathbf{x}_i - \mathbf{x}_j||)^{-1}. \quad (3.3)$$

Here, i and j represents all BSs except for the associated cell x_c , which can either be an MBS or an SBS.

3.1.3 Cell Association and Resource Allocation

The UE can be served by only one cell, either from the IAB-donor node or from the IAB-child node based on the maximum received power rule. i.e., the UE will connect to the serving node maximizing the received power. The backhaul link association of the IAB-child nodes is determined by the minimum pathloss rule, where the child-node will connect to the donor-node with the minimum path loss.

For resource allocation, on the other hand, the mmWave spectrum available is partitioned into the access and backhaul links such that

$$\begin{cases} W_{\text{Backhaul}} = \mu W, \\ W_{\text{Access}} = (1 - \mu)W, \end{cases} \quad (3.4)$$

with $\mu \in [0, 1]$ being the percentage of bandwidth resources on backhauling. Also, W_{backhaul} and W_{access} denote the backhaul and the access bandwidths, respectively, while total bandwidth is W . The bandwidth allocated for each SBS, i.e., child IAB, by the fiber-connected MBS, i.e., IAB donor, is proportional to its load and the number of UEs in the access link. The resource allocation is determined based on the instantaneous load in which each SBS informs its current load to the associated MBS each time. Thus, the backhaul-related bandwidth for the j -th IAB node is given by

$$W_{\text{backhaul},j} = \frac{\mu W N}{\sum_{\forall j} N_j}, \forall j, \quad (3.5)$$

where N_j denotes the number of UEs connected to the j -th IAB node and the access spectrum is equally shared among the connected UEs according to

$$W_{\text{access},u} = \frac{(1 - \mu)W}{\sum_{\forall u} N_{j,u}}, \forall u, \quad (3.6)$$

where N is the number of UEs at the considered SBS and j represents each SBS connected to the MBS. Also, u represents the UEs, and $N_{j,u}$ denotes the load at the IAB node j of which UE u is connected. The signal-to-interference-plus-noise ratio (SINR) values are obtained in accordance with (3.3) by

$$\text{SINR} = P_r / (I_u + N_0), \quad (3.7)$$

where N_0 is the noise power. Then, considering sufficiently long codewords, which is an acceptable assumption in IAB networks, the rates experienced by the UEs in

access links can be expressed by

$$R_u = \begin{cases} \frac{(1-\mu)W}{N_m} \log(1 + \text{SINR}(x_u)), & \text{if } \mathbf{x}_c \in \phi_m, \\ \min \left(\frac{(1-\mu)WN}{\sum_{\forall u} N_{j,u}} \log(1 + \text{SINR}(x_u)), \right. \\ \left. \frac{\mu WN}{\sum_{\forall j} N_j} \log(1 + \text{SINR}(x_b)) \right), & \text{if } \mathbf{x}_c \in \phi_s \end{cases} \quad (3.8)$$

and the backhaul rate is given by

$$R_b = \frac{\mu WN}{\sum_{\forall j} N_j} \log(1 + \text{SINR}(x_b)). \quad (3.9)$$

Here, m represents the associated MBS and s denotes the SBS. Based on the association cell, there are two cases for the rate of the UEs. First, is the case in which the UEs are associated to the MBSs, as denoted by $x_c \in \phi_m$ in (3.8). Since the MBSs, i.e., IAB donor nodes, have fiber backhaul connection, the rate will depend on the access bandwidth available at the UE. In the second case, the UEs are connected to the SBSs, as denoted by $x_c \in \phi_s$ in (3.8). Here, the SBSs have shared backhaul bandwidth from the IAB donor nodes i.e., MBSs, and thus the UEs data rates depend on the backhaul rate of the connected SBS as well. Thus, in this case the UE is bounded to get the minimum between backhaul and access rate.

3.2 Topology Optimization

In general, it is preferred to have IAB-IAB backhaul links with strong line-of-sight (LoS) signal strength, although Rel-16 supports non-line-of-sight (NLoS) backhauling, since IAB network performance is considerably influenced by the quality of the backhaul links. Moreover, in most cases, a fraction of SBSs can be connected via dedicated non-IAB backhaul links. Thus, it has become important to identify the SBSs that are crucial to be backhauled using such links for optimum performance. However, since analytical solutions for the appropriate node location sets and non-IAB backhaul link placement schemes are not feasible in large network sizes, it is important to design feasible algorithms with low complexity which can provide the (sub)optimal solutions for both of the cases. Figure 3.1 depicts the general system model of the IAB network with topology and constraint optimizations.

For example, in a use case with N_s SBSs and the possibility for a total of N_f non-IAB backhauled SBSs, we could have $\binom{N_s}{N_f}$ possible combinations of non-IAB backhauled SBS selections, which may need a lot of computational capacity if the

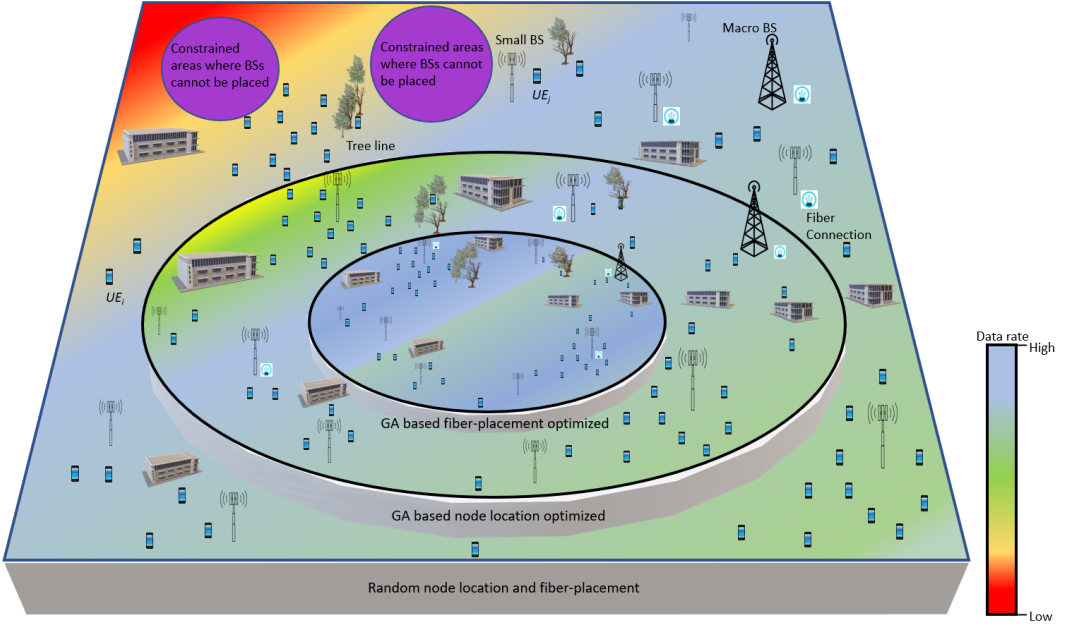


Figure 3.1: Schematic of system model.

solutions are obtained using exhaustive search, especially when the network size is large.

In Paper A, we study the potentials and challenges of IAB networks concentrating on millimeter wave-based communications on different use cases and deployment conditions, e.g, urban, suburban, blockage, tree foliage and rain. In particular, we use a finite stochastic geometry model, with random distributions of IAB nodes as well as UEs to study the service coverage probability defined as the probability of the event that the UEs' minimum rate requirements are satisfied. Furthermore, we summarize the recent Rel-16 as well as the upcoming Rel-17 3GPP discussions on IAB, and highlight the main IAB-specific agreements on different protocol layers.

With this background from Paper A and the need for topology optimization of IAB networks, in Paper B, we propose GA-based schemes [80] which outputs 1) the optimal locations of SBSs to be non-IAB backhauled and 2) optimal node locations within the network area, as described in Algorithms 1 and 2, respectively. Details are presented in the appended Paper B, i.e., [81]. The utility function that is supposed to be maximized is the service coverage probability, i.e., the fraction of UEs that have instantaneous data rates R_U equal to or higher than that of a pre-defined threshold data rate η . Using these notations, the service coverage probability is given by

$$\text{CP} = \Pr(R_U \geq \eta). \quad (3.10)$$

As we show in [81], our proposed algorithms result in significantly lower complexity compared to the cases with exhaustive search, since they only evaluate KN_{it} number of potential solutions, where K is the possible selection strategies in each iterations and N_{it} is the maximum number of iterations pre-considered by the network designer. Moreover, as in each iteration we evaluate $K - J - 1$ possible random solutions, where $J < K$, the algorithms can mimic the exhaustive search if $N_{\text{it}} \rightarrow \infty$, i.e., they can achieve the global optimum selection if asymptotically large number of iterations are considered [80].

Algorithm 1 GA-based non-IAB Backhaul Link Placement

In each iteration with a budget for N_f non-IAB backhaul-connected SBSs, and $N_s > N_f$ SBSs, do the followings.

- I. Consider K sets of N_f non-IAB backhaul-connected SBSs, where each of those sets is denoted by F_k . Then, for each set create the corresponding channel matrix H_k , $k = 1, \dots, K$, according to the considered channel model.
- II. For each selected possible solution set F_k , evaluate the objective function U_k , $k = 1, \dots, K$. For instance, considering the service coverage probability CP as the objective function, U_k is given by (3.10).
- III. Find the set of the SBSs among the considered solution sets $F_k, \forall k$, which results in the best value of the objective function, service coverage probability (defined as the *Queen*), e.g., F_i where $\text{CP}(H_k) \leq \text{CP}(H_i), \forall k = 1, \dots, K$.
- IV. $F_1 \leftarrow F_i$
- V. Generate $J < K$, sets of SBSs $F_j^{\text{new}}, j = 1, \dots, J$, around the Queen, i.e., F_i . These sets of SBSs are generated by making small changes to the Queen, for instance, by replacing few SBSs with other SBSs.
- VI. $F_{j+1} \leftarrow F_j^{\text{new}}, j = 1, \dots, J$.
- VII. Use the same procedure as in Step I and regenerate the remaining sets $F_j, j = J + 2, \dots, K$, randomly.
- VIII. Proceed to Step II and continue the process for N_{it} iterations pre-considered by the network designer.

Return the Queen as the optimal SBS selection rule for non-IAB backhaul link placement.

In words, both algorithms are based on the same procedure described below.

Algorithm 2 GA-based SBS Location Selection

With N_s SBSs, from all possible locations in the space, do the followings.

- I. Consider K sets of L_k locations, and for each set create the corresponding channel matrix H_k , $k = 1, \dots, K$, according to the considered channel model.
- II. Evaluate the objective function for each set, i.e., U_k , $k = 1, \dots, K$. For instance, considering the service coverage probability CP as the objective function, U_k as given by (3.10).
- III. Find the *Queen*, i.e., the set of locations which gives the best value of the objective function, i.e., service coverage probability, among the considered sets, e.g., L_i where $\rho(H_k) \leq \rho(H_i)$, $\forall k = 1, \dots, K$,
- IV. $L_1 \leftarrow L_i$
- V. Generate $J < K$, sets of locations L_j^{new} , $j = 1, \dots, J$, around L_i . These sets of locations are generated by making small changes to the Queen, for instance, by replacing few locations with another sets of locations.
- VI. $L_{j+1} \leftarrow L_j^{\text{new}}$, $j = 1, \dots, J$.
- VII. Use the same procedure as in Step I and regenerate the remaining sets L_j , $j = J + 2, \dots, K$, randomly.
- VIII. Proceed to Step II and continue the process for N_{it} iterations pre-considered by the network designer.

Return the Queen as the optimal SBS location selection rule.

Firstly, K possible selection strategies are considered and then, in each iteration we calculate the utility function and obtain the best strategy, i.e., selected solution, that maximizes the considered utility function. This best strategy is named as the Queen and thereby the Queen is considered as one of the possible solutions in the next iteration of the algorithm in order to guarantee the monotonic improvement of the algorithm performance in later successive iterations. Thereby, the Queen has become the regeneration operator in GA. Then, for each iteration, we create $J < K$ sets around the queen by applying slight changes to the Queen as a kind of mutation. Also, $K - J - 1$ sets of selection strategies are generated randomly in each iteration in order to avoid the scenario of the algorithm getting trapped in a local minimum. Thereby, this procedure will continue for N_{it} iterations determined by the network designer to output the best set solutions. Noteworthy is that, since in Step VII of the algorithms we check $K - J - 1$ random possible solutions in each iteration, the proposed algorithms can reach the globally optimal selection if asymptotically large number of iterations are considered.

3.3 Constraints of IAB Networks

In general, there are constraints on spatial deployment of IAB networks and thus, there are locations where the nodes cannot be deployed. On one hand, the mentioned constraints can be due to the regulatory restrictions from the authorities in protected areas [82]. These restrictions can be regional and country specific. Still, all provinces have their own enacted building and landscape protection laws, that could potentially create such constraints. Furthermore, national laws have to be followed when placing nodes, e.g., forest conservation, archaeological or listed buildings etc. On the other hand, these constraints can be imposed due to network planning especially to limit the interference.

As introduced in Sec. 2.1, the 3GPP RAN4 recognizes two types of IAB nodes categorically, i.e., wide-area and local-area IAB networks, where the differences mainly lie in the node capabilities and their level of network planning to accomodate them [83], [84]. Noteworthy, as specified in 3GPP RAN4, wide-area IABs are supposed to have a minimum inter-node distance to avoid extreme interference being created at the neighbouring nodes with LoS connections. However, local-area IAB networks can be comparatively unplanned as its main task is to give a boosting capacity to an already established service area served by an IAB node. However, the spatial constraints may still prevent installation of IAB nodes anywhere.

Network planning is crucial for IAB deployments due to the sensitivity of the backhaul links and the high rate demands. The paper analyses and optimizes service coverage probability of IAB networks focusing on cases with either geographical or interference management constraints where IAB nodes may not be permitted/feasible to be deployed freely. To that end, we propose various mmWave blocking-aware

constrained deployment optimization approaches. The results indicate that, even with limitations on deployment optimization, network planning boosts the coverage probability of IAB networks considerably

With this background, Paper C analyses and optimizes the service coverage probability of IAB networks focusing on cases with either geographical or interference management constraints where IAB nodes may not be permitted/feasible to be deployed freely. As such, Algorithm 3 and Algorithm 4 in Paper C, [68] optimize the network performance for minimum inter-IAB distance requirement and the presence of constrained area use cases in, e.g., wide-area and local-area networks, respectively.

Algorithm 3 IAB placement with minimum inter-IAB distance requirement

With N_d IAB donors, N_c IAB child nodes inside the network area, do the followings:

- I. Place the 1st node, $i = 1$, randomly in the considered network area.
- II. Place the next node $i + 1$ where $i = 1, 2, 3, \dots, (N_c + N_d - 1)$.
- III. Find the minimum inter-node distances s_i between $(i + 1)$ th node and each of other nodes.
- IV. If any $s_i < r_{th}$, redistribute the last node $(i + 1)$ th by repeating Steps II-IV until $s_i > r_{th}$.
- V. For the obtained node locations, calculated the coverage. Then, proceed to Step I and continue the process for N_{it} iterations pre-considered by the network designer, saving the best set of node locations L_b among the considered solutions $L_j, \forall j, j = 1, 2, 3, \dots, N_{it}$, which gives in the best value of the service coverage.

Return the set of the node locations in Step V as the optimal node location set.

In words, Algorithm 3, places the first IAB-node, $i = 1$, at a random location inside the network area. Then it continues to place the $i + 1$ th node from the set of IAB-donors N_d and IAB-child nodes N_c . Subsequently, the algorithm finds the minimum inter-node distances s_i between each of the other nodes and the $i + 1$ th node. If any of the inter-node distances is less than a threshold r_{th} , then the $i + 1$ th node is redistributed by repeating Steps II-IV given in the Algorithm 3, until all $s_i > r_{th}$. Then, for the obtained set of node locations the service coverage probability CP is calculated, and the process is repeated until N_{it} iterations, pre-determined by the designer. The best set of node locations L_b giving the highest CP, is returned as the optimal node location set, which satisfies the inter-IAB distance requirement while maximizing the utility function.

Algorithm 4 firstly allocates a random set of node locations for the IAB-donors N_d and IAB-child nodes N_c within the network area without considering the constrained areas. Then, identifying the nodes falling inside the constrained areas, they are redistributed inside the network area. We repeat this process until all nodes fall outside

Algorithm 4 IAB placement in the presence of constrained areas restricting IAB node placement

With N_d IAB donors, N_c IAB child nodes and a set of constrained areas inside the network area, do the followings:

- I. Place the IAB donors/IAB nodes randomly in the considered network area.
- II. Identify the IAB node(s) falling inside the constrained areas.
- III. For each of the nodes identified in Step II, redistribute the nodes.
- IV. Proceed to Step II and continue the process until all IAB nodes fall outside the constrained areas. Save the set of locations as L_i .
- V. For the saved set of node locations L_i , compute the utility function, i.e., the service coverage given by (3.10). Proceed to Step I and continue the process for N_{it} iterations pre-considered by the network designer, saving the best set of node locations L_b among the considered solutions $L_i, \forall i, i = 1, \dots, N_{it}$ which gives in the best value of the utility function, e.g., service coverage.

Return the set of the node locations in V as the optimal node location set.

the constrained areas. Then, the service coverage probability is calculated as our utility function which is averaged over multiple samples of UE PPP distributions and is saved as $L_i, i = 1, \dots, N_{it}$. This process is repeated over N_{it} iterations, where the best set of node locations resulting in the highest CP is saved as L_b . At the end of the N_{it} iterations, the L_b is returned as the optimal node locations set.

CHAPTER 4

Contributions and Future Work

This chapter summarizes the contributions of each appended publication and lays out possible directions for future work based on the topics in this thesis.

4.1 Paper A

"On Integrated Access and Backhaul Networks: Current Status and Potentials", *IEEE Open Journal of the Communications Society*, vol. 1, pp. 1374-1389, Sept. 2020

This article introduces and studies the potentials and challenges of IAB as one of the key techniques for 5G and beyond networks. Evaluation has been carried out in different perspectives where we summarize the recent Rel-16 as well as some of the Rel-17 3GPP discussions on IAB which were available at the time of publishing the paper. Also, we highlight the main IAB-specific agreements on different protocol layers. Thereby, concentrating on millimeter wave-based communications at 28 GHz, the performance of IAB networks in both dense and suburban areas is evaluated. A finite homogeneous Poisson point process (FHPPP) based stochastic geometry model with random IAB nodes and UE distributions is considered and evaluated for service coverage probability. The network resilience for tree foliage, rain and blockage are studied. As shown, IAB is an attractive backhaul option for 5G and beyond.

A part of the work was performed prior to the PhD and the paper is published in IEEE Open Journal of Communication, Sept., 2020.

4.2 Paper B

"On Topology Optimization and Routing in Integrated Access and Backhaul Networks: A Genetic Algorithm-Based Approach", *IEEE Open Journal of the Communications Society*, vol. 2, pp. 2273-2291, Sep. 2021

This paper studies the topology optimization and routing in IAB networks. Here, we design efficient GA-based methods to optimize IAB node placement and non-IAB backhaul link distribution in mmWave bands and evaluate the effect of temporal blockages on routing. Furthermore, the Rel-16 and Rel-17 3GPP discussions on routing are summarized and the effect of different parameters including blockage, tree foliage and antenna gain are analyzed. The paper is published in IEEE Open Journal of Communication, Sept., 2021.

4.3 Paper C

"Constrained Deployment Optimization in Integrated Access and Backhaul Networks", *Submitted to IEEE Wireless Communications and Networking Conference (WCNC)' 2023, Glasgow, United Kingdom.*

Network planning is crucial for IAB deployments due to the sensitivity of the backhaul links and the high rate demands. The paper analyses and optimizes service coverage probability of IAB networks focusing on cases with either geographical or interference management constraints where IAB nodes may not be permitted/feasible to be deployed freely. To that end, we propose various mmWave blocking-aware constrained deployment optimization approaches. The results indicate that, even with limitations on deployment optimization, network planning boosts the coverage probability of IAB networks considerably. The paper is submitted to IEEE WCNC'2023.

4.4 Related other contributions

Contributions from related other publications by the author, but not included in the thesis are described below. In Paper D, "Joint Scheduling and Throughput Maximization in Self-backhauled Millimeter Wave Cellular Networks" in *Proc. IEEE ISWCS*, Berlin, Germany, Sept. 2021, pp. 1-6, we discuss the Joint Scheduling and Throughput Maximization in IAB networks over mmWave cellular networks. In particular, IAB networks have the potential to provide high data rate in both access and backhaul networks by sharing the same spectrum. Due to the dense deployment of SBSs,

IAB networks connect SBSs to the core network in a wireless manner without the deployment of high-cost optical fiber. As large spectrum is available in mmWave bands and high data rate is achieved by using directional beamforming. The access and backhaul links can be integrated in the same frequency band while satisfying quality-of-service constraints. This paper optimizes the scheduling of access and backhaul links such that the minimum throughput of the access links is maximized based on the revised simplex method. By considering a probability based line-of-sight (LOS) and non-line-of-sight (NLOS) path loss model and the antenna array gains, the paper compares the achievable minimum access throughput of the IAB network with the network having only macro base stations, and studies the effect of the network topology and antenna parameters on the achievable minimum throughput. Simulation results show that, for a broad range of parameter settings, the implementation of IAB networks improves the access minimum achievable throughput.

In Paper E, "Uplink Power Control in Integrated Access and Backhaul Networks" in *Proc. IEEE DySPAN*, Los Angeles, CA, USA, Dec. 2021, pp. 163-168, power control combined with resource allocation algorithms is used to develop efficient IAB networks with high service coverage. Particularly, the paper develops a genetic algorithm-based solution for the power control of both user equipments and IAB nodes such that the network uplink service coverage probability is maximized. Finally, considering millimeter wave channel models, the paper studies the effect of different parameters including minimum data rate requirement, coverage distance and transmit power on the network performance. As the results show, a power allocation scheme with well-tuned parameters can improve the uplink performance of IAB networks considerably. Moreover, with millimeter wave communications and a proper network deployment, the effect of interference on the service coverage probability is negligible.

4.5 Future Work

The thesis is contributing in evaluating IAB networks and design effective techniques to improve the performance for 5G NR and beyond, focusing on a two-hop (tier) multi-cellular system. The thesis focuses on IAB in various aspects including an overview of 3GPP discussion.

However, further investigation/research can be made in the future given IAB has become a new and broad topic.

- Identify efficient algorithms for resource allocation.
- Conduct theoretical analysis of FHPPP in IAB node distributions.
- Design re-configurable intelligent surface (RIS)-assisted IAB networks.

- Study on better interference cancellation in the in-band IAB.
- Derive the optimal value for access and backhaul bandwidth allocation.
- Study joint beamforming for access and backhaul in IAB networks.
- Study IAB and optimal fronthaul/backhaul split in context of cell-free access using distributed antenna systems.
- Study the potential and challenges of mIAB.

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Part II

Papers

On Integrated Access and Backhaul Networks: Current Status and Potentials

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Abstract

—In this paper, we introduce and study the potentials and challenges of integrated access and backhaul (IAB) as one of the promising techniques for evolving 5G networks. We study IAB networks from different perspectives. We summarize the recent Rel-16 as well as the upcoming Rel-17 3GPP discussions on IAB, and highlight the main IAB-specific agreements on different protocol layers. Also, concentrating on millimeter wave-based communications, we evaluate the performance of IAB networks in both dense and sub-urban areas. Using a finite stochastic geometry model, with random distributions of IAB nodes as well as user equipments (UEs) in a finite region, we study the service coverage rate defined as the probability of the event that the UEs' minimum rate requirements are satisfied. We present comparisons between IAB and hybrid IAB/fiber-backhauled networks where a part or all of the small base stations are fiber-connected. Finally, we study the robustness of IAB networks to weather and various deployment conditions and verify their effects, such as blockage, tree foliage, rain as well as antenna height/gain on the coverage rate of IAB setups, as the key differences between the fiber-connected and IAB networks. As we show, IAB is an attractive approach to enable the network densification required by 5G and beyond.

Index terms— Integrated access and backhaul, IAB, densification, millimeter wave (mmWave) communications, 3GPP, Stochastic geometry, Poisson point process, Coverage probability, Germ-grain model, ITU-R, FITU-R, Wireless backhaul, 5G NR, Rain, Tree foliage, Blockage, Relay

1 INTRODUCTION

Different reports, e.g., [1], predict a steep increase of Internet devices connected through wireless access as well as a massive increase in mobile traffic. To cope with such requirements, along with utilizing more spectrum, the fifth generation (5G) wireless networks and beyond propose different ways for spectral efficiency and capacity improvements. Network densification [2], [3] is one of the key enablers among the alternative approaches, e.g., various distributed antenna systems techniques, including cell-free massive multiple-input-multiple-output (MIMO) and can be achieved via the deployment of many access points of different types, so that there are more resource blocks per unit area.

The base stations (BSs) need to be connected to the operators' core network via a

transport network. A transport network may consist of wired or wireless connections. Typically, wireless connections are used for backhaul transport in the radio access network (RAN), closer to the BSs, while wired high-capacity fiber connections are used for transport closer to the core network and in the core network, where the network needs to handle aggregated traffic from many BSs.

The deployed backhaul technology today has large regional variations, but on a global scale, wireless microwave technology has historically been a dominating media for a long time. Over the last 10 years there has however been a large increase in fiber deployments attributed to, e.g., geopolitical decisions and major governmental investments. Over the same time, the use of copper as a media has reduced a lot due to increasing demands on capacity and lower maintenance. Going forward there are thus two dominating backhaul media – microwave and fiber. Historical and predicted global backhaul media distribution can be found in [4].

Fiber offers reliable high-capacity transport with demonstrated Tbps rates. However, the deployment of fiber requires a noteworthy initial investment for trenching and installation, which could take a considerable installation time, and even might not be possible/allowed in, certain areas where trenching is not an option.

Wireless backhauling using microwave represents a competitive alternative to fiber since it today provides 10's of Gbps in commercial deployments and even 100 Gbps has recently been demonstrated [5]. Microwave is a backhaul technology used by most mobile operators worldwide, and this trend is likely to continue. This is because microwave is a scalable and economical backhaul option that can meet the increasing requirements of 5G systems. A key advantage over fiber is that wireless backhauling comes with significantly lower cost and flexible/timely deployment (e.g., no digging, no intrusion or disruption of infrastructure, and possible to deploy in principle everywhere) [4], [6]. Today microwave backhauling operates in licensed point-to-point (PtP) spectrum, typically in the 4–70/80 GHz range. However, with the introduction of 5G in millimeter wave (mmWave) spectrum and with the foreseen need for even wider bandwidths for backhaul, microwave is currently being extended to even higher frequencies, above 100 GHz.

For the same reasons, and driven by network densification and access to wide bandwidth in mmWave spectrum, integrated access and backhaul (IAB) networks, where the operator can utilize part of the radio resources for wireless backhauling, has recently received considerable attention [7], [8]. The purpose of IAB is to provide flexible wireless backhauling using 3GPP new radio (NR) technology in international mobile telecommunications (IMT) bands, *providing not only backhaul but also the existing cellular services in the same node*. Thus, IAB serves as a complement to microwave PtP backhauling in dense urban and suburban deployments, while it comes at the expense of using IMT bands not only for access but also for backhaul traffic.

Wireless backhauling has been studied earlier in 3GPP in the scope of LTE Rel-10, also known as LTE relaying [9]. However, there have been only a handful of

commercial LTE relay deployments, mainly because the existing LTE spectrum is very expensive to be used for backhauling, and also small-cell deployments did not reach the anticipated potential in the 4G timeline.

For 5G NR, IAB has been standardized in 3GPP Rel-16 and, as we detail later in the paper, standardization will continue in Rel-17. The main reason why NR IAB is expected to be more commercially successful than LTE relaying is that:

- The limited coverage of mmWave access creates a high demand for denser deployments, which, in turn, increases the need for backhauling.
- Also, the larger bandwidth available in mmWave spectrum provides more economically viable opportunity for wireless backhauling.
- Finally, MIMO, multi-beam systems, and multiple access, which are inherent features of NR, enable efficient backhauling of multiple radio BSs using the same equipment.

There have been several studies on the performance of IAB networks. For instance, cost-optimal node placement [10], resource allocation [11]–[14] and routing [11]–[17] are studied in the cases with different numbers of hops. Particularly, [10] provides an overview of multi-hop IAB techniques supported in the 3GPP rel-16 standard and discusses its design strategies. A joint node placement and resource allocation scheme maximizing the downlink sum rate is developed in [18]. Also, [19] uses simulated annealing algorithms for joint scheduling and power allocation. The maximum extended coverage area of a single fiber site using multi-hop relaying is investigated in [20], and [21], [22] perform end-to-end simulations to check the feasibility/challenges of mmWave-based IAB networks. Also, [23] provides useful insights for IAB deployments, especially, related to network densification and multi-hop topology, as it simulates a multi-hop mmWave pico-cell network, and evaluates the user throughput. The potential of using IAB in a fixed wireless access use-case is evaluated in [24]. The impact of dynamic time division duplex (TDD)-based resource allocation on the throughput of IAB networks, how its performance compares with static TDD and FDD (F: frequency), is discussed in [25], [26]. Moreover, [27]–[29] characterize the coverage probability of IAB-enabled mmWave heterogeneous networks via infinite Poisson point processes (PPPs). Precoder design and power allocation, to maximize the network sum rate, is considered in [30]. Finally, [31] investigates the usefulness of IAB in unmanned aerial vehicle (UAV)-based communications, and [32] develops a reinforcement learning-based resource allocation scheme in such networks.

In this paper, we study the performance of IAB networks from different perspectives. We start by summarizing the most recent 3GPP discussions in Rel-16 as well as the upcoming ones in Rel-17, and highlight the main IAB-specific features on different protocol layers. Then, concentrating on mmWave-based communications, we analyze the performance of IAB networks, and compare their performance with those

achieved with hybrid IAB/fiber-connected networks. Here, the results are presented for the cases with an FHPPP (FH: finite homogeneous)-based stochastic geometry model, e.g., [27], [33], i.e., a PPP which depends on a constant density, with random distributions of the IAB nodes as well as the user equipments (UEs) in a finite region. Particularly, we study the network service coverage probability, defined as the probability of the event that the UEs' minimum data rate requirements are satisfied.

One of the key differences between fiber-connected and IAB networks is that, the backhaul link in IAB networks may, like any wireless link, be impacted by various weather effects and deployment conditions such as rain, blockage, antenna heights, and tree foliage. For this reason, we evaluate the impacts of these aspects. The results are presented for both suburban and urban areas, with the main focus on dense deployments, since that is the most interesting scenario for IAB.

In summary, the paper presents an easy-to-follow description of the most recent 3GPP agreements on IAB, gives cost/performance comparisons between the IAB and fiber-connected networks, and verifies the robustness of the network to different environmental effects, which makes the paper completely different from the related literature.

As we demonstrate, along with microwave backhauling, IAB is a cost-effective complement of fiber, especially in dense metropolitan areas. Moreover, independently of the cost, IAB is an appropriate tool in a number of use-cases of interest in 5G. Finally, as we show, while the coverage rate of the IAB network is slightly affected by heavy rainfall in suburban areas, for a broad range of parameter settings and different environments, the blockage and the rain are not problematic for IAB networks, in the sense that their impact on the coverage probability is negligible. High levels of tree foliage, however, may reduce the coverage probability of the network, especially in suburban areas.

The rest of the paper is organized as follows. Section 2 summarizes the key 3GPP discussions in Rel-16 and 17 on IAB. Section 3 describes the performance evaluation of IAB networks, compares their performance with those achieved in hybrid IAB/fiber-connected networks, and verifies the robustness of the IAB setup to different weather and deployment parameters. Finally, conclusions and a number of interesting open research problems that encourages researchers to contribute are provided in Section 4.

2 IAB in 3GPP

NR IAB was introduced in 3GPP Rel-16. It provides functionality that allows for the use of the NR radio-access technology not only for the link between BSs and devices, sometimes referred to as the access link, but also for wireless backhaul links, see Figure 1.

Wireless backhauling, that is, the use of wireless technology for backhaul links, has

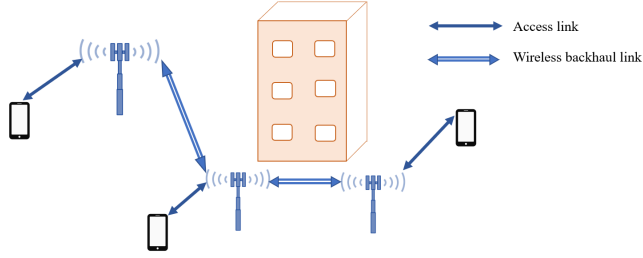


Figure 1: Integrated access and backhaul.

been used for many years. However, this has then been mainly based on radio technologies different from those used for the access links. Additionally, wireless backhaul has typically been based on proprietary, i.e., non-standardized¹, radio technology operating in mmWave spectrum above 10 GHz² and constrained to line-of-sight (LOS) propagation conditions.

However, along with massive amount of available spectrum due to the move to mmWave, there are at least two factors that now make it more relevant to consider an IAB solution, that is, reusing the standardized cellular technology, normally used by devices to access the network, also for wireless-backhaul links:

- With the emergence of 5G NR, the cellular technology is extending into the mmWave spectrum, a spectrum range that historically is used for wireless backhaul.
- With the emergence of small-cell deployments with BSs located, for example, on street level, there is a demand for a wireless-backhaul solution that allows for backhaul links to operate also under non-line-of-sight (NLOS) conditions, the kind of propagation scenarios for which the cellular radio-access technologies have been designed.

2.1 IAB Architecture

The IAB standard that is being specified in 3GPP Rel-16 [35] is based on the split architecture introduced in 3GPP Rel-15, where a base station (gNB) is split into a centralized unit (CU), which terminates the Packet Data Convergence Protocol (PDCP) and the Radio Resource Control (RRC) protocol, and a distributed unit (DU) that terminates the lower layer protocols, i.e., Radio Link Control (RLC),

¹Some aspects of microwave backhauling are standardized, but there is significant room for proprietary solutions.

²Traditional wireless backhaul operates also below 10 GHz, for example the longhaul links are typically at 6 GHz [34].

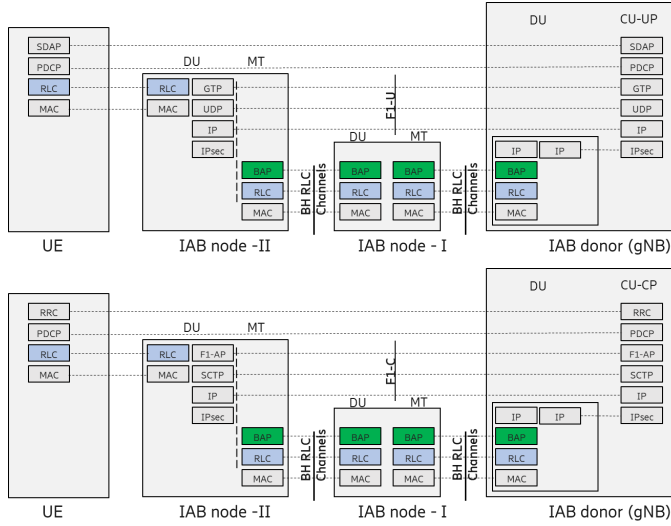


Figure 2: User plane and control plane protocol stack of a multi-hop IAB network according to 3GPP Rel-16.

Medium Access Control (MAC) and the physical layer [36]. The motivation for the CU/DU functional split is that all time-critical functionalities, e.g., scheduling, fast retransmission, segmentation etc., can be realized in the DU, i.e., close to the radio and the antenna, while it is possible to centralize and resource-pool the less time-critical radio functionalities in the CU. A specified interface (F1 interface) is used to convey both the control-plane (F1-C) and user-plane (F1-U) messages between the CU and DU. The CU/DU split is transparent to the UE, i.e., it does not impact UE functionality or protocol stack.

Figure 2 shows the control and user plane protocol stack of a multi-hop IAB network according to 3GPP Rel-16. The IAB donor node is the node that is connected to the rest of the network in a conventional way (e.g., fiber or microwave) and serves the IAB nodes and other UEs that are directly connected to it. The IAB nodes have a mobile termination (MT) part and a DU part. The MT part is used to connect to a parent DU (which could be the donor DU or the DU part of another IAB node), while the DU part of an IAB node is used to serve UEs or the MT part of child IAB nodes.

In many respects, the MT part of an IAB node behaves like a UE in the sense that it communicates with the parent DU very much like a UE. On the other hand, from the UE point-of-view, the DU of an IAB node appears as a normal DU. This is necessary to preserve backwards compatibility so that legacy (pre Rel-16) NR UEs could also access the network via an IAB node.

As in legacy CU/DU split, for the user plane, the service data adaptation protocol

(SDAP) and PDCP are terminated at the UE and the user plane part of the CU (CU-UP), and the corresponding packets are transported over an F1-U interface (basically, a set of GTP tunnels for each bearer) between the CU-UP and the DU part of the IAB node serving the UE (known as access IAB node). Similarly, for the control plane, the RRC and PDCP are terminated at the UE and the CU-CP, and the corresponding packets are transported over an F1-C interface, which is realized via a set of stream control transport protocol (SCTP) associations/streams between the CU-UP and the DU part of the access IAB node. The IAB-MTs can employ all the functionalities available to UEs such as carrier aggregation and dual connectivity to multiple parent nodes. The IAB nodes's protocol/architecture is transparent to the UE, i.e., UEs cannot differentiate between normal gNBs and IAB nodes.

In Rel-16, only a directed acyclic graph (DAG) multi-hop topology was supported, i.e., no mesh-based connectivity. Also, only decode-and-forward relaying was considered, where the signal is decoded in each hop and, with a successful decoding, it is re-encoded and transferred to the next hop. Compared to other relaying techniques, this gives the best E2E performance in the multi-hop setup and make it possible to scale the network to the cases with different numbers of hops, especially, due to its full processing capability. The IAB nodes are interconnected with each other at layer 2 level and a hop-by-hop RLC is employed. This provides a better performance than having an end-to-end (E2E) RLC between the donor and the UE because retransmissions, if any, are required only over the affected hop, rather than between the UE and the donor, leading to faster and most efficient recovery to transmission failures. Hop-by-hop RLC also leads to lower buffering requirements at the end points. With regard to security, no hop-by-hop security is needed between the IAB nodes since the PDCP at the UE and CU ensure E2E encryption and integrity protection (optional for user plane).

On Backhaul Adaptation Protocol

A new protocol known as backhaul adaptation protocol (BAP) is specified that is responsible for the forwarding of packets in the intermediate hops between the donor DU and the access IAB node [37]. Each IAB node is configured with a unique BAP ID by the donor node. For downlink (DL) packets, the donor DU inserts a BAP routing ID on the packets it is forwarding to the next hop, which is the BAP ID of the access IAB node serving the UE and a path identifier, in case there are several possible paths to reach the access IAB node. Similarly, for uplink (UL) packets, the access IAB node inserts the UL BAP routing ID, which is the BAP ID of the donor DU and a path identifier, in case there are several possible paths to reach the DU. Each IAB node is configured with UL and DL routing tables, which indicates to which child node (in the case of DL) or parent node (in the case of UL) the packet should be forwarded. When an access IAB node receives a packet that is destined

to it, the packet will be forwarded to higher layers and processed the same way a normal DU processes incoming F1-U or F1-C packets.

In addition to forwarding packets to a child or parent node, the BAP protocol also performs the mapping between ingress and egress backhaul RLC channels, to ensure that the packets are treated with the proper quality of service (QoS) requirements. Similar to RLC channels between a DU and a UE, the backhaul RLC channels can be configured with different QoS parameters such as priority and guaranteed bit rates. For bearers that have very strict QoS requirements, a 1:1 mapping could be used, where there is a dedicated backhaul RLC channel on each hop. Otherwise, an 1:N mapping can be employed where packets belonging to several bearers could be transported/multiplexed over a given backhaul RLC channel. Similar to the routing table, the IAB nodes are configured with a mapping configuration to determine which egress backhaul RLC channel a packet should be forwarded to once the next child/parent node has been identified via the routing table.

On Integration Procedure

Before becoming fully operational, the IAB node performs the IAB integration procedure, which is illustrated in Fig. 3 (interested reader is referred to [38] for the details). In the first step (startup), the IAB node performs an RRC connection establishment, like a normal UE, using its MT functionality. Once the connection is set up, it indicates to the network that it is an IAB node, which the network verifies/authenticates. Connectivity to the Operation and Maintenance (OAM) part of the network could also be performed at this phase to update configurations.

In the second step, the required/default backhaul RLC channel(s) are established, to enable the bootstrapping process where the DU part of the IAB node establishes the F1 connection with the donor as well as enable OAM connectivity (if not performed during the first step). A routing update is also made, which includes several sub-procedures such as IP address allocation for the IAB node and the (re)configuration of the BAP sub-layer at the IAB node and possibly all ancestor IAB nodes (BAP routing identifier(s) for downstream/upstream directions, routing table updates, etc.).

In the last step, the DU part of the IAB node can initiate an F1 connection request towards the donor CU, using its newly allocated IP address. After the F1 connection is set up, the IAB node can start serving UEs like a normal DU. Reconfigurations can be made anytime after this step, on a need basis, to update the backhaul RLC channels, routing tables, bearer mapping, etc.

2.2 Spectrum for IAB

As already mentioned, although IAB supports the full range of NR spectrum, for several reasons the mmWave spectrum is most relevant for IAB:

- The potentially large amount of mmWave spectrum makes it more justifiable

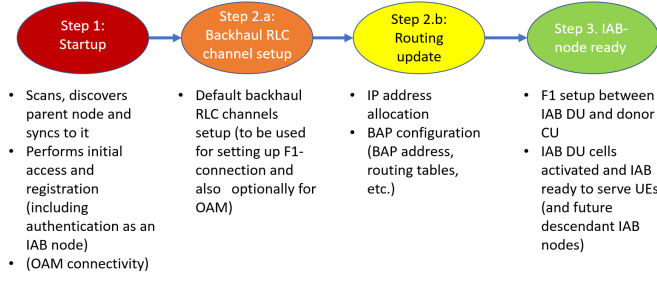


Figure 3: Schematic diagram of the IAB integration procedure in 3GPP Rel-16.

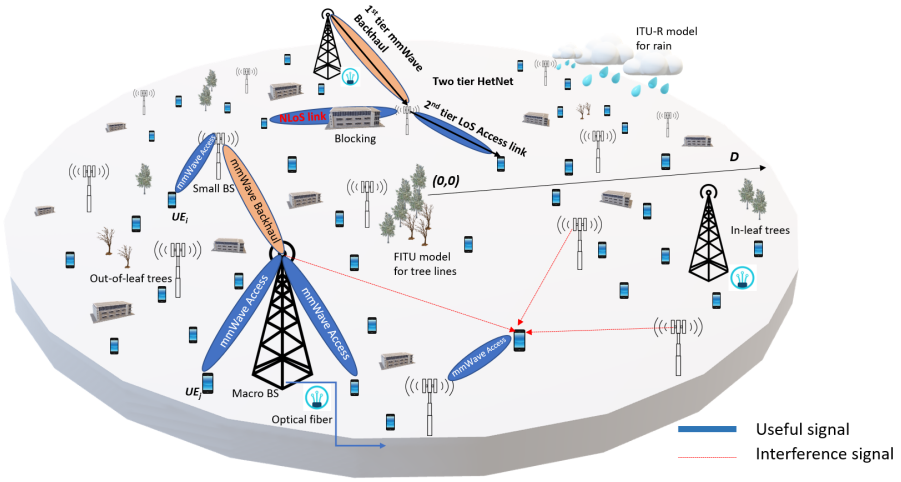


Figure 4: Schematic of the IAB system model.

to use part of the spectrum resources for wireless backhaul.

- Massive beamforming enabled at higher frequencies is especially beneficial for the wireless-backhaul scenario with stationary nodes at both ends of the radio link.

Higher-frequency spectrum is mainly organized as unpaired spectrum. Thus, operation in unpaired spectrum has been the main focus for the 3GPP discussions on IAB. IAB supports both outband and inband backhauling:

- Outband backhauling:** The wireless backhaul links operate in a different frequency band, compared to the access links.
- Inband backhauling:** The wireless backhaul links operate in the same frequency band, as the access links.

2.3 The IAB Radio Link

In most respects, the backhaul link, between a parent-node DU and a corresponding child IAB-node MT operates as a conventional network-to-device link. Consequently, the IAB-related extensions to the NR physical, MAC, and RLC layers are relatively limited and primarily deal with the need to coordinate the IAB-node MT and DUs for the case of inband operation when simultaneous DU and MT operation is not possible.

Similar to UEs, a time-domain resource of an IAB-node MT can be configured/indicated as:

- Downlink (DL): The resource will only be used by the parent node in the DL direction.
- Uplink (UL): The resource will only be used by the parent node in the UL direction.
- Flexible (F). The resource may be used in both the DL and UL directions with the instantaneous transmission direction determined by the parent-node scheduler.

Similarly, the time-domain resources of the DU part of an IAB node can be configured as:

- Downlink (DL): The DU can only use the resource in the DL direction.
- Uplink (UL): The DU can only use the resource in the UL direction.
- Flexible (F): The DU can use the resource in both the DL and UL directions.

In parallel to the DL/UL/F configuration, DU time-domain resources could be configured as hard or soft. In case of a hard configuration, the DU of a node can use the resource without having to consider the impact on its MTs ability to transmit/receive according to its configuration and scheduling. In practice this means that, if a certain DU time-domain resource is configured as hard, the parent node must assume that the IAB-node MT may not be able to receive/transmit. Consequently, the parent node should not schedule transmissions to/from the MT in this resource.

In contrast, in case of a DU time-domain resource configured as soft, the DU can use the resource if and only if this does not impact the MTs ability to transmit/receive according to its configuration and scheduling. This means that the parent node can schedule a DL transmission to the MT in the corresponding MT resource and assume that the MT is able to receive the transmission. Similarly, the parent node can schedule MT UL transmission in the resource and assume that the MT can carry out the transmission.

The possibility to configure soft DU resources allows for more dynamic resource utilization. Take, as an example, a soft DU resource corresponding to an MT resource configured as UL. If the MT does not have a scheduling grant for that resource, the IAB node knows that the MT will not have to transmit within the resource. Consequently, the DU can dynamically use the resource, for example, for DL transmission, even if the IAB node is not capable of simultaneous DU and MT transmission.

The possibility to configure soft DU resources also gives an IAB node the chance to benefit from being able to perform simultaneous DU and MT operation. Whether or not a specific IAB node is capable of simultaneous DU and MT operation may depend on the IAB-node implementation and may also depend on the exact deployment scenario. Thus, an IAB node designed or deployed so that it can support simultaneous DU and MT operation can use a soft DU resource without the parent node even knowing about it.

These situations, when an IAB node, by itself, can conclude that it can use a soft DU resource has, in the 3GPP discussions, been referred to as implicit indication of availability of soft DU resources. The parent node can also provide an explicit indication of availability of a soft DU resource by means of layer-1 signaling.

Finally, it should be noted that, along with resource multiplexing which has been the main topic of discussions in RAN1, the over-the-air (OTA) timing alignment, the random access channel (RACH) as well as the extensions of SSBs for inter-IAB-node discovery and measurements have been discussed in 3GPP. However, due to space limits, we do not cover these topics, and the interested reader can find the final agreements in [39]. Moreover, while we concentrated mostly on RAN1 and RAN2 discussions, the main discussions/agreements in RAN3 and RAN4 can be found in [40]-[41] and [42], respectively (also see [10]).

2.4 IAB in Rel-17

The physical-layer part of the IAB Rel-16 specifications was finalized at the end of 2019 and the remaining parts (higher-layer protocols and architecture) are expected to be finalized in June 2020. Further enhancements to IAB will then be carried out within 3GPP Rel-17, with expected start in August 2020 [43]. The Rel-17 work aims to improve on various aspects such as robustness, degree of load-balancing, spectral efficiency, multi-hop latency and end-to-end performance. More specifically, the following is planned to be covered:

- Enhancements to the resource multiplexing between child and parent links of an IAB node, including:
 - Enhanced support of simultaneous operation (transmission and/or reception) of IAB-node's child and parent links, including enhancements such as new DU/MT timing relations, DL/UL power control and cross link interference mitigation.

Table 1: The Definition of the Parameters.

Parameter	Definition	Parameter	Definition
ϕ_M	FHPPP of the MBSs	ϕ_U	FHPPP of the UEs
ϕ_S	FHPPP of the SBSs	λ_U	UE density
ϕ_B	FHPPP of the blocking walls	θ	Orientation of blocking wall
ϕ_T	FHPPP of the tree lines	l_{hop}	Average hop length
λ_M	MBSs density	λ_S	SBSs density
H	Homogeneous Poisson Process	λ_B	Blocking wall density
l_B	Blocking wall length	ρ	Service coverage probability
A	Circular disk	D	Radius of the disk
P_t	Transmission power	P_r	Received power
h	Fading coefficient	G	Antenna gain
$L_{(1\text{m})}$	Reference path loss at 1 meter distance	L	Propagation path loss
x	Location of the node	r	Propagation distance between the nodes
α	Path loss exponent	N	Number of UEs connected
f_c	Carrier frequency	φ	Angle between the BS and UE
θ_{HPBW}	Half power beamwidth of the antenna	G_0	Maximum gain of directional antenna
$g(\varphi)$	Side lobe gain	R_{th}	Minimum data rate threshold
x_c	Associated cell	R	Rain intensity
x_u	Connected UE at the location	i, j	Node index
F_T	Tree foliage	γ_R	Rainloss
d	Vegetation depth	W	Bandwidth of the DL
μ	Percentage of bandwidth resources on backhaul	l_T	Tree line length
λ_T	Tree blocking density	v	SBS antenna height

- Support for dual-connectivity scenarios for topology redundancy for improved robustness and load balancing.
- Enhancements in scheduling, flow and congestion control to improve end-to-end performance, fairness, and spectral efficiency.
- Introduction of efficient inter-donor IAB-node migration, increasing the robustness of IAB networks allowing for more refined load-balancing and topology management.
- Reduction of service interruption time caused by IAB-node migration and backhaul RLF recovery improves network performance, allows network deployments to undergo more frequent topology changes, and provides stable backhaul performance.

Finally, it should be mentioned that in 3GPP RAN4 a number of simulations have been performed to evaluate the feasibility/efficiency of IAB networks, e.g., [44]. There, it has been mainly concentrated on defining RF requirements for both backhaul and access links of an IAB-node including requirements for their co-existence, and evaluate the performance in different possible scheduling scenarios of the the DU and MT. In Section 3, we mainly concentrate on the comparison between the performance of IAB and fiber networks as well as studying the robustness of IAB networks to different environmental effects using a novel stochastic geometry modeling for mmWave networks and 3D maps topology information. Such results provide insights about if the IAB performance expectations will be met in urban and suburban areas.

3 Performance Evaluation

This section studies the service coverage rate of IAB networks with various parameterizations, and compares the performance with those achieved by (partially) fiber-connected networks. First, we present the system model, including the channel model, the considered UE association rule as well as the rain, the blockage and the tree foliage models, which are followed by the simulation results.

3.1 System Model

As shown in Fig. 4., consider an outdoor two tier heterogeneous network (HetNet), i.e., a two-hop IAB network, with multiple MBSs (M: macro), SBSs (S: small) and UEs. This is motivated by different evaluations, e.g., [27]–[30], where, although the standardization does not limit the number of hops, increasing the number of hops may lead to backhaul traffic aggregation. In an IAB deployment, both the MBSs and the SBSs use wireless connections for both access and backhaul. Also, only the MBSs are fiber-connected while the SBSs receive data from the MBSs wirelessly by using IAB. That is, following the 3GPP definitions (see Section 2), the MBSs and the SBSs can be considered as the donor and the child IABs, respectively. Therefore, throughout the section, we may use the terminologies MBS/SBS and donor IAB/IAB interchangeably. Considering an inband operation, the bandwidth is shared among access and backhaul links of the IAB nodes such that the network service coverage rate is maximized. For simplicity, the MBSs and the SBSs are assumed to have constant power over the spectrum of the system and are all active throughout the analysis³.

³Developing adaptive power allocation schemes for IAB networks is an interesting open research topic.

Spatial Model

Table I summarizes the parameters used in the analysis. We model the IAB network by an FHPPP, e.g., [33], [45], which suits well to model a random number of nodes in a finite region. Particularly, FHPPPs ϕ_M and ϕ_S with densities λ_M and λ_S , respectively, are used to model the spatial distributions of the MBSs and the SBSs, respectively.

The MBSs' FHPPP is given by $\phi_M = H \cap A$, where H with density λ_M is an HPPP (H : homogeneous) and $A \subset \mathbb{R}^2$ is a finite region. For simplicity and without loss of generality, we let A be a circular disk with radius D . However, the study is generic and can be applied on arbitrary regions A . The SBSs and the UEs are also located within the same A in accordance with two other FHPPPs ϕ_S and ϕ_U having densities λ_S and λ_U , respectively, which are all mutually independent.

We study the system performance for two blocking conditions. First, we use the well-known germ grain model [46, Chapter 14], which provides accurate results compared to stochastic models that assume the blocking in different links to be independent. Moreover, the germ grain model fits well for environments with large obstacles as it takes the obstacles induced blocking correlation into account. The model is an FHPPP, i.e., the blockages are distributed according to the FHPPP ϕ_B distributed in the same area A with density λ_B . This is a 2D model where all blockings are assumed to be walls of length l_B and orientation θ , which is an independently and identically distributed (IID) uniform random variable in $[0, 2\pi]$. The walls are distributed in random locations uniformly as of the FHPPP.

With the 2D channel model, the elevation of the blocking and the BSs or the terrain information of the land are not taken into account. For this reason, in Subsection 3.3, we demonstrate the system performance for an example 3D use-case. Particularly, we distribute the same spatial arrangement of the MBSs, the SBSs and the UEs with their respective nodes heights on top of map data with real world blocking terrain using OpenStreetMap 3D environment. That is, while different MBS and SBS nodes are distributed randomly based on their corresponding FHPPPs, they are placed, on different heights, and the blockages are determined based on the map information. This enables us to evaluate the effect of the nodes and blocking heights on the service coverage probability.

Channel Model

We consider an inband communication setup, where both the access and backhaul links operate in the same mmWave spectrum band. Following the state-of-the-art mmWave channel model, e.g., [45], the received power at each node can be expressed as

$$P_r = P_t h_{t,r} G_{t,r} L_{(1m)} L_{t,r} \|x_t - x_r\|^{-1} F_{t,r} \gamma_{t,r}. \quad (\text{A.1})$$

Here, P_t denotes the transmit power in each link, and $h_{t,r}$ represents the independent small-scale fading for each link. The small-scale fading is modelled as a normalized Rayleigh random variable in our analysis. Then, $G_{t,r}$ represents the combined antenna gain of the transmitter and the receiver of the link, $L_{t,r}$ which is a function of the distance between x_t and x_r , denotes the path loss due to propagation, and $L_{(1m)}$ is the reference path loss at 1 meter distance. The tree foliage loss is denoted by $F_{t,r}$ while $\gamma_{t,r}$ represents the rain loss between the transmitter and the receiver of the link in linear scale. The total path loss, in dB, is characterized according to the 5GCM UMa close-in model described in [47]. The path loss is given by

$$\kappa = 32.4 + 10 \log_{10}(r)^\alpha + 20 \log_{10}(f_c), \quad (\text{A.2})$$

where f_c is the carrier frequency, r is the propagation distance between the nodes, and α is the path loss exponent. Depending on the blockage, LOS and NLOS links are affected by different path loss exponents. The propagation loss of the path loss model is given by

$$L_{t,r} = \begin{cases} r^{\alpha_L}, & \text{if LoS,} \\ r^{\alpha_N}, & \text{if NLoS,} \end{cases} \quad (\text{A.3})$$

where α_L and α_N denote path loss exponents for the LOS and NLOS scenarios, respectively. In 5G, large antenna arrays with directional beamforming are used to mitigate the propagation losses. We model the beam pattern as a sectorized-pattern antenna array and thus the antenna gain between two nodes can be expressed by

$$G_{i,j}(\varphi) = \begin{cases} G_0 & -\frac{\theta_{\text{HPBW}}}{2} \leq \varphi \leq \frac{\theta_{\text{HPBW}}}{2} \\ g(\varphi) & \text{otherwise.} \end{cases} \quad (\text{A.4})$$

Here, i, j are the indices of the considered transmit and receive nodes, and φ is the angle between them in the considered link. Also, θ_{HPBW} is the half power beamwidth of the antenna, and G_0 is the directional antenna's maximum gain while $g(\varphi)$ is the side lobe gain. Also, we let the UE antenna gain to be 0 dB. This is in harmony with, e.g., [27], [29], [48], and because the UE has an omni-directional radiation pattern. For discussions on how the antenna gain is affected by the antenna array properties, see, e.g., [45].

We assume that we have high beamforming capability in the IAB-IAB backhaul links. Consequently, we ignore the interference in the backhaul links and assume them to be noise-limited. Also, the inter-UE interferences are neglected due to the low power of the devices and with the assumption of sufficient isolation [24]. On the other hand, as illustrated in Fig. 4, the interference model focuses on the aggregated interference on the access links, due to the neighbouring interferers, which for UE u

Table 2: Coefficients for ITU-R model. Here, β_h , k_h are the horizontal polarization coefficients and β_v , k_v denote the vertical polarization coefficients [49].

Frequency (GHz)	β_h	β_v	k_h	k_v
28	0.9679	0.9277	0.2051	0.1964

is given by

$$I_u = \sum_{i,j \in \phi_{i,j} \setminus \{\mathbf{x}_c\}} P_j h_{i,j} G_{i,j} L_{(1m)} L_{x_i, x_j} \|\mathbf{x}_i - \mathbf{x}_j\|^{-1}. \quad (\text{A.5})$$

Here, i and j represents all BSs except for the associated cell x_c which can either be an MBS or an SBS.

Rain and Tree Foliage Model

With the need of understanding the performance of IAB networks in rainy conditions, we use the ITU-R Rec 8.38-3 rain model [49] to entail the rain effect on the links. This is an appropriate model used to methodically determine the amount of rain attenuation on radio links. The model is widely used in all regions of the world, for the frequency range from 1 GHz to 1000 GHz with no rain rate obligation. The model describes the rain loss as

$$\gamma_R = kR^\beta, \quad (\text{A.6})$$

where γ_R is the rain loss in dB/km, and R is the rain intensity in mm/hr. Moreover, k and β are coefficients that are precalculated depending on the carrier frequency. Table II shows the coefficients for horizontal and vertical losses at rainy conditions in 28 GHz on which we concentrate in the simulations.

Finally, FHPPP ϕ_T with density λ_T is used to spatially distribute the tree lines of length l_T [50]. We use the Fitted International Telecommunication Union-Radio (ITU-R) tree foliage model [51, Chapter 7] to model the effect of the trees on the received signal power. This is an appropriate model for the cases with frequency dependancy and with non-uniform vegetation. The model is suitable for the mmWave frequencies from 10 to 40 GHz and has been derived by further developing the ITU-R vegetation model. In this way, considering two, namely, *in-leaf* and *out-of-leaf*, vegetation states, the tree foliage in dB is obtained by

$$F_T = \begin{cases} 0.39 f_c^{0.39} d^{0.25}, & \text{in-leaf} \\ 0.37 f_c^{0.18} d^{0.59}, & \text{out-of-leaf,} \end{cases} \quad (\text{A.7})$$

where f_c is the carrier frequency expressed in MHz and d is the vegetation depth in meter.

3.2 Association and Allocation Strategy

In our setup, the UE can be served by either an MBS or an SBS following open access strategy and based on the maximum average received power rule. Also, in harmony with 3GPP, we do not take joint transmission into account, i.e., each UE can be connected to only one MBS or SBS. In this way, the association rule for UE u suffices

$$\sum_{\forall j} u_j = 1, \forall u \in U, u_i \cdot u_j = 0, \forall j \neq i, \quad (\text{A.8})$$

where $u_j \in \{0, 1\}$ is a binary variable indicating the association with 1 and 0 denoting the unassociated cell. For the access links of the UEs, we have

$$u_j = \begin{cases} 1 & \text{if } P_i G_{z,x} h_{z,x} L_{(1m)} L_{z,x} (\|\mathbf{z} - \mathbf{x}\|)^{-1} \\ & \geq P_j G_j h_{z,y} L_{(1m)} L_{z,y} (\|\mathbf{z} - \mathbf{y}\|)^{-1}, \\ & \forall \mathbf{y} \in \phi_j | \mathbf{x} \in \phi_i, i, j \in \{m, s\} \\ 0, & \text{otherwise.} \end{cases} \quad (\text{A.9})$$

As in (A.9) for each UE u , the association binary variable u_j becomes 1 for the cell giving the maximum received power at the UE, while for all other cells it is 0 since the UE can only be connected to one IAB node.

Because the IAB nodes, i.e., both the MBSs and the SBSs, are equipped with large antenna arrays and can beamform towards the required direction, the antenna gain over the backhaul links can be assumed to be the same, and backhaul link association can be well determined based on the minimum path loss rule, i.e., by

$$x_{b,m} = \begin{cases} 1 & \text{if } L_{b_m} (\|\mathbf{z} - \mathbf{x}\|)^{-1} \geq L_{b_m} (\|\mathbf{z} - \mathbf{y}\|)^{-1}, \\ & \forall \mathbf{y} \in \phi_m | \mathbf{x} \in \phi_m, \\ 0, & \text{otherwise} \end{cases} \quad (\text{A.10})$$

(For the effect of interference in the backhaul links, see Fig. 6). For resource allocation, on the other hand, the mmWave spectrum available is partitioned into the access and backhaul links such that

$$\begin{cases} W_{\text{Backhaul}} = \mu W, \\ W_{\text{Access}} = (1 - \mu) W, \end{cases} \quad (\text{A.11})$$

with $\mu \in [0, 1]$ being the percentage of bandwidth resources on backhauling. Also, W_{backhaul} and W_{access} denote the backhaul and the access bandwidths, respectively, while total bandwidth is W . The bandwidth allocated for each SBS, i.e., child IAB, by the fiber-connected MBS, i.e., IAB donor, is proportional to its load and the number of UEs in the access link. The resource allocation is determined based on

the instantaneous load in which each SBS informs its current load to the associated MBS each time. Thus, the backhaul-related bandwidth for the j -th IAB node is given by

$$W_{\text{backhaul},j} = \frac{\mu W N_j}{\sum_{\forall j} N_j}, \forall j, \quad (\text{A.12})$$

where N_j denotes the number of UEs connected to the j -th IAB node. Therefore, the bandwidth allocated to the j -th IAB node is proportional to the ratio between its load, and the total load of its connected IAB donor. Meanwhile, the access spectrum is equally shared among the connected UEs at the IAB node according to

$$W_{\text{access},u} = \frac{(1-\mu)W}{\sum_{\forall u} N_{j,u}}, \forall u, \quad (\text{A.13})$$

where u represents the UEs, and j represents each IAB node. Also, $N_{j,u}$ denotes the users connected to the j -th IAB node of which UE u is connected. The signal-to-interference-plus-noise ratio (SINR) values are obtained in accordance with (A.5) by

$$\text{SINR} = P_r / (I_u + N_0), \quad (\text{A.14})$$

where N_0 is the noise power. Then, considering sufficiently long codewords, which is an acceptable assumption in IAB networks, the rates experienced by the UEs in access links can be expressed by

$$R_u = \begin{cases} \frac{(1-\mu)W}{N_m} \log(1 + \text{SINR}(x_u)), & \text{if } \mathbf{x}_c \in \phi_m, \\ \min \left(\frac{(1-\mu)W}{\sum_{\forall u} N_{j,u}} \log(1 + \text{SINR}(x_u)), \right. \\ \left. \frac{\mu W N_j}{\sum_{\forall j} N_j} \log(1 + \text{SINR}(x_b)) \right), & \text{if } \mathbf{x}_c \in \phi_s \end{cases} \quad (\text{A.15})$$

and the backhaul rate is given by

$$R_b = \frac{\mu W N_j}{\sum_{\forall j} N_j} \log(1 + \text{SINR}(x_b)). \quad (\text{A.16})$$

Here, m represents the associated MBS and s denotes the SBS. Based on the association cell, there are two cases for the rate of the connected UEs, x_u at the location. First, is the case in which the UEs are associated to the MBSs, as denoted by $x_c \in \phi_m$

Table 3: Simulation Parameters.

Parameters	Value
Carrier frequency	28 GHz
Minimum data rate threshold	100 Mbps
Bandwidth	1 GHz
IAB node and UE density	$\{\text{MBS, SBS, UE}\} = (8, 100, 500) / \text{km}^2$
Blocking	$\{\text{Density, Length}\} = (500 / \text{km}^2, 5 \text{ m})$
Path loss exponents	$\{\text{LoS, NLoS}\} = (2, 3)$
Main lobe antenna gains	$\{\text{MBS, SBS, UE}\} = (24, 24, 0) \text{ dBi}$
Side lobe antenna gains	$\{\text{MBS, SBS, UE}\} = (-2, -2, 0) \text{ dBi}$
Half power beamwidth	$\{\text{azimuthal, elevation}\} = (60, 25)$
Noise power	5 dB
In-leaf percentage	20%
Tree depth	5 m
Antenna heights	$\{\text{MBS, SBS, UE}\} = (25, 10, 1) \text{ m}$

in (A.15). Since the MBSs, i.e., IAB donor nodes, have fiber backhaul connection, the rate will depend on the access bandwidth available at the UE. In the second case, the UEs are connected to the SBSs, as denoted by $x_c \in \phi_s$ in (A.15). Here, the SBSs have shared backhaul bandwidth from the IAB donor nodes i.e., MBSs, and thus the UEs data rates depend on the backhaul rate of the connected SBS as well. Thus, in this case the UE is bounded to get the minimum between backhaul and access rate.

3.3 Simulation Results and Discussions

The simulation results are divided into three parts in which 1) we compare IAB, hybrid IAB/fiber-connected, and fiber-connected networks, 2) verify the robustness of IAB networks, and 3) study the system performance in an example of 3D network deployment. Note that the 2D model is considered mainly to limit the simulation complexity. However, for different cases, the same qualitative conclusions as those presented in the 2D model hold in the 3D model as well. The general system parameters are summarized in Table 3 and, for each figure, the specific parameters are given in the figure caption. The network is deployed in a disk of radius of $D = 1$ km, where the rain occurrence, the blockage, and the vegetation distributions are also probable according to the statistical models described in Section 3.1. In all fig-

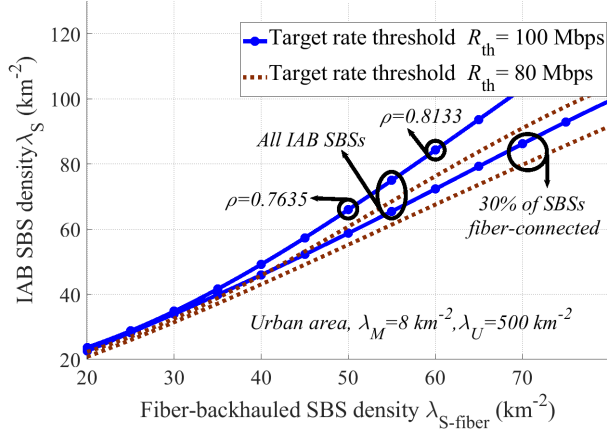


Figure 5: Density of the IAB nodes sufficing the performance of fiber-backhauled network, in terms of service coverage probability. The parameters are set to $\lambda_B = 500 \text{ km}^{-2}$, no rain, $R_{th} = 100 \text{ Mbps}$, and $P_{MBS}, P_{SBS}, P_{UE} = (40, 24, 0) \text{ dBm}$.

ures, except for Figs. 8 and 9 which study the system performance in both urban and suburban areas, we concentrate on dense areas as the most important point of interest in IAB networks. We assume that we have high beamforming capability in the IAB-IAB backhaul links. Consequently, in all figures except for Fig. 6, we ignore the interference in the backhaul links, in harmony with, e.g., [27]–[29]. In Fig. 6, however, we verify this assumption, and study the system performance in the cases where the interference is not ignored in the IAB-IAB links (More insights on mmWave interference in cellular networks are discussed in, e.g., [52], [53].)

Our metric of interest is the service coverage probability [54], defined as the fraction of the UEs which have instantaneous UE data rates higher than or equal to a threshold R_{th} . That is, using (A.15), the service coverage probability is given by

$$\rho = \Pr(R_U \geq R_{th}). \quad (\text{A.17})$$

IAB versus Fiber

In Figs. 5-6, we compare the coverage probability of the IAB networks with those obtained by the cases having (a fraction of) fiber-connected SBSs, as well as the cases with no SBS. Also, Fig. 6 verifies the effect of the interference in the backhaul links on the system performance. In these figures, different parameters, e.g., bandwidth allocation between the access and backhaul, have been optimized to maximize the coverage probability in each case. Note that, in practice and depending on the network topology, a number of SBSs may also be fiber-connected. For this reason, in Figs. 5-6, we also consider the cases with a fraction of SBSs having fiber

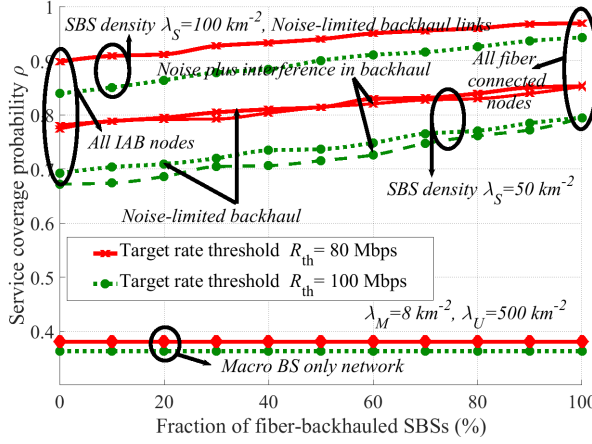


Figure 6: Service coverage probability as a function of the percentage of the fiber-backhauled SBSs for a dense network with $\lambda_B = 500 \text{ km}^{-2}$, no rain and $P_{\text{MBS}}, P_{\text{SBS}}, P_{\text{UE}} = (40, 24, 0) \text{ dBm}$.

connections. In such cases, we assume the fiber-connected SBSs to be randomly distributed, and adapt the association and allocation rules as well as the achievable rates, correspondingly.

Figure 5 demonstrates the required number of IAB nodes to guarantee the same coverage probability as in the cases with hybrid IAB/fiber-connected SBSs. Then, Fig. 6 shows the network service coverage rate as a function of the fraction of fiber-connected SBSs, and compares the system performance with the cases having no SBS.

As demonstrated in Figs. 5-6, for a broad range of parameter settings, the same performance as in the fully fiber-connected networks can be achieved by the IAB network, with relatively small increment in the number of IAB nodes. As an example, consider the parameter settings of Fig. 5 and the UEs' target rate 100 Mbps. Then, a fully fiber-connected network with SBSs densities 50 and 60 km^{-2} corresponds, in terms of coverage probability, to an IAB network having densities $\lambda_S = 65 \text{ km}^{-2}$ and 85 km^{-2} , respectively, leading to coverage probabilities 0.76 and 0.81. Interestingly, with a 30% of SBSs having fiber connections, which is practically reasonable, these numbers are reduced to $\lambda_S = 70$ and 85 km^{-2} , i.e., only 16% and 21% increase in the required number of SBSs. Then, as the network density increases, the effect of the UEs target rate as well as the relative performance gap of the IAB and fiber-connected networks decrease (Fig. 6). Moreover, in harmony with intuitions and motivated by the high beamforming capability of the IAB nodes, the effect of the interference in the backhaul links is negligible, and the IAB-IAB links can be well assumed to be noise-limited (Fig. 6).

Here, it should be noted that our results, based on the FHPPP and random node drop, give a pessimistic performance of IAB networks. In practice, the network topology will be fairly well-planned, further reducing the gap between the performance of IAB and fiber-connected networks. Also, for simplicity and in order to mainly concentrated on the effect of environmental parameters, we considered the minimum path loss rule in the backhaul links. A smart network operator may, however, use load balancing techniques to avoid congestion in the network, e.g., [55], [56]. Finally, while we considered a fixed bandwidth split between the access and backhaul which limits the resource allocation/coordination complexity, an adaptive split between access and backhaul of different nodes would improve the network performance.

On Some Practical Benefits of IAB

Using IAB with such a relatively small increment of the nodes reduces the network cost considerably⁴. This is because an SBS is much cheaper than fiber⁵. For example, and only to give an intuitive view, as reported in [57], Table 7], in an urban area the fiber cost is estimated to be in the range of 20000 GBP/km, while an SBS in 5G is estimated to cost around 2500 GBP per unit [58]⁶. More importantly, internal evaluations at Ericsson indicates that, for dense urban/suburban areas, even in the presence of dark fiber, the deployment of IAB networks is an opportunity to reduce the total cost of ownership (TCO) as well as the time-to-market. Especially, the same hardware can be used both for access and backhaul such that no extra and separate system is needed for backhaul.

Thus, although IAB may not support the same peak rate as fiber, IAB will be sufficient and a cost-effective solution for SBSs in dense networks, and with no digging⁷, traffic jam and/or infrastructure displacement.

Along with the cost reduction, IAB increases the network flexibility remarkably. With optical fiber, the access points, of different types, can be installed only in the places with fiber connection. Such a constraint is, however, relaxed in IAB networks, and the nodes can be installed in different places as long as they have fairly good connection to their parent nodes. These are the reasons that different operators have shown interest to implement IAB in 5G networks [61], and it is expected that IAB would be ultimately used in up to 10-20% of 5G sites, e.g., [62].

It is interesting to note that, regardless of the cost, IAB is an attractive solution

⁴It is reasonable to consider almost the same cost for an IAB node and a typical SBS.

⁵Indeed, the exact cost of the fiber varies vastly in different regions, due to many factors including labour cost, etc. However, for different areas, fiber laying accounts to a significant fraction of the total network cost.

⁶The price estimates are based on [57], and [58], and should not be considered as the cost estimations in Ericsson.

⁷According to different reports, e.g., [59], [60], for fiber connection in metropolitan areas, a large portion (about 85%) of the total cost figure is tied to trenching and installation.

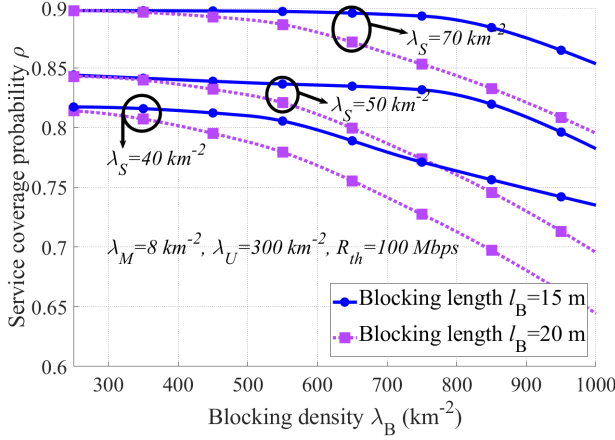


Figure 7: Service coverage probability of the IAB network as a function of the blocking density λ_B , with $P_{MBS}, P_{SBS}, P_{UE} = (40, 24, 0)$ dBm, and no rain/tree foliage.

for a number of use-cases:

- Street trenching and digging not only are expensive but also may destroy historical areas or displace trees. For such reasons, some cities may consider a moratorium on fiber trenching [59], and instead rely on wireless backhaul methods such as IAB and microwave backhaul.
- Fiber installation may take a long time, as it requires different permissions, labor work, etc. In such cases, IAB can establish new radio sites quickly. Thus, starting with IAB and, if/when needed, replacing it by fiber is expected to become a quite common setup.
- Low income zones of dense cities suffer from poor Internet connection. This is mainly because current fiber-based solutions are not economically viable, and the companies are not interested in fiber installation in such areas. Here, IAB is a low TCO solution to reduce the cost of Internet infrastructure.
- Public safety, and in general mission critical (MC), systems should be able to provide temporally on-demand coverage in all scenarios where the MC UEs are within terrestrial cellular network coverage or out of terrestrial cellular network coverage. In such cases, an IAB node, e.g., on a drone or a fire truck, can extend the coverage with high reliability and low latency⁸.

Finally, as expected and also emphasized in Fig. 6, as the number of UEs increases,

⁸It should be noted that, within Rel-16 and 17, mobile IAB is not supported. Thus, with an IAB on, e.g., a drone, the node position should remain fixed during the data transmission.

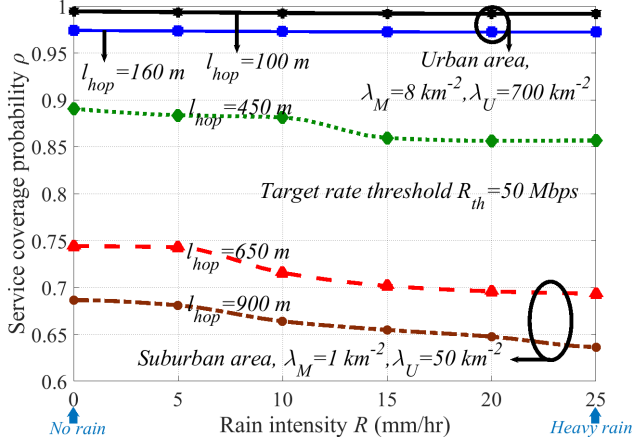


Figure 8: Service coverage probability of the IAB network as a function of the rain intensity in urban and suburban areas and for different average hop distances. The parameters are set to $P_{MBS}, P_{SBS}, P_{UE} = (45, 33, 0)$ dBm, $\lambda_B = 500 \text{ km}^{-2}$ for urban area and no blocking for the suburban area. Average hop distances $l_{hop} = 100, 160, 450, 650, 900$ m correspond to SBS densities $\lambda_S = 100, 50, 8, 5, 3 \text{ km}^{-2}$, respectively.

MBSs alone can not support the UEs' QoS requirements, and indeed we need to densify the network with, e.g., using (IAB) nodes of different types.

Effect of Rain, Blocking and Tree Foliage

As opposed to fiber-connected setups, an IAB network may be affected by blockage, rain and tree foliage, the effects of which are analyzed in Figs. 7-9, respectively. Particularly, considering the 2D FHPPP blockage model, Fig. 7 investigates the coverage probability for different blockage densities λ_B and walls lengths l_B (also, see Fig. 11 for the effect of blockage in a 3D model).

Although IAB is of particular interest in dense urban areas, it has the potential to be used in suburban areas as well. For this reason, in Figs. 8 and 9 we demonstrate the coverage probability as a function of, respectively, the rain intensity, R in (6), and the tree line length l_T in both urban and suburban areas. Here, the results are presented for the average hop distances $l_{hop} = 100, 160, 450, 650, 900$ m which correspond to SBSs densities $\lambda_S = 100, 50, 8, 5$ and 3 km^{-2} , respectively. For a suburban area, i.e., the cases with large average hop distance, we consider a single MBS, no blockage and UEs' density $\lambda_U = 50 \text{ km}^{-2}$. On the other hand, for the cases with urban areas, i.e., low average hop distance, the blockage and the UEs, densities are set to $\lambda_B = 500 \text{ km}^{-2}$ and $\lambda_U = 700 \text{ km}^{-2}$, respectively. According to Figs. 7-9, the following points can be concluded:

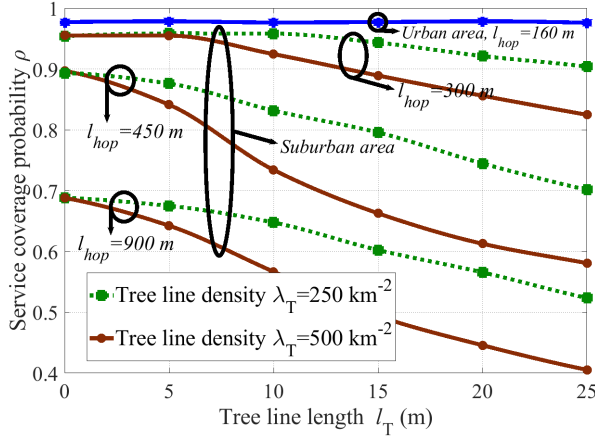


Figure 9: Service coverage probability of the IAB network, in both suburban and urban areas, as a function of the tree line length l_T with $R_{th} = 50$ Mbps, $P_{MBS}, P_{SBS}, P_{UE} = (45, 33, 0)$ dBm, $d = 5$ m, in (A.7), and no rain. In the suburban area, we set $\lambda_M = 1 \text{ km}^{-2}$, $\lambda_U = 50 \text{ km}^{-2}$ with no blockage, while for the urban area we set $\lambda_M = 8 \text{ km}^{-2}$, $\lambda_U = 700 \text{ km}^{-2}$ with blockage having density $\lambda_B = 500 \text{ km}^{-2}$ and length $l_B = 5$ m. Average hop distances $l_{hop} = 160, 300, 450, 900$ m correspond to SBS densities $\lambda_S = 50, 20, 8, 3 \text{ km}^{-2}$, respectively.

- Unless for low network densities, the coverage probability is not much affected by the blockage density/length (Fig. 7. also, see Fig. 11 for the effect of blockage in a 3D example use-case). This is intuitive because, as the network density increases, with high probability each UE can be connected to an SBS with strong LOS signal component.
- Considering 28 GHz, rain will not be a problem for IAB, unless for the cases with very heavy rainfall in suburban areas (Fig. 8). Particularly, the system performance is robust to different rain intensities in suburban/urban areas. Moreover, in suburban areas, even with high intensities the rain reduces the coverage probability slightly⁹.
- As opposed to the rain and the blockage, depending on the network density, in the cases with low/moderate IABs' densities the coverage probability may be considerably affected by the tree foliage. For instance, consider the parameter settings of Fig. 9, in suburban area, with 1 MBS, $\lambda_U = 50 \text{ km}^{-2}$ and an average hop distance of $l_{hop} = 900$ m, corresponding to $\lambda_S = 3 \text{ km}^{-2}$. Then, the presence of trees with line length $l_T = 15$ m and density $\lambda_T = 250 \text{ km}^{-2}$

⁹It should be noted that, while Fig. 8 presents the results for 28 GHz which is the frequency of interest for IAB, the effect of the rain will be more visible at higher carrier frequencies.



Figure 10: An example of the distribution of the IAB network in 3D space with OpenStreetMap.

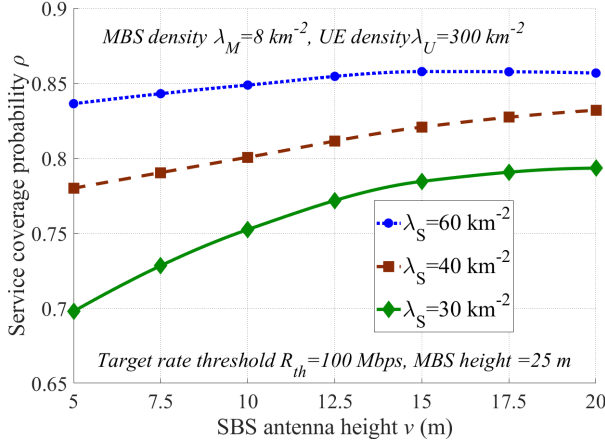


Figure 11: Service coverage probability as a function of the SBSs antenna height v for the cases with no rain and $P_{\text{MBS}}, P_{\text{SBS}}, P_{\text{UE}} = (40, 24, 0)$ dBm.

reduces the coverage probability from 70% for the cases with no trees to 60%, i.e., for 10% more of the UEs the rate requirement 50 Mbps can not be provided. Thus, in the presence of tree foliage, more IAB nodes are required to satisfy the same QoS requirement. On the other hand, with high network density, the coverage probability is not affected by the tree foliage (Fig. 9). In general, predicting the link performance for IAB is difficult when accepting foliage. This is because, for instance, the backhaul link quality may change due to wet trees, snow on the trees, wind and varying percentage of leaves in different seasons. However, based on the presented results, we believe that, with appropriate nodes heights, mmWave IAB will work well for areas with low/moderate foliage level.

Finally, it should be mentioned that in Figs. 8-9 we considered the same parameter settings for the IAB nodes, independently of their area of implementation. However, in practice, different types of short-range and wide-area IAB nodes, with considerably higher capabilities for the wide-area IAB nodes, may be developed and used in urban and suburban areas, respectively [63]. This will help to reduce the effect of rain/foliage in suburban areas even more.

Performance Evaluation in an Example 3D Use-case

In Figs. 5-9, we investigate the system performance in the 2D FHPPP-based model. To evaluate the effect of the nodes and blockages heights, in this subsection we study the coverage probability in an example 3D setup. Particularly, as shown in Fig. 10, the UEs and the IAB nodes (both MBSs and SBSs) are still randomly distributed

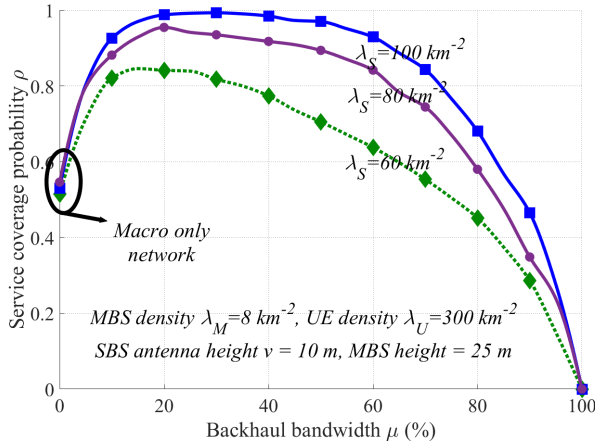


Figure 12: Service coverage probability as a function of the backhaul bandwidth allocation percentage μ in (A.11) for a dense network, no rain, $R_{\text{th}} = 100$ Mbps, and $P_{\text{MBS}}, P_{\text{SBS}}, P_{\text{UE}} = (40, 24, 0)$ dBm.

based on their corresponding FHPPPs, while they are positioned at different heights. Moreover, the blockages (as well as the distance between the nodes) are determined based on the map information, i.e., the real world blocking terrain is considered using OpenStreetMap 3D environment. The results have been tested on a disk of radius $D = 0.5$ km over the Chalmers University of Technology, Gothenburg, Sweden. Particularly, considering the MBSs and the UEs heights to be 25 and 1 m, respectively, Figs. 11 and 12 show the coverage probability as a function of the SBSs' heights and the backhaul bandwidth allocation percentage, μ in (A.11), respectively.

As demonstrated in Fig. 11, with a low SBS density, increasing the height of the SBSs helps to reduce the required number of IAB nodes considerably. For instance, with the parameter settings of Fig. 11, the same coverage probability as in the cases with density $\lambda_S = 40 \text{ km}^{-2}$ and height $v = 5$ m is achieved by a setup having $\lambda_S = 30 \text{ km}^{-2}$ and $v = 15$ m. However, as the network density increases, the effect of the SBSs height becomes negligible. This is intuitively because, with moderate/high densities, with high probability one can always find IAB donor-IAB, IAB-UE, and IAB donor-UE links with strong LOS signal components, even if the IAB nodes are located on the street level.

Finally, as shown in Fig. 12, with an optimal bandwidth allocation between the access and backhaul, IAB network increases the coverage probability, compared to the cases with only MBSs, significantly (Also, see Fig. 6). With $\mu = 0$, the system performance decreases to those achieved by only MBSs, as no bandwidth is allocated for backhauling. With $\mu = 100\%$, on the other hand, no resources are considered for access, and the coverage probability tends to zero. Thus, for different parameter

settings, there is an optimal value for the portion of backhaul/access bandwidth allocation maximizing the coverage probability (Fig. 12). Deriving this optimal value, which increases with the SBSs' density and decreases with the UEs' density, is an open research topic for which the results of [27] is supportive.

4 Conclusion

We studied IAB networks from both standardization and performance points of view. As we showed, depending on the QoS requirements, IAB can be considered as a cost-effective alternative to optical fiber that complements conventional microwave backhaul, in different use-cases and areas. Particularly, the same coverage probability as in fiber-connected networks is achieved by relatively small increment in the number of IAB nodes, leading to considerable network cost reduction/flexibility increment. Moreover, unless for the cases with moderate/high tree foliage in suburban areas, the system performance is not much affected by, e.g., the blockage, the rain, and the tree foliage, which introduces the IAB as a robust setup for dense networks.

While the industry has well proceeded in standardization of different aspects of the network, there are still many open research problems to be addressed by the academia. Among such research topics are topology optimization using, e.g., machine learning, studying the effect of hardware impairments on the system performance, developing efficient methods for simultaneous transmission/reception, improving the system performance using network coding, designing efficient (hybrid) beamforming methods for IAB networks, combination of IAB nodes and repeaters/intelligent surfaces, as well as mobile IAB. Also, load balancing and adaptive routing in a mesh-based network are interesting research topics for which the fundamental results of relay networks, e.g., [64]–[66], will be supportive. Although some of these topics are not supported in Rel-16 and 17, a deep analysis of such problems may pave the way for further enhancements of IAB in industry.

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**On Topology Optimization and Routing in Integrated Access and
Backhaul Networks: a Genetic Algorithm-Based Approach**

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The layout has been revised.

Abstract

In this paper, we study the problem of topology optimization and routing in integrated access and backhaul (IAB) networks, as one of the promising techniques for evolving 5G networks. We study the problem from different perspectives. We develop efficient genetic algorithm-based schemes for both IAB node placement and non-IAB backhaul link distribution, and evaluate the effect of routing on bypassing temporal blockages. Here, concentrating on millimeter wave-based communications, we study the service coverage probability, defined as the probability of the event that the user equipments' (UEs) minimum rate requirements are satisfied. Moreover, we study the effect of different parameters such as the antenna gain, blockage, and tree foliage on the system performance. Finally, we summarize the recent Rel-16 as well as the upcoming Rel-17 3GPP discussions on routing in IAB networks, and discuss the main challenges for enabling mesh-based IAB networks. As we show, with a proper network topology, IAB is an attractive approach to enable the network densification required by 5G and beyond.

Index terms— Integrated access and backhaul, IAB, Genetic algorithm, Node selection, Topology optimization, Densification, Millimeter wave, (mmWave) communications, 3GPP, Stochastic geometry, Poisson point process, Coverage probability, Germ-grain model, Wireless backhaul, 5G NR, Blockage, Relay, Routing, Tree foliage, Machine learning

1 INTRODUCTION

Several reports have shown an exponential growth of demand on wireless communications, the trend which is expected to continue in the future [1]. To cope with such demands, 5G and beyond networks propose various methods for capacity and spectral efficiency improvement. Here, one of the promising techniques is network densification, i.e., the deployment of many base stations (BSs) of different types such that there are more resource blocks per unit area [2]–[5].

The BSs need to be connected to the operators' core network via a transport network, the problem which becomes challenging as the number of BSs increases. Such a transport network may be provided via wireless or wired connections. Wired (fiber) connections are typically used for transport closer to the core network and in the core network, where we need to handle aggregated traffic from multiple BSs. Wireless connections, on the other hand, are used for backhaul transport in the radio access network (RAN) closer to the BSs.

As reported in [2], the backhaul technology has large regional variations. However, on a global scale, wireless microwave technology has been a dominating media for the last few decades. Recently, there is an increase in fiber deployments attributed to geopolitical decisions and major governmental investments. Thus, going forward, it is expected that microwave and fiber will be two dominating backhaul technologies.

Fiber offers reliable connection with high peak data rates. However, 1) the deployment of fiber requires a noteworthy initial investment for trenching and installation, 2) may take a long installation time, 3) may be even not allowed in, e.g., metropolitan areas. Wireless backhaul using microwave is a well-established alternative to fiber, providing 10's of Gbps in commercial deployments¹. Importantly, microwave is a scalable and economical backhaul technique that can meet the increasing requirements of 5G networks. Compared to fiber, wireless backhauling comes with significantly lower cost and time-to-market as well as higher flexibility, with no digging, no intrusion or disruption of infrastructure, and is possible to deploy in principle everywhere [2].

With the same reasoning and motivated by availability of massive bandwidth in millimeter wave (mmWave) spectrum/network densification, integrated access and backhaul (IAB) network has recently received considerable attention [7]–[9]. With IAB, the goal is to provide flexible wireless backhauling using 3GPP new radio (NR) technology in international mobile telecommunications bands, and provide not only backhaul but also the existing cellular services in the same node and via the same hardware. This, in addition to creating more flexibility and reducing the time-to-market, is generally to reduce the cost for a wired backhaul, which in certain deployments could impose a large cost for the installation and operation of the BS. Importantly,

- Internal evaluations at Ericsson shows that, even in the presence of dark fiber, the deployment of IAB network gives an opportunity to reduce the total cost of ownership in urban/suburban areas. This is partly because the same hardware can be used both for access and backhaul, i.e., less extra equipment is required especially for in-band backhauling.
- An integrated access/backhaul solution improves the possibilities for pooling of spectrum where it can be up to the operator to decide what spectrum resources to use for access and backhaul, rather than having this decided in an essentially static manner by spectrum regulators.

In this way, IAB serves as a complement to microwave and fiber backhaul specially in dense urban and suburban deployments.

Although IAB can in principle operate in every spectrum for which NR operation is specified, the focus of the 3GPP work on IAB has been on mmWave spectrum. This is intuitive because of the access to wide bandwidth in mmWave spectrum,

¹Recent results demonstrate even more than 100 Gbps over MIMO backhaul links [6].

while the existing LTE spectrum is very expensive to be used for backhauling. With a mmWave spectrum, however, blockage and tree foliage may be challenging, as they reduce the achievable rate significantly. Properly planned and optimized networks could reap higher performances, and save costs to network operators as they can avoid static blockages such as buildings/trees [10], [11]. On the other hand, along with enabling traffic-based load balancing, routing can well compensate for temporal blockages, e.g., busses/trucks passing by. However, as the network size increases in dense areas, which is the main point of interest in IAB networks, deriving closed-form solutions for optimal network topology/routing becomes infeasible.

It should be mentioned that the network deployment optimization can be done offline, and recalculated whenever there are substantial changes in the blocking situations, service rate requirements, and addition of new set of BSs. Still, the optimization problem quickly becomes very large, thus motivating a potentially suboptimal machine learning approach, since an exhaustive search over all possible deployment options quickly becomes infeasible (see Section 5 for further details). In such cases, machine learning techniques give effective (sub)optimal solutions with reasonable implementation complexity.

1.1 Literature Review

The performance of IAB networks have been studied from different perspectives. Particularly, [12]–[16], develop various resource allocation schemes, and [17], [18] study the effect of time/frequency division duplex based resource allocation on the throughput of IAB networks. Moreover, [19]–[21] utilize infinite Poisson point processes (PPPs) to evaluate the coverage probability of multi-hop IAB networks. Then, [22], [23] investigate the feasibility/challenges of mmWave-based IAB networks via end-to-end simulations. Also, [24] and [25] evaluate the potentials of using IAB in fixed wireless access and unmanned aerial vehicle-based communication setups, respectively. In [26] and [27], we provide an overview of 3GPP Rel-16 discussions on IAB. Moreover, [27] uses a FHPPP (FH: finite homogeneous), i.e., a PPP with a constant density and random distributions of the nodes in a finite region, to analyze the performance between the IAB and fiber-connected networks, and verify the robustness of IAB to various environmental effects. Finally, [28] develops simulated annealing algorithms for joint scheduling and power allocation, and [29] designs a joint precoder design and power allocation scheme maximizing the network sum rate.

The problem of routing in IAB networks has been previously studied in the cases with different numbers of hops [12]–[16], [30]–[32]. Also, [26] develops a cost-optimal node placement scheme, and [33] proposes a joint node placement and resource allocation scheme maximizing the downlink sum rate of IAB networks. On the other hand, with different (non-IAB) network topologies/use-cases, various machine-learning based solutions have been previously proposed for topology optimization.

For instance, [34]–[43] develop deep reinforcement (DR) algorithm-based solutions for topology optimization of different network configurations. Deep Q-learning is used in [44] to evaluate the cumulative transmission rate in vehicular networks. Spectrum allocation and access mode selection evaluations are considered in [45], while the potential of using K -means clustering algorithm to design ultra-reliable and low-latency wireless sensor networks is evaluated in [46]. In addition, [47] and [48] use DR learning-based algorithms to solve the large-scale load balancing problem for ultra-dense networks.

Note that the mentioned works neither consider the non-IAB backhaul links distribution optimization nor the joint optimization of the non-IAB backhaul links distribution and the IAB nodes placement. This, although is of interest in practice, may be due to the fact that such optimization problems are NP-hard with a large search space. Therefore, one needs to design efficient algorithms which can find (semi)optimal solutions within a limited simulation period. Moreover, [12]–[48] concentrate on multi-hop communications, while the usefulness and challenges of meshed-based IAB have not yet been studied. Here, it is important to consider both the performance evaluations and the standardization issues, as meshed IAB has not yet been discussed in 3GPP 5G NR. These are the motivations for our work as presented in the following.

1.2 Contributions

In this paper, we study the problem of topology optimization and routing in IAB networks. We study the problem from different points of views:

- We design effective genetic algorithm (GA)-based techniques not only for IAB node placement but also for dedicated non-IAB backhaul connection distribution. Here, concentrating on the characteristics of mmWave communications, we present the results for the cases with an FHPPP-based stochastic geometry model [19], [49]. As the metric of interest, we consider the network service coverage probability which is defined as the probability of the event that the UEs' minimum data rate requirements are satisfied.
- We study the effect of temporal blockages and routing on the coverage probability. In this way, one can avoid both the long-term and temporal blockages via topology optimization and routing, respectively. Also, the setup gives hints on the effectiveness of mesh-based communication in IAB networks, although it is not yet considered by 3GPP IAB standardization.
- We summarize the main 3GPP Rel-16 agreements as well as the upcoming Rel-17 discussions on routing, and highlight the main challenges which need to be solved before meshed IAB can be implemented.

- We study the effect of different parameters such as antenna gain, blockage and tree foliage on the system performance in both cases with well-planned and random network deployments.
- Finally, we compare the performance of the GA-based scheme with different state-of-the-art topology optimization methods. Also, we study the efficiency of the deployment optimization in the cases with constraint on the network topology, where the IAB nodes and the non-IAB backhaul links can not be freely deployed in every place.

Compared to the related literature, e.g., [10]-[49], we consider more realistic algorithms and network configurations. Moreover, our discussions on the effect of environmental parameters/deployment constraints on the system performance as well as the 3GPP agreements on IAB-based routing have not been presented before. Also, we optimize the IAB network for both node locations and non-IAB backhaul link placement independently, as well as jointly which further improves the coverage probability. We compare the performance of the proposed algorithms with different state-of-the-art schemes. These make our discussions and the conclusions completely different from those presented in the state-of-the-art works.

As we show, machine learning techniques provide effective solutions for deployment optimization which can be easily adapted for different channel models, constraints and metrics of interest with no need for mathematical analysis. Moreover, compared to random deployment, deployment planning increases the coverage probability of the IAB networks significantly. On the other hand, with a well-planned network and for a broad range of blockage/tree foliage densities, the network can well handle these blockages with small routing updates. Finally, while the service coverage probability of the IAB network is slightly affected by stationary/temporal blockages in urban areas, for a broad range of parameter settings, the blockage is not problematic for well-planned routing-enabled IAB networks, in the sense that its impact on the coverage probability is negligible. On the other hand, high levels of tree foliage may reduce the coverage probability of the network in suburban areas; the problem which can be solved by proper deployment planning.

2 IAB in 3GPP

IAB was introduced as part of Rel-16 of the 5G NR specification, with the specification finalized in fall 2020 [50]. Currently, Rel-17 work item on IAB enhancements is going on, which is expected to finish in early 2022 [51].

The overall architecture for IAB is based on the CU/DU split of the gNB, introduced already in 3GPP Rel-15. With such architecture, a gNB consists of two functionally different parts with a standardized interface (referred to as the F1 interface) in between:

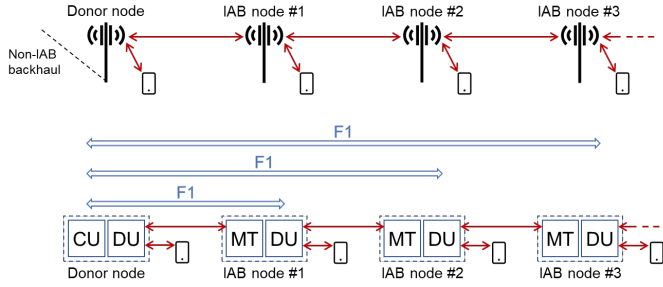


Figure 1: Types of network nodes.

- A Centralized Unit (CU) including the packet data convergence protocol (PDCP) and radio resource control (RRC) protocols,
- One or several Distributed Units (DUs) consisting of radio link control (RLC), medium access control (MAC), and physical layer protocols.

IAB specifies two types of network nodes (see also Fig. 1):

- The IAB-Donor-node is the node consisting of CU and DU functionalities, and connects to the core network via non-IAB, for example fiber, backhaul.
- The IAB node includes two modules, namely, DU and mobile terminal (MT). IAB-DU serves UEs as well as, potentially, downstream IAB nodes in case of multi-hop wireless backhauling. At its other side, an IAB-MT is the unit that connects an IAB node with the DU of the parent/upstream node.

The IAB architecture is thus based on a hierarchical or, at least, a-cyclical structure where it is well-defined if a certain node is “above” or “below” a certain other node and where information flows in well-defined down-stream and up-stream directions. The possibility for a more mesh-like structure with no well-defined hierarchy was briefly discussed during the initial phase of the 3GPP work on IAB. However, majority of the companies discard the idea owing to its complexity and no clear benefits.

When it comes to the connectivity with the parent node, the IAB-MT connects to the DU of its parent node essentially as a normal UE. The Uu interface, i.e., the link between the parent node DU and the MT of the IAB node then provides the lower-layer functionality and relays the F1 messages between the donor-node CU and the IAB-node DU. The specification of the F1 interface only defines the higher-layer protocols, for example, the signaling messages between the CU and DU, but is agnostic to the lower-layer (i.e., transport network layer) protocols. With IAB, the NR radio-access technology (the RLC, MAC, and physical layer protocols) together with some IAB-specific protocols, provides the lower-layer functionality on top of

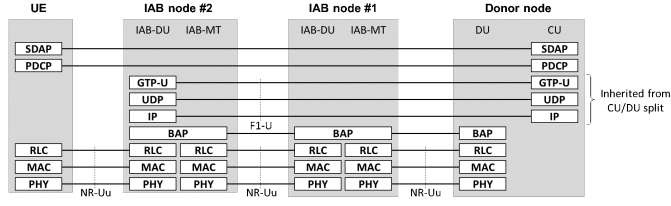


Figure 2: IAB protocol stack of the user-plane.

which the F1 interface is implemented. See Fig. 2 showing the user-plane protocols of a multi-hop IAB network (the control plane has a similar structure).

2.1 Backhaul Adaptation Protocol

Backhaul adaptation protocol (BAP) is a new IAB-specific protocol responsible for routing and bearer mapping of packets in the IAB network. More specifically, the BAP layer is responsible for forwarding of the packets in the intermediate nodes/hops between the IAB-donor-DU and the access IAB-node. For the downstream traffic, the BAP layer of the IAB-Donor-DU will add a BAP header to packets received from the upper layer. Similarly, for the upstream traffic, the BAP layer of the access IAB-node will add a BAP header to the upper layer packets. Figure 3 shows the structure for the BAP header, which contains a 10-bit BAP address field and a 10-bit BAP path ID field apart from 1-bit flag and 3 reserve bits for future use. Note that 3GPP specifications use the BAP Routing ID as a cover term for BAP address and BAP path ID fields. The purpose of the BAP address field is to carry the address of the destination IAB-node, while the Path ID field contains the path identity to be used for traversing the packets towards the destination IAB-node. This latter field is important for situations where multiple paths are configured for an IAB-node to improve network robustness/resilience and achieve load balancing by transporting a part of the traffic via each path towards the IAB-node.

To illustrate the above concept, figure 4 shows an example topology for IAB network where two paths (i.e., Path 1 and Path 2) have been configured for IAB-node 5 by the IAB-donor-CU. This means that the routing tables in the BAP layer of all the intermediate IAB-nodes (i.e., IAB1, IAB2, IAB3, etc.) are properly configured with next-hop link information for all the BAP addresses and BAP path IDs carried in the packets BAP header that these nodes will route in the network. Furthermore, the IAB-donor-DU will have mapping rules (configured by the donor-CU) how to select the BAP address and BAP path ID fields for packets from the upper layer based on the information in the IP address fields (i.e., DS/DSCP) of the F1-AP signaling.

Suppose the IAB-donor-DU receives a packet with IP address fields marked with information that is mapped to BAP address 5 and BAP path ID 1, the donor-DU will

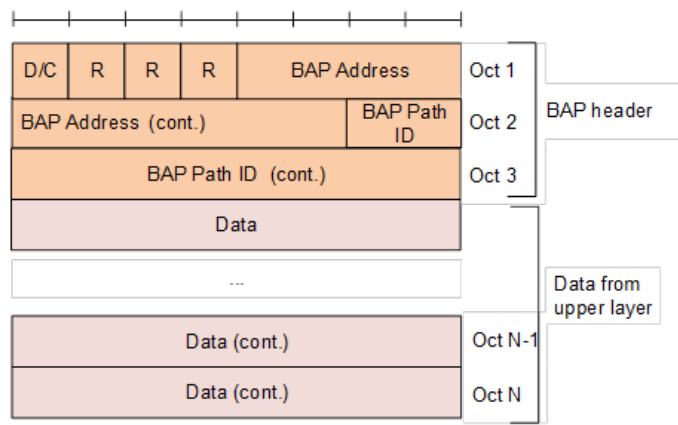


Figure 3: Structure for the BAP header.

add a BAP header with proper field values (i.e., address 5 and path ID 1) and will forward the packet to IAB2. Once IAB2 receives the packet, the node will examine the BAP header of the packet and based on the BAP address (carried in the packet) and its routing table information will transmit the packet towards IAB4. Similarly, IAB4 will route the packet to IAB5, where the IAB5 upon examining the BAP header field of the packet will notice that the packet is destined for it. Hence, IAB4 will remove the BAP header before delivering the packet to its upper layer for further processing.

In another scenario, if IAB1 receives a packet (from IAB-donor-DU) with BAP header containing BAP address 5 and path ID 2, IAB1 will forward the packet towards IAB3 instead of IAB2, and so on IAB3 will forward the packet to IAB4. When it comes to the upstream traffic, the BAP layer of IAB5 will add a BAP header containing IAB-donor-DU BAP address and appropriate path ID (either path ID 1 or path ID 2 based on the configuration information) to packets received from the upper layer. Next, IAB5 will forward the packets to IAB4, which will be further forwarded by IAB4 either to IAB1 or IAB2 depending on the path ID field value carried in the packets BAP headers. Once the packets reach IAB-donor-DU, the DU will remove the BAP header before delivering the packets to the upper layer for subsequent processing.

2.2 IAB extensions in 3GPP release 17

3GPP is considering further extensions and enhancements to IAB as part of NR Rel-17. One topic for Rel-17 is to look further into the support for dual-connectivity scenarios for IAB. For the regular network-to-device link, dual-connectivity, supported for both NR and 4G/LTE, implies that a device has established a link to

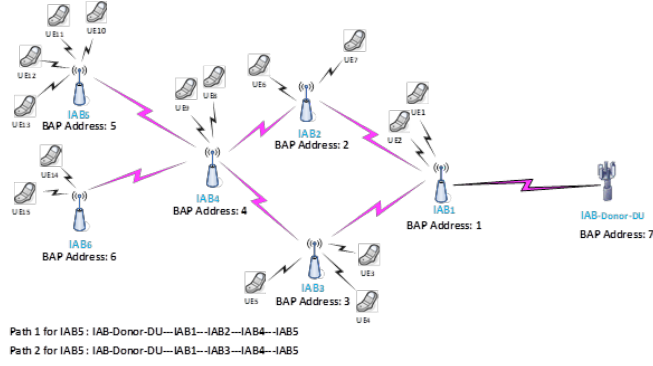


Figure 4: Example of routing in IAB network.

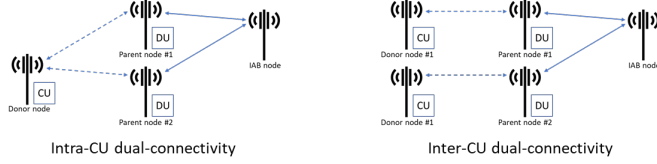


Figure 5: Intra-CU dual connectivity vs inter-CU dual-connectivity

multiple cells operating on different carrier frequencies. In the context of IAB, dual-connectivity like-wise implies that an IAB-DU is connected to multiple parent nodes via its collocated IAB-MT. Such IAB dual connectivity can be either intra-CU, that is, the same donor node is serving both parent nodes. Alternatively, dual-connectivity can be inter-CU, that is, there are multiple IAB-Donor-nodes (see Fig. 5). Clearly, the inter-CU dual-connectivity has a larger impact on the IAB network in terms of specification work and complexity.

IAB dual-connectivity is envisioned to provide higher reliability due to an additional redundancy in the wireless backhaul. It may also enable additional possibilities for load-balancing within the wireless backhaul, i.e., the possibility to more dynamically route data via different paths depending on the instantaneous load conditions on different links.

3 System Model

This section presents the system model, including the channel model, the considered UE association rule as well as the achievable data rates in the backhaul and access links. Table 1 summarizes the parameters used in the analysis. Consider a dense urban area with a two-tier heterogeneous network (HetNet), i.e., a two-hop IAB network, where multiple MBSs (M: macro) and SBSs (S: small) serve the UEs (see

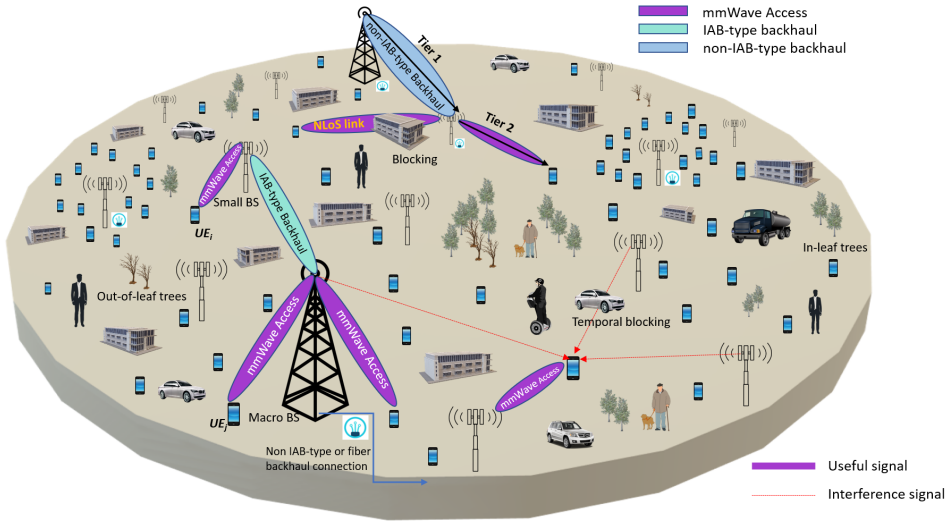


Figure 6: Schematic of the considered IAB network. A majority of the SBSs rely on IAB for backhauling. A small fraction of the SBSs, however, may have non-IAB type backhaul where such a backhauling can be provided by fiber or wirelessly.

Fig. 6). In this way, following the 3GPP definitions (see Section 2), the MBSs and the SBSs represent the donor and the child IABs, respectively, and throughout the paper we may use the terminologies MBS/SBS and donor IAB/IAB interchangeably. With the IAB setup, both the MBSs and the SBSs are used for both access and backhaul. However, the donor IABs, i.e., the MBSs, are non-IAB backhauled to the core network.

Note. In practice, a majority of the SBSs receive IAB-type backhaul from the MBSs wirelessly. However, a fraction of the SBSs may have access to non-IAB type dedicated backhaul connections, where such a backhaul can be provided either by fiber or a wireless radio link operating on a different frequency than the IAB network (see Fig. 6). In this paper, along with optimizing the SBSs' locations, one of our goals is to determine the proper nodes with non-IAB type backhauling such that the coverage probability is maximized. In terms of performance evaluation, our analysis does not depend on if these non-IAB backhaul links are provided by fiber or wirelessly. In practice, however, the network performance may depend on the type of such non-IAB links; Wireless radio backhaul link is quite flexible, and one can provide an SBS with wireless non-IAB backhaul as long as there is a strong LoS connection between the SBS and an MBS. Fiber connections, on the other hand, may be available in specific areas, and there may be low flexibility in fiber distribution between the nodes. In summary, depending on the type of the non-IAB backhaul links, to the SBSs, our non-IAB backhaul link distribution method, presented in Algorithm 1,

may give an ultimate opportunistic potential of the network performance.

Note that the consideration of two-hop network, e.g., [17]–[19], [27], [52], [53], in our work is motivated by the fact that, although the 3GPP standardization does not limit the possible number of hops, as also reported in, e.g., [26], [54]–[56], traffic aggregation in the backhaul links and end-to-end latency become challenging as the number of hops increases. Moreover, because IAB is of most interest in dense metropolitan areas with already existing limited number of fiber links, in most cases appropriate coverage can be provided with a maximum of two hops (For instance, see the Ericsson simulation results in the London area [[57], Fig. 3] where the required QoS is satisfied mostly by only a single backhaul hop).

We model the IAB network using an FHPPP based random distribution of the nodes in a finite region [19]–[21], [29]. Particularly, without topology optimization, which we use as the benchmark to evaluate the performance of planned networks, the FHPPPs χ_M, χ_S, χ_U with densities, λ_M, λ_S and λ_U , respectively, are used to model the spatial distributions of the MBSs, the SBSs and the UEs, respectively. With our topology optimization, however, while the number of nodes are still determined based on some random process, the locations of the SBSs as well as the location of the non-IAB backhaul connections to a fraction of the SBSs are optimized, in terms of network service coverage probability (see Section 5 for the details).

In our setup, in-band communication is considered where both the access and backhaul links share and operate in the same mmWave spectrum band. This is motivated by the fact that in-band communication gives better flexibility for resource allocation, at the cost of coordination complexity. For simplicity, assume the network to be distributed over a circular disk D . However, the model can be well applied on every arbitrary region D .

For the blockage, we use the well-known germ grain model described in [58, Chapter 14], which provides accurate blind spot prediction, compared to stochastic models that assume independent blocking. Particularly, the model takes induced blocking correlation into account and, thus, suits well for environments with large obstacles. Here, an FHPPP χ_{bl} models the blockage distribution in the area D with λ_{bl} denoting the density. The blockings are considered to be walls of length l_{bl} and independently and identically distributed orientation θ_{bl} . Later, we use a GA-based approach to optimize the SBSs locations inside the region D to preferably avoid blockage in the backhaul links.

Following the state-of-the-art mmWave channel model, e.g., [59], the received power at each node can be expressed as

$$P_r = P_t h_{t,r} G_{t,r} \gamma_{(1m)} \gamma_{t,r} \|x_t - x_r\|^{-1} \kappa_{t,r}. \quad (B.1)$$

Here, P_t represents the transmit power in each link, and $h_{t,r}$ denotes the independent small-scale fading in individual links. Particularly, in our study Rayleigh fading is considered for small-scale fading. Thereby, $G_{t,r}$ denotes the combined antenna

Table 1: The Definition of the Parameters.

Parameter	Definition	Parameter	Definition
χ_M	FHPPP of the MBSs	χ_U	FHPPP of the UEs
χ_S	FHPPP of the SBSs	χ_{bl}	FHPPP of the blockings
χ_T	FHPPP of the tree lines	λ_U	UEs density
λ_M	MBSs density	λ_S	SBSs density
λ_{bl}	Blocking density	λ_T	Tree density
ρ	Service coverage probability	d	Vegetation depth
θ	Orientation of the blocking wall	φ	Angle between transmitter and receiver
D	Circular disk	R	Radius of the disk
P_t	Transmission power	P_r	Received power
h	Fading coefficient	G	Antenna gain
$\gamma_{(1m)}$	Reference path loss at 1 meter distance	γ	Propagation path loss
x	Location of the node	r	Propagation distance between the nodes
α	Path loss exponent	N	Number of connected UEs
f_c	Carrier frequency	R_{th}	Minimum data rate threshold
w_u	Associated cell	w_s	Associated BS in backhaul link
N_f	Number of non-IAB backhauled SBSs	κ	Tree foliage loss
N_s	Number of SBSs	S_c	Number of possible solution checkings
l_T	Tree line length	l_h	Hop length
λ_{temp}	Temporal blocking density	K	Number of random sets in the GA
J	Number of sets around the Queen in GA	N_{it}	Number of iterations in the GA
B	Bandwidth	ψ	Percentage of bandwidth resources on backhaul

gain of the transmitter and receiver in the link, $\gamma_{t,r}$ is the propagation path loss, and $\gamma_{(1m)}$ is the reference path loss at one meter distance while $\kappa_{t,r}$ is the tree foliage loss.

The total path loss, in dB, is characterized according to the 5GCM UMa close-in model described in [60]. Here, the path loss is characterized by

$$PL = 32.4 + 10 \log_{10}(r)^\alpha + 20 \log_{10}(f_c), \quad (\text{B.2})$$

where f_c is the carrier frequency, r is the propagation distance between the nodes, and α is the path loss exponent. Depending on the blockage, line-of-sight (LoS) and NLoS (N: Non) links are affected by different path loss exponents. The propagation loss of the path loss model is given by

$$\gamma_{t,r} = \begin{cases} r^{\alpha_L}, & \text{if LoS,} \\ r^{\alpha_N}, & \text{if NLoS,} \end{cases} \quad (\text{B.3})$$

where α_L and α_N denote path loss exponents for the LoS and NLoS scenarios, respectively.

5G and beyond systems are equipped with large antenna arrays which are used to minimize the propagation loss. We use the sectored-pattern antenna array model to characterize the beam pattern and antenna gain, which is given by

$$G_{t,r}(\varphi) = \begin{cases} G_0 & -\frac{\theta_{\text{HPBW}}}{2} \leq \varphi \leq \frac{\theta_{\text{HPBW}}}{2} \\ g(\varphi) & \text{otherwise.} \end{cases} \quad (\text{B.4})$$

Here, φ represents the angle between the transmit and receive antennas. Furthermore, θ_{HPBW} is the half power beamwidth, and G_0 denotes the main lobe gain of the antenna while $g(\varphi)$ is the side lobe gain [59]. Finally, as in, e.g., [19], [21], [27], for tractability we assume that the UE antenna gain to be 0 dB due to its omnidirectional beam pattern, although UE beamforming in mmWave is an interesting future work to incorporate.

Unless otherwise stated and in harmony with, e.g., [19]–[21], [27], we assume that the backhaul links are noise-limited. This assumption, which has been verified in [27], is motivated by the high beamforming capacity in the inter IAB backhaul links and the fact that simultaneous transmission/reception is not considered in our setup. Then, Section 5 validates this assumption, and we verify the effect of the backhaul interference on the coverage probability. Also, the inter-UE interference is neglected with the assumption of sufficient isolation and low power of the UEs [24]. Particularly, the interference model focuses on the aggregated interference on the access links,

caused by the neighbouring interferers, which for UE u is expressed as

$$I_u = \sum_{\mathbf{i}, \mathbf{u} \in \chi_{i,u} \setminus \{\mathbf{w}_u\}} P_i h_{i,u} G_{i,u} \gamma_{(1m)} \gamma_{x_i, x_u} \|\mathbf{x}_i - \mathbf{x}_u\|^{-1}, \quad (\text{B.5})$$

where i denotes the set of BSs excluding the associated BS w_u of user u . Also, for SBS s , the aggregated interference on the backhaul links is given by

$$I_s = \sum_{\mathbf{j}, \mathbf{s} \in \chi_{j,s} \setminus \{\mathbf{w}_s\}} P_j h_{j,s} G_{j,s} \gamma_{(1m)} \gamma_{x_j, x_s} \|\mathbf{x}_j - \mathbf{x}_s\|^{-1}, \quad (\text{B.6})$$

where j denotes the set of transmitting BSs excluding the associated BS w_s of SBS s .

We use an FHPPP denoted by χ_T with density λ_T to model the spatial distribution of the tree lines of length l_T [61]. The tree foliage loss is estimated using the Fitted International Telecommunication Union-Radio (FITU-R) tree foliage model [62, Chapter 7]. The model is well known for its applicability in cases with non-uniform vegetation and frequency dependency within 10-40 GHz range. Particularly, considering both in-leaf and out-of-leaf, vegetation states, the tree foliage loss in (B.1) is expressed as

$$\kappa = \begin{cases} 0.39 f_c^{0.39} d^{0.25}, & \text{in-leaf} \\ 0.37 f_c^{0.18} d^{0.59}, & \text{out-of-leaf}, \end{cases} \quad (\text{B.7})$$

where d is the vegetation depth measured in meter.

In our setup, each UE has the ability to be connected to either an MBS or an SBS depending on the maximum average received power. Let $a_u \in \{0, 1\}$ be a binary variable indicating the association with 1, while 0 representing the opposite. Thus, for the access links

$$a_u = \begin{cases} 1 & \text{if } P_i G_{z,x} h_{z,x} \gamma_{(1m)} \gamma_{z,x} (\|\mathbf{z} - \mathbf{x}\|)^{-1} \\ & \geq P_j G_j h_{z,y} \gamma_{(1m)} \gamma_{z,y} (\|\mathbf{z} - \mathbf{y}\|)^{-1}, \\ & \forall \mathbf{y} \in \chi_j, j \in \{\mathbf{m}, \mathbf{s}\} | \mathbf{x} \in \chi_i, \\ 0, & \text{otherwise,} \end{cases} \quad (\text{B.8})$$

where i, j denote the BS indices, i.e., MBS or SBS. As in (3) for each UE u , the association binary variable a_u becomes 1 for the cell giving the maximum received power at the UE, while for all other cells it is 0, as the UE can only be connected to one IAB node.

Since the MBSs and the SBSs have large antenna arrays and can beamform towards the desired direction, the antenna gain over the backhaul links can be assumed to be the same, and backhaul link association can be well determined based on the

minimum path loss rule, i.e., by

$$a_{b,m} = \begin{cases} 1 & \text{if } \gamma_{b_m}(\|\mathbf{z} - \mathbf{x}\|)^{-1} \geq \gamma_{b_m}(\|\mathbf{z} - \mathbf{y}\|)^{-1}, \\ & \forall \mathbf{y} \in \chi_m | \mathbf{x} \in \chi_m, \\ 0, & \text{otherwise.} \end{cases} \quad (\text{B.9})$$

For resource allocation, on the other hand, the mmWave spectrum available is partitioned into the access and backhaul links such that

$$\begin{cases} B_{\text{Backhaul}} = \psi B, \\ B_{\text{Access}} = (1 - \psi)B, \end{cases} \quad (\text{B.10})$$

In practice, along with the MBSs which are non-IAB backhaul-connected, a portion of the SBSs may have dedicated non-IAB backhaul connections, resulting in a hybrid IAB network. Therefore, in our deployment, some of the SBSs are IAB backhauled wirelessly and the others are connected to dedicated non-IAB backhaul links.

Let us initially concentrate on the IAB-type backhauled SBSs. Also, let, B_{backhaul} and B_{access} denote the backhaul and the access bandwidths, respectively, while total bandwidth is $B = B_{\text{backhaul}} + B_{\text{access}}$. The bandwidth allocated for each IAB-type wirelessly backhauled SBS, namely, child IAB, by the MBS, i.e., IAB donor, is proportional to its load and the number of UEs in the access link. The resource allocation is determined based on the instantaneous load where each IAB-type backhauled SBS informs its current load to the associated MBS each time. Thus, the backhaul-related bandwidth for the j -th IAB node, if it does not have dedicated non-IAB backhaul connection, is given by

$$B_{\text{backhaul},j} = \frac{\psi B N_j}{\sum_{\forall j} N_j}, \forall j, \quad (\text{B.11})$$

where N_j denotes the number of UEs connected to the j -th IAB-type backhauled node and $\psi \in [0, 1]$ is the fraction of the bandwidth resources on backhauling. Therefore, the bandwidth allocated to the j -th IAB-type backhauled node is proportional to the ratio between its load, and the total load of its connected IAB donor. Meanwhile, the access spectrum is equally shared among the connected UEs at the IAB node according to

$$B_{\text{access},u} = \frac{(1 - \psi)B}{\sum_{\forall u} N_{j,u}}, \forall u, \quad (\text{B.12})$$

where u denotes the UEs indices, and j represents each IAB-type backhauled node. Moreover, $N_{j,u}$ is the number of UEs connected to the j -th IAB-type backhauled node to which UE u is connected. Finally, the signal-to-interference-plus-noise ratio

(SINR) is obtained in accordance with (B.5) by

$$\text{SINR} = P_r / (I_u + \sigma^2), \quad (\text{B.13})$$

where σ^2 is the noise power.

With our setup, the network may have three forms of access connections, i.e., MBS-UE, IAB-type backhauled SBS-UE, non-IAB backhauled SBS-UE, and the individual data rates will behave according to the form in which the UE's connection has been established. Particularly, the rates experienced by the UEs in access links that are connected to MBSs or to the IAB type-backhauled SBSs are given by

$$R_u = \begin{cases} \frac{(1-\psi)B}{N_m} \log(1 + \text{SINR}(x_u)), & \text{if } \mathbf{w}_u \in \chi_m, \\ \min \left(\frac{(1-\psi)BN}{\sum_{\forall u} N_{j,u}} \log(1 + \text{SINR}(x_u)), \right. \\ \left. \frac{\psi BN}{\sum_{\forall j} N_j} \log(1 + \text{SINR}(x_b)) \right), & \text{if } \mathbf{w}_u \in \chi_s, \end{cases} \quad (\text{B.14})$$

where j represents each IAB-type backhauled SBS connected to the MBS. Then, m gives the associated MBS, s denotes the SBS, and u represents the UEs' indices. Unlike an MBS which shares some of its bandwidth with IAB-type backhauled SBSs, a non-IAB backhauled SBS has a bandwidth of B for access, and does not need to share its bandwidth for backhauling. Thus, the UEs connected to a non-IAB backhauled SBS experience the rate given by

$$R_u = \frac{B}{N_u} \log(1 + \text{SINR}(x_u)), \text{ if } \mathbf{w}_u \in \chi_s, \quad (\text{B.15})$$

where N_u denotes the total number of UEs connected to the non-IAB backhauled SBS of which the considered UE is associated. Depending on the associated cell, there are three possible cases for the data rate of the UEs. First is the case when the UEs are connected to the MBSs, i.e., IAB donor, as denoted by $w_u \in \chi_m$ in (B.14). Since the MBSs have non-IAB backhaul connection, the rate will only depend on the access bandwidth available at the UE. In the second case, the UEs are connected to the IAB-type backhauled SBSs, as denoted by $w_u \in \chi_s$ in (B.14). Here, the SBSs have shared backhaul bandwidth from the IAB-Donor-nodes i.e., MBSs, and thus the UEs data rates depend on the backhaul rate of the connected IAB-type backhauled SBS as well. Thus, in this case the UE is bounded to get the minimum between backhaul and access rate. Then, the third case is when the UEs are associates with the non-IAB backhauled SBSs as denoted in (B.15). Unlike in the previous case, here the SBSs have full bandwidth B which is not shared with backhauling.

In the following, we present the GA-based schemes to optimize the locations of

the SBSs as well as the non-IAB backhaul link distribution to a fraction of the SBSs such that the network service coverage probability is maximized.

4 Proposed Algorithm

In general, Rel-16 IAB network supports NLoS backhauling. However, the performance of the IAB networks is considerably affected by the quality of the backhaul links, where, if possible, it is preferred to have IAB-IAB channels with strong LoS signal strength. Also, in hybrid networks where a fraction of the SBS nodes may be backhauled via dedicated non-IAB backhaul links, it is important to obtain the set of SBSs that are critical to be non-IAB backhaul-connected for optimal performance. However, depending on the network size, it may be difficult to obtain the appropriate location of the SBSs and/or the non-IAB backhaul link placement scheme for SBSs analytically.

For instance, with N_s SBSs and a budget of having N_f non-IAB backhauled SBSs, there are $\binom{N_s}{N_f}$ possible combinations of non-IAB backhauled SBS selections. Therefore, the optimal set of SBSs suitable for non-IAB backhaul link placement can indeed be obtained via exhaustive search for the cases with few SBSs. However, as the network size increases, it is not feasible to search over all possible solutions. The problem becomes even more challenging with determining the optimal locations of the SBSs as they can be distributed in the whole network area. Thus, it is important to design efficient algorithms to obtain the (sub)optimal SBS locations as well as dedicated non-IAB backhaul link placement with low complexity.

With this background, the state-of-the-art works mainly concentrate on either modeling the network by placing the BSs on a grid or distribute them randomly based on stochastic geometry models. However, none of these models are accurate, as they give an optimistic or a pessimistic estimate of the network performance, respectively. Also, in practice, the network may be well planed such that, at least, high-quality backhaul links are guaranteed. This is the motivation for our GA-based approach in which we propose a fairly simple network deployment optimization algorithm with no need for detailed mathematical analysis. This is important specially because

- as we show in the following, with a well-planned network topology the need for routing, to compensate for temporal blockages, decreases which results in considerable implementation complexity reduction.
- Moreover, with our proposed GA-based approach it is possible to scale the network with proper deployment as more IAB nodes/non-IAB backhaul link connections are added to the network.
- Finally, due to the generic characteristics of machine learning schemes, one can apply the same technique as our proposed GA method for both non-IAB

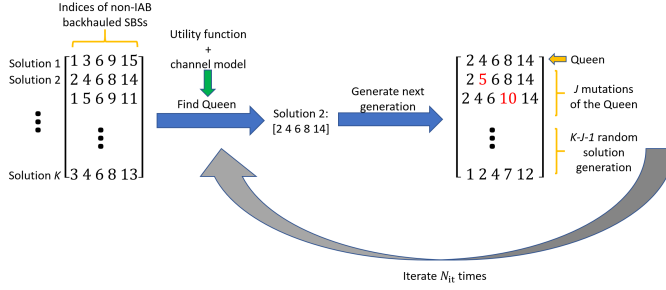


Figure 7: An example of the proposed GA in Algorithm 1 for non-IAB backhaul link distribution between a fraction of the SBSs. In each iteration, the best solution (the Queen) is regenerated. Then, J solutions are generated by small mutations in the Queen and $K - J - 1$ possible solutions are generated randomly to avoid local minimums. The iterations continue for a number of times and the Queen of the last round is returned as the final solution.

backhaul link placement and SBS location optimization, as well as for the cases with different channel models/metrics of interest.

It should be noted that, we are interested in the potential of optimal partial non-IAB type backhaul connections in order to find an upper bound on the performance of any real network that might be constrained. Such a constrained partial non-IAB type backhaul link deployment optimization would also be an interesting extension of this work, and any such network performance would be in between the optimized and the random partial non-IAB type backhaul link deployment.

Particularly, in this paper, we propose two GA-based approaches [63] to identify the optimal SBSs to be non-IAB backhaul-connected and the optimal locations for the SBSs, as explained in Algorithms 1 and 2, respectively. The algorithms are used to maximize the service coverage probability defined as the fraction of the UEs which have instantaneous UE data rates higher than or equal to a threshold R_{th} . That is, using (B.14) and (B.15), the service coverage probability is given by

$$\rho = \Pr(R_U \geq \eta). \quad (\text{B.16})$$

In words, both algorithms are based on the procedure described below. As shown in Fig. 7, we start the algorithm by considering K possible selection strategies. For instance, Algorithm 1 considers K possible SBS sets for non-IAB backhaul link placement and Algorithm 2 considers K possible location sets for the SBSs. Then, in each iteration, we find the best strategy, i.e., selected solution, that maximizes the considered utility function, compared to the other $K - 1$ selected strategies. This best strategy is referred to as the Queen. The Queen is considered as one of the possible solutions in the next iteration of the algorithm to guarantee the

monotonic improvement of the algorithm performance in successive iterations. That is, the Queen represents the regeneration operator in GA. Also, for each iteration we create $J < K$ sets around the Queen. These matrices are created by applying slight modifications to the Queen, i.e., as a kind of mutation. For example, changing few SBSs of the set associated with the Queen generates these new sets needed for optimal SBS selection for non-IAB backhaul link placement in Algorithm 1. Also, in each iteration $K - J - 1$ sets of selection strategies are generated randomly, to avoid the network to be trapped in a local minimum, and the iterations continue for N_{it} iterations decided by the network designer depending on the problem at hand (See Section 5). After running all considered iterations, the ultimate Queen is returned as the best selection rule for the current network instance. Particularly, Algorithm 1 returns the optimal SBS selection rule for non-IAB backhaul link placement, while Algorithm 2 returns the optimal SBS location selection rule. The suitable parameter setting for K , J and N_{it} in the algorithms can be obtained by the designer.

Considering Algorithms 1 and 2, the following points are interesting to note:

- Our proposed algorithms result in significantly lower complexity, in comparison with the exhaustive search, as it only checks KN_{it} number of possible solutions (see Section 5).
- Moreover, due to Step 7 of the algorithms, where $K - J - 1$ random possible solutions are checked in each iteration, the proposed algorithms mimic the exhaustive search if $N_{it} \rightarrow \infty$, and they reach the globally optimal selection rule if asymptotically many iterations are considered [63].
- Unlike typical GAs, we do not use the crossover operation and instead evaluate a few random solutions in each iteration. This is because the proposed algorithms work well with no need for the additional complexity of the crossover operation, and converge with a few iterations (see Section 5). However, it is straightforward to include the crossover into the proposed algorithms where, for instance, the Queen and the next best solutions are combined to generate new possible solutions.
- The proposed algorithms optimize the network deployment off-line. However, it is straightforward to scale the network and adapt the algorithm in an on-line manner. For instance, adding new set of SBSs to an already-planned network deployment, one can rerun the algorithm for only a few iterations with the initial considered solutions not randomly but based on the Queen of the already-planned network.

Since the considered problem is polynomial time reducible, it is NP-hard [64], [65]. Moreover, unless for the cases with very small networks, the search space increases rapidly with the network density which makes exhaustive search based optimization infeasible. As an example, the number of possible solution checkings of exhaustive

Algorithm 5 GA-based non-IAB Backhaul Link Placement.

In each network instance with a budget for N_f non-IAB backhaul-connected SBSs, and $N_s > N_f$ SBSs, do the followings:

- I. Consider K sets of N_f non-IAB backhaul-connected SBSs, F_k , and for each set create the corresponding channel matrix. Then, for each matrix H_k , $k = 1, \dots, K$, implement the system model in Section 3.
- II. For each selected possible solution F_k , evaluate the objective function U_k , $k = 1, \dots, K$. For instance, considering the service coverage probability ρ as the objective function, U_k is given by (B.16).
- III. Find the set of the SBSs among the considered solutions $F_k, \forall k$, which gives in the best value of the objective function, service coverage probability (the Queen), e.g., F_i where $\rho(H_k) \leq \rho(H_i), \forall k = 1, \dots, K$.
- IV. $F_1 \leftarrow F_i$
- V. Generate $J < K$, sets of SBSs $F_j^{\text{new}}, j = 1, \dots, J$, around the Queen, i.e., F_i . These sets of SBSs are generated by making small changes to the Queen, for instance, by replacing few SBSs with other SBSs.
- VI. $F_{j+1} \leftarrow F_j^{\text{new}}, j = 1, \dots, J$.
- VII. Use the same procedure as in Step 1 and regenerate the remaining sets $F_j, j = J + 2, \dots, K$, randomly.
- VIII. Proceed to Step 2 and continue the process for N_{it} iterations pre-considered by the network designer.
Return the Queen as the optimal SBS selection rule for non-IAB backhaul link placement.

=0

search when optimizing the selection of non-IAB backhaul connected SBSs in a fixed network area is given by

$$S_c = \binom{N_s}{N_f}, \quad (\text{B.17})$$

where $\binom{n}{k}$ denotes the " n choose k " operator. In this way, for moderate/large values of N_f and/or N_s , the search space soon becomes so large that exhaustive search is not feasible. However, the complexity of Algorithm 1 for a similar use case will be in the linear order of KN_{it} , reducing the complexity compared to exhaustive search significantly.

Finally, it should be noted that:

- Depending on the infrastructures and the availability of non-IAB backhaul link connection, in practice it may not be possible to provide some SBSs with a non-IAB backhaul link connection (either fiber or a dedicated LoS nonIAB wireless backhaul). This is because the those connections may be available in specific areas. In this way, as explained in Section 3, Algorithm 1 gives an optimistic ultimate network performance, as we consider no limitation for non-IAB backhaul link distribution among the SBSs. Then, depending on the specific network deployment, it is straightforward to adapt Algorithm 1 to consider restrictions on non-IAB backhaul link distribution among the SBSs.
- According to the 3GPP discussions, one can consider two different, namely, wide-area and local-area, IAB network deployments. Local-area IAB deployment refers to the cases with an unplanned network where the mobile terminal (MT) module of the IAB nodes have UE-type functionality, in terms of transmit power etc. Wide-area IAB network, on the other hand, refers to the cases with well-planned deployment and gNB-type functionalities for the IAB nodes. In this way, the proposed scheme mainly concentrates on the wide-area IAB network deployment, as the main use-case of the IAB networks.

5 Performance Evaluation Of Deployment Optimization

The simulation results and discussions are divided into three main areas in which 1) we evaluate the convergence behaviour of the proposed algorithms, and we study their effect on optimizing the IAB network performance, 2) verify the effect of environmental parameters on the coverage probability, and 3) evaluate the system performance for different transmission capabilities of the nodes. Then, in Section 6, we investigate the effect of routing on the performance of IAB networks experiencing temporal blockings.

The general system parameters are presented in Table 2 and, in each figure, we give the detailed system parameters in the figure captions. The IAB network is deployed

Algorithm 6 GA-based SBS Location Selection.

In each network instance with N_s SBSs, from all possible locations in the space, do the followings:

- I. Consider K sets of L_k locations, and for each set create the corresponding channel matrix H_k , $k = 1, \dots, K$, according to the system model in Section 5.
- II. Evaluate the objective function for each set, i.e., U_k , $k = 1, \dots, K$. For instance, considering the service coverage probability ρ as the objective function, U_k is given by (B.16).
- III. Find the Queen, i.e., the set of locations which gives the best value of the objective function, i.e., service coverage probability, among the considered sets, e.g., L_i where $\rho(H_k) \leq \rho(H_i)$, $\forall k = 1, \dots, K$,
- IV. $L_1 \leftarrow L_i$
- V. Generate $J < K$, sets of locations L_j^{new} , $j = 1, \dots, J$, around L_i . These sets of locations are generated by making small changes to the Queen, for instance, by replacing few locations with another sets of locations.
- VI. $L_{j+1} \leftarrow L_j^{\text{new}}$, $j = 1, \dots, J$.
- VII. Use the same procedure as in Step 1 and regenerate the remaining sets L_j , $j = J + 2, \dots, K$, randomly.
- VIII. Proceed to Step 2 and continue the process for N_{it} iterations pre-considered by the network designer.
Return the Queen as the optimal SBS location selection rule.

=0

Table 2: Simulation Parameters.

Parameters	Value
Carrier frequency	28 GHz
Bandwidth	1 GHz
IAB node and UEs density	$\{\text{MBS, SBS, UE}\} = (2, 50, 500) / \text{km}^2$
Blocking density	$500 / \text{km}^2$
Path loss exponents	$\{\text{LoS, NLoS}\} = (3, 4)$
Main lobe antenna gains	$\{\text{MBS, SBS, UE}\} = (18, 18, 0) \text{ dBi}$
Side lobe antenna gains	$\{\text{MBS, SBS, UE}\} = (-2, -2, 0) \text{ dBi}$
Half power beamwidth	30
Noise power	5 dB
Percentage of non-IAB backhauled SBS nodes	10%
In-leaf percentage	15%
Tree depth	7.5 m

in a 2D disk, in which the blockage, and the tree distributions are also modelled using statistical models described in Section 3. In particular, the network is a hybrid IAB deployment, of which a fraction of the SBSs will be non-IAB backhaul-connected while the others are backhauled using IAB. In all figures, except for Fig. 13 which studies the system performance in suburban areas, we focus on dense areas as the most important use-case in IAB networks. Also, in all figures, except in Fig. 15, we ignore interference in the backhaul links, and assume them to be noise-limited. In Figs. 8,12, 13-10, we study the system performance in the cases with non-IAB backhaul link placement optimization (Algorithm 1). Figures 9, 14, 11 and 17 present the results for the cases with Algorithm 2 optimizing the SBSs locations.

5.1 On the Performance of the Proposed Algorithms

In Figs. 8-9, we study the convergence performance of the proposed algorithms, and compare the results with the cases having only MBSs or random network deployment. Figure. 8 shows the service coverage probability achieved for different numbers of iterations in Algorithm 1 with optimal non-IAB backhaul link connection distribution and different algorithm parameters K and J . Here, the results are presented for the cases with 10% of the SBSs having the possibility to be non-IAB backhaul-connected. Then, Fig. 9 demonstrates the IAB network service coverage probability

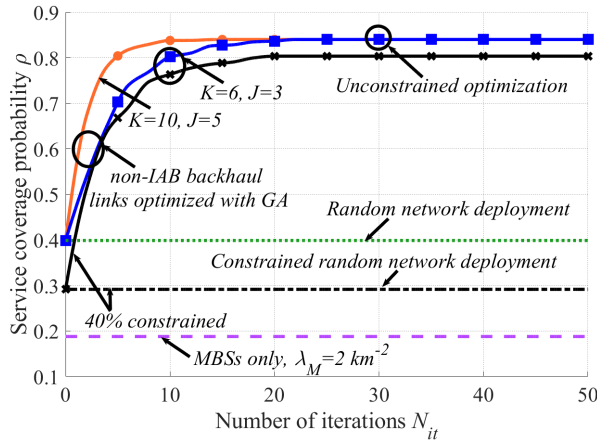


Figure 8: Service coverage probability as a function of the number of iterations in Algorithm 1 with non-IAB backhaul link connection distribution, and $P_m, P_s, P_u = (40, 24, 0)$ dBm. The parameters are set to $\lambda_M = 2 \text{ km}^{-2}$, $\lambda_S = 50 \text{ km}^{-2}$ and $\lambda_U = 500 \text{ km}^{-2}$. The results are presented in both cases with constrained and free non-IAB backhaul link distribution in the coverage area.

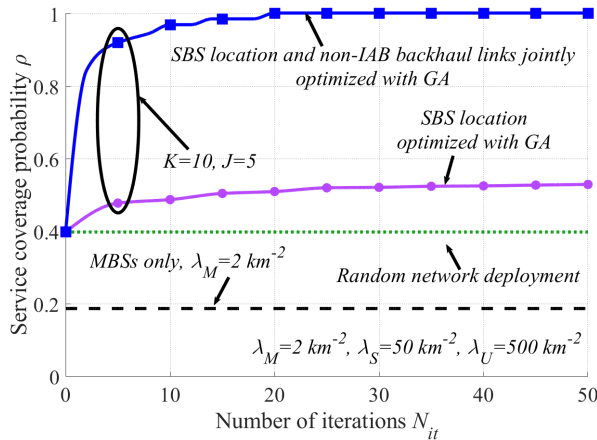


Figure 9: Service coverage probability as a function of the number of iterations in Algorithm 2 with IAB node placement optimization, IAB node placement and non-IAB backhaul links joint optimization and $P_m, P_s, P_u = (40, 24, 0)$ dBm. The parameters are set to $\lambda_M = 2 \text{ km}^{-2}$, $\lambda_S = 50 \text{ km}^{-2}$ and $\lambda_U = 500 \text{ km}^{-2}$.

as a function of the number of iterations in Algorithm 2, and compares the results with the benchmark schemes using only MBSs or random network deployment of which 10% of the SBSs are non-IAB backhaul-connected.

As in every machine learning-based algorithm applied in large systems, the main challenge of the proposed scheme is to achieve reasonably good results within limited iterations. This is challenging specially in the cases with large network density and/or joint optimization of the non-IAB backhaul links distribution and IAB nodes placements, as the search space increases rapidly. However, as shown in the evaluations (Figs. 8-9), with a proper setting of the algorithms parameters, the GA converges with a few number of iterations.

As seen in Figs. 8 and 9, the developed Algorithms 1 and 2 converge rapidly to give a maximum service coverage probability. For example, Fig. 8 converges with almost $N_{it} = 20$ iterations which, with $K = 6$, leads to a total of 120 possible solution checkings. As a result, the proposed algorithm reduces the complexity compared to exhaustive search significantly because with $\lambda_s = 50 \text{ km}^{-2}$ and the network area of 1 km^{-2} exhaustive search requires $\binom{50}{5} \simeq 2 \times 10^6$ solution checkings, i.e. $\simeq 17000$ times larger search than those in our proposed scheme. In particular, the proposed algorithms have improved the service coverage probability, compared to the IAB network with random node locations and random non-IAB backhaul connections, significantly. For instance, with the parameter settings of Fig. 8, optimizing the non-IAB backhaul link distribution among 10% of the SBSs increases the coverage probability from 40% with random non-IAB backhaul link distribution to 85%. Moreover, with the parameter settings of Fig. 9, optimizing the SBSs location leads to a coverage probability increment from 40% with random network deployment to 55%, while the joint optimization of non-IAB backhaul link distribution and SBS location further improves the coverage probability reaching the maximum of 100%.

In the simulations, we considered no constraints on the SBSs and non-IAB backhaul links locations. However, in practice, it may not be possible to place the SBSs and the non-IAB backhaul links freely. To evaluate this point, in Fig. 8 we study the system performance in the cases with constraints on the non-IAB backhaul link distribution. Particularly, Fig. 8 shows the coverage probability in the cases where the non-IAB backhaul links can not be placed in 40% of the area selected randomly. Here, the results presented for both cases with random and optimized distributions of the non-IAB backhaul links in the 60% of the coverage area. As seen in Fig. 8, although the constraint on topology optimization may limit the benefit of IAB, still the system performance is improved compared to the cases with only MBSs. Also, for a broad range of parameter settings, the effect of topology constraints on the network performance is not significant.

Finally, as expected and also demonstrated in Figs. 8-9, as the UEs density increases, MBSs alone can not support the UEs' coverage probability requirements, and indeed we need to densify the network using (IAB) nodes of different types. In

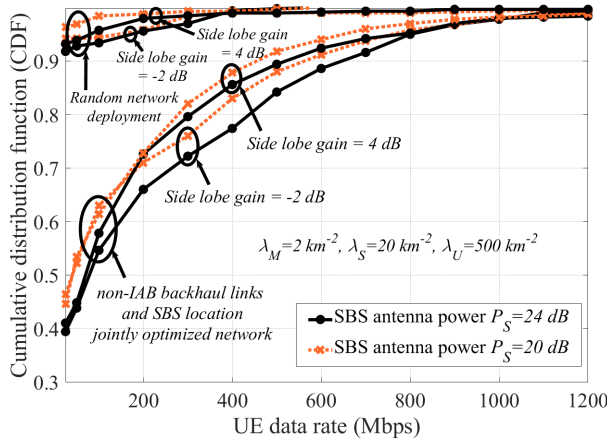


Figure 10: CDF of the achievable rates with $P_m, P_u = (40, 0)$ dBm for SBS location and non-IAB backhaul links joint optimization. The parameters are set to $\lambda_M = 2 \text{ km}^{-2}$, $\lambda_S = 20 \text{ km}^{-2}$ and $\lambda_U = 500 \text{ km}^{-2}$.

this way, as also experienced in practical network implementations, a well-planned network deployment results in significant performance improvement, which reduces the need for high network node density as well as the implementation cost.

Note that, while Figs. 8-9 show monotonic improvement of the system performance in successive iterations, in some iterations the proposed algorithms may follow a ladder-shape convergence pattern. This is because the service coverage probability does not necessarily improve in each iteration, and there is a possibility to reach a local optimum in some iterations. However, we always elude the local minima due to Step 7 of Algorithms 1 and 2. Thus, given that sufficiently large number of iterations are carried out, the algorithm converges to a (sub)optimal solution.

In Figs. 10 and 11, we study the cumulative distribution function (CDF) of the UEs achievable data rates in the cases with SBS location optimization as well as joint non-IAB backhaul link distribution and SBS location optimization, and compare the results with random network deployment. Here, the parameters are set to $\lambda_M = 2 \text{ km}^{-2}$, $\lambda_S = 20 \text{ km}^{-2}$ and $\lambda_U = 500 \text{ km}^{-2}$, and in all cases 10% of the SBSs are non-IAB backhaul-connected. Also, the joint optimization follows the same setup as in Algorithms 1-2.

As can be seen in Fig. 10, with a random deployment and the parameter settings of the figure, (almost) all UEs maximum achievable rates are below 400 Mbps, the result which holds for both considered values of the IAB nodes transmit powers and side lobe gains. On the other hand, jointly optimizing the non-IAB backhaul link distribution and SBSs locations gives the chance to support higher access data rates, depending on the UEs position and their associated backhaul links qualities. For

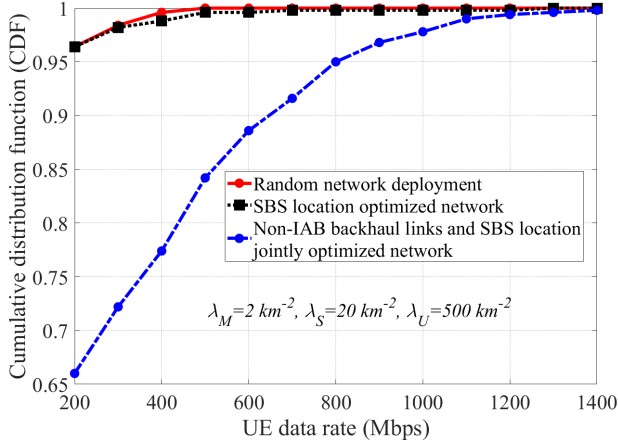


Figure 11: CDF of the achievable rates with $P_m, P_u = (40, 0)$ dBm for SBS location optimization, SBS location and non-IAB backhaul links joint optimization. The parameters are set to $\lambda_M = 2 \text{ km}^{-2}$, $\lambda_S = 20 \text{ km}^{-2}$ and $\lambda_U = 500 \text{ km}^{-2}$.

instance, as opposed to the cases with random network deployment, with $P_s = 24$ dBm around 25% of the UEs may experience > 400 Mbps access rates, if the non-IAB backhaul link distribution and the SBSs locations are properly planned (Fig. 10).

In our simulations, we consider relatively low side lobe gains, compared to the main lobe gain. This is motivated by the fact that, to guarantee high-rate reliable backhaul performance at mmw spectrum, IAB nodes are expected to be equipped with a large number of antennas and be capable of directional beamforming. However, depending on the hardware properties, in practice there may be cases with relatively high side lobe gains [66]. For this reason, in Fig. 10 we study the effect of the side lobe gain on the network performance, and verify the coverage probability for different values of side lobe gains. As demonstrated in the figure, while the coverage probability is slightly reduced by increasing the side lobe gain, for a broad range of parameter settings, the relative performance loss is negligible.

In harmony with Fig. 10, Fig. 11 shows that, the SBS location-optimized network can support UEs data rates up to 1200 Mbps while non-IAB backhaul link distribution and SBS locations jointly optimized network can support UEs data rates up to around 1400 Mbps. In this way, the joint optimization improves the performance, compared to optimizing one of the parameters, at the cost of higher computational complexity. Finally, note that, along with simplifying the optimization process, one of the motivations for separate optimization of the SBSs locations and non-IAB backhaul links distribution is that in practice the SBSs and the non-IAB backhaul links may be deployed by different companies or in different times, which makes joint optimization difficult.

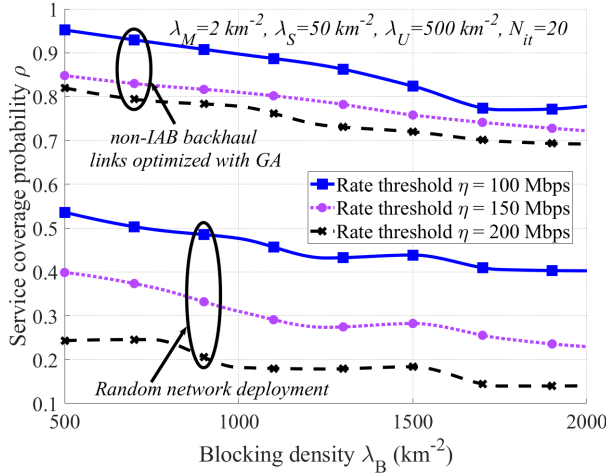


Figure 12: Service coverage probability of the IAB network as a function of the blocking density λ_B , with $P_m, P_s, P_u = (40, 24, 0)$ dBm and different methods of non-IAB backhaul link connection distribution among 10% of the SBSs. The parameters are set to $\lambda_M = 2 \text{ km}^{-2}$, $\lambda_S = 50 \text{ km}^{-2}$, $\lambda_U = 500 \text{ km}^{-2}$ and $N_{it} = 20$.

5.2 Effect of Blocking and Tree Foliage

In contrast to the non-IAB backhaul-connected networks, IAB networks may be affected by environmental effects specially the blockage and the tree foliage². In Figs. 12 and 13, we respectively study the effect of the blockage and tree foliage on the coverage probability of the IAB network with random deployment or GA-optimized non-IAB backhaul link distribution. Here, the results are presented for different rate thresholds of the UEs, i.e., η in (15). In particular, Fig. 12 shows the service coverage probability considering the FHPPP-based germ-grain blockage model for different blocking densities.

Although urban areas are the main point of interest for IAB network, to study the potentials of its usage in suburban areas, in Fig. 13 we demonstrate the service coverage probability as a function of the tree density in the suburban areas. Here, we present the results for the average hop distance $l_h = 450$ m corresponding to SBSs density, $\lambda_S = 8 \text{ km}^{-2}$. This is motivated by, e.g., [67], reporting the tree foliage as one of the main challenges of IAB in suburban areas. According to Figs. 12-13, the following points can be concluded:

- The GA-based planned deployment shows significant improvement and resilience to blockage and tree foliage, compared to random deployment, where

²As reported in [25], with the typical hop lengths of the IAB networks and 28 GHz, the effect of the rain on the coverage probability of IAB network is negligible.

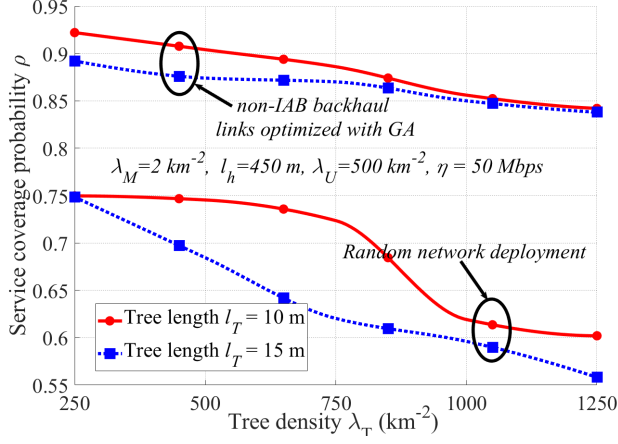


Figure 13: Service coverage probability of the IAB network as a function of tree density λ_T , with $P_m, P_s, P_u = (40, 33, 0)$ dBm and different methods of non-IAB backhaul link connection distribution among 10% of the SBSs. The parameters are set to $\lambda_M = 2 \text{ km}^{-2}$, $l_h = 450 \text{ m}$, $\lambda_U = 500 \text{ km}^{-2}$ and $\eta = 50 \text{ Mbps}$.

the coverage probability is not much affected by the blockage (Fig. 12). For instance, with the given system configuration in Fig. 12, the GA optimized setup shows 0.85 service coverage probability at $\eta = 150 \text{ Mbps}$, $\lambda_B = 1000 \text{ km}^{-2}$, while the coverage probability reduces to 0.72 at $\lambda_B = 2000 \text{ km}^{-2}$, i.e., only 15% coverage loss by doubling the blockage density. On the other hand, with a random network deployment, $\eta = 150 \text{ Mbps}$ and $\lambda_B = 1000$, the coverage probability is only 0.4 and it is dropped to 0.23, i.e., 42% performance degradation, as the blockage density increases to $\lambda_B = 2000 \text{ km}^{-2}$.

- In suburban area and with a random network deployment, the coverage probability is considerably affected by the tree foliage, especially when the trees density and/or length increase. However, we note that the introduction of GA optimization on selecting the SBSs with non-IAB backhaul-connection has brought resilience to the tree foliage. This is due to the fact that the algorithm finds the optimum set of nodes minimizing the SBS links with high losses due to tree foliage. For instance, considering the settings of Fig. 13 and the random FHPPP model with $l_T = 15 \text{ m}$, the service coverage probability drops from 0.75 to 0.55 (26% coverage degradation) when the tree density is increased from 250 to 1250 km^{-2} . However, the same tree density increase at $l_T = 15 \text{ m}$ in GA-optimized network gives a drop only from 0.88 till 0.83, i.e., only 5% performance drop, the result which is almost independent of the tree length.

In general, the robustness of IAB in the presence of tree foliage is hard to predict

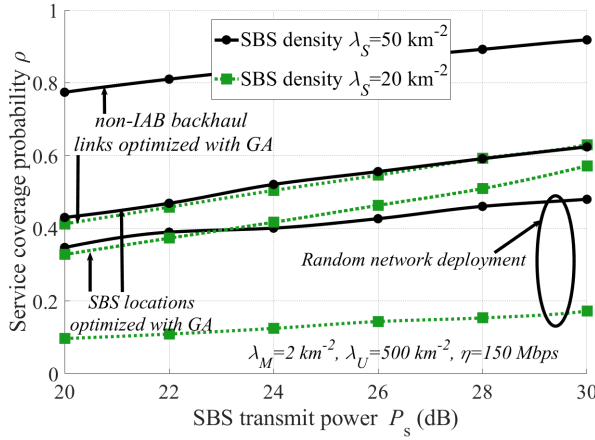


Figure 14: Service coverage probability of the IAB network as a function of the SBSs transmit power P_s , with $P_m, P_u = (40, 0)$ dBm for both non-IAB backhaul link location and node placement optimization methods, $\lambda_M = 2 \text{ km}^{-2}$, $\lambda_U = 500 \text{ km}^{-2}$ and $\eta = 150 \text{ Mbps}$.

due to the fact that the link quality can vary depending on the characteristics of the tree lines. Particularly, the backhaul links quality may change due to wet trees, snow on the trees, wind and varying percentage of leaves in different seasons. However, we conclude that, although the IAB is prone to medium/highly densified tree foliage in suburban areas, network planning can reduce much of its adverse effect, and the mmWave IAB is expected to work well for areas with low/moderate foliage level.

5.3 Effect of Antenna Gain and Transmit Power

In Fig. 14, we demonstrate the service coverage probability as a function of the SBS transmit power for three scenarios, namely, random FHPPP-based deployment, GA-based non-IAB backhaul link distribution and GA-based SBS location optimization. Also, Fig. 15 shows the service coverage probability as a function of the SBS antenna gain for random FHPPP-based deployment with 10% non-IAB backhaul-connected SBSs, macro-only network and GA-optimized non-IAB backhaul link distribution between 10% of the SBSs. In addition, to verify the effect of interference in the backhaul links, the figure shows the service coverage probability in the presence of both noise-limited and noise plus interference limited backhaul links. Here, we increase the SBS antennas' main lobe gain, while fixing the side lobe gain at -2 dB.

As we observe in Fig. 14, both GA-optimization methods used for selecting the dedicated non-IAB backhauled nodes and selecting SBSs locations have significantly increased the system coverage probability, compared to random deployment, and the

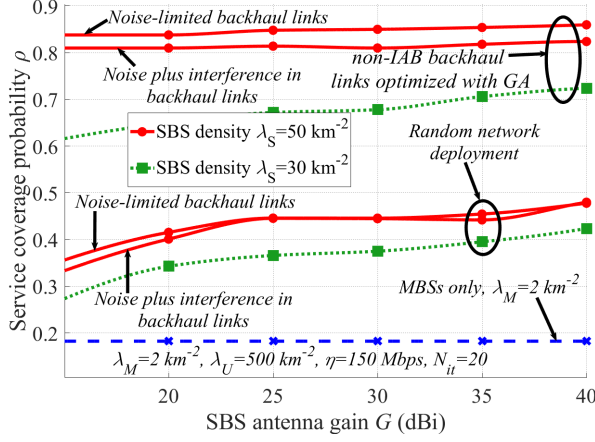


Figure 15: Service coverage probability of the IAB network as a function of the SBSs antenna gain G , with $P_m, P_s, P_u = (40, 24, 0)$ dBm for non-IAB backhaul link location optimization, $\lambda_M = 2 \text{ km}^{-2}$, $\lambda_U = 500 \text{ km}^{-2}$, $\eta = 150 \text{ Mbps}$ and $N_{it} = 20$.

relative effect of network planning increases with the SBSs' transmit power (Fig. 14). Moreover, with different deployment conditions and the considered range of transmit powers, the coverage probability increases almost linearly with the SBSs transmit power, while the relative benefit of the transmit power increment increases in the cases with a well-planned network (Fig. 14). Also, Fig. 15 demonstrates that, for the considered parameter setting of the figure and moderate/high antenna gains, the system performance is almost insensitive to the antenna gain specially if the network is well planned. Finally, as seen in Fig. 15, the impact of the interference in the backhaul links is negligible, and thus, the backhaul links can be well assumed to be noise-limited (Also, see [19]–[21], [27] for further discussions).

In Fig. 16, we compare the coverage probability of the proposed GA-based scheme with those obtained by different state-of-the-art algorithms including exhaustive search, Tabu algorithm [68] and Greedy algorithm [69]. Note that Tabu is an evolutionary algorithm with a specific method of producing the generations (see [70] for details) while with Greedy algorithm, e.g., the non-IAB backhaul links locations are determined one-by-one [69]. Here, the parameters are set to $\lambda_M = 2 \text{ km}^{-2}$, $\lambda_U = 500 \text{ km}^{-2}$, and in all cases 10% of the SBSs are non-IAB backhaul-connected. Thereby, we optimize the non-IAB backhaul links distribution and, as can be seen in Fig. 16, the GA converges rapidly with limited iterations to the maximum coverage probability achieved by exhaustive search. This is an indication of the efficiency of the proposed method with considerably lower complexity, compared to exhaustive search. Moreover, for a given number of iterations, the GA outperforms the greedy

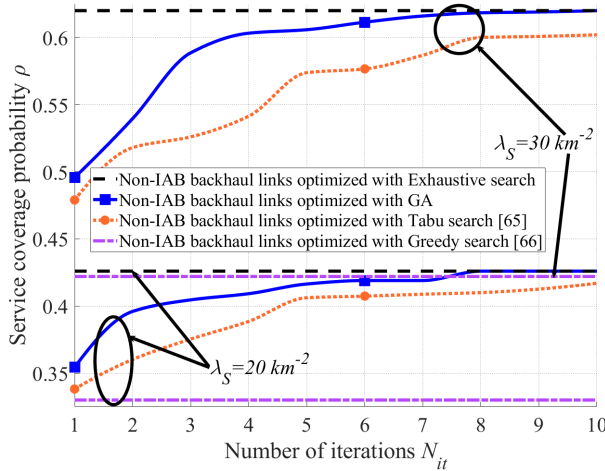


Figure 16: Service coverage probability as a function of the number of iterations in Algorithm 1 with non-IAB backhaul links optimization. The parameters are set to $P_m, P_s, P_u = (40, 24, 0)$ dBm, $\lambda_M = 2 \text{ km}^{-2}$, and $\lambda_U = 500 \text{ km}^{-2}$.

and the Tabu algorithms, in terms of coverage probability. Note that, while the greedy algorithm is easy to implement, it may not always lead to the global optimum due to the fact that it does not consider the entire search space. Finally, note that the results of Fig. 16 are presented for a given example channel realization for which one can run the exhaustive search in limited time³. However, the effectiveness of semi-optimal algorithms is more visible when studying the average system performance over multiple channel realizations, where running exhaustive search is not feasible within limited time.

6 On the Effect of Routing

As demonstrated, deployment planning can compensate for stationary blockages/tree foliage. On the other hand, depending on, e.g., the height of the SBSs, the (backhaul) links may be temporally blocked by, for instance, trucks passing by. In such cases, routing can be used to reduce the coverage probability degradation. For this reason, in this section, we study the effect of routing on the performance of IAB networks (see Section 2 for 3GPP standardization agreements on routing). Note that, in general, routing can be utilized not only for temporal blockages but also for load balancing in the cases with varying data traffic. In this paper, we concentrate on temporal

³We have checked the results of Fig. 16 for a number of channel realizations and observed the same qualitative conclusions.

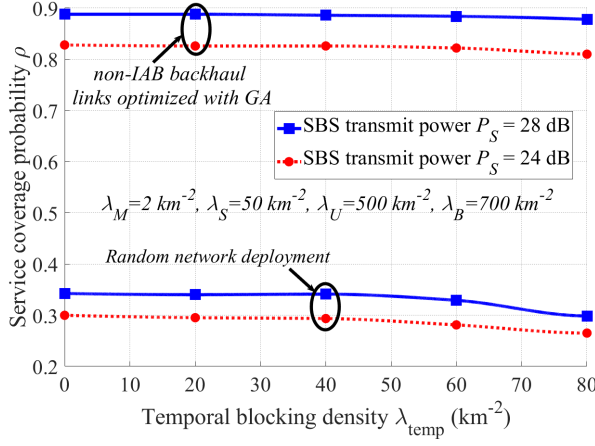


Figure 17: Service coverage probability of the IAB network as a function of the temporal blocking density λ_{temp} , with $P_m, P_u = (40, 0)$. The parameters are set to $\lambda_M = 2$ km⁻², $\lambda_S = 50$ km⁻², $\lambda_U = 500$ km⁻² and $\lambda_B = 700$ km⁻²

blockage, and load balancing-based routing is out of the scope of our work. Note that, here, the network deployment is first optimized based on static blockages/tree foliage. Then, by temporal blockage we refer to the blockages that are added to the network after the deployment optimization is performed.

Figure 17 shows the service coverage probability considering a static blocking density $\lambda_B = 700$ km⁻² for different temporal blocking densities. In addition, to understand the IAB sensitivity for temporal blockings and the effect of the routing, in Fig. 18, we plot the percentage of the links that have been updated by routing as a function of the density of the temporal blockings added to the network. The results are presented for various cases with random deployment, GA-optimized non-IAB backhaul link distribution or GA-optimized SBS locations. Here, by routing, the received powers are recalculated, the association matrix is re-updated and thereby the data rates are calculated again, i.e., (8), (9), (13) and (14), are adapted based on the presence of temporal blockages such that the coverage probability degradation is minimized. Also, by percentage of routing update we refer to the fraction of links in the network that have changed their associated BS, both in the access and backhaul links. Here, the results are demonstrated for different transmit powers of the SBSs. According to Fig. 17-18 the following points can be concluded.

- Unless for high densities of temporal blockings, the service coverage probability of the IAB network is not degraded much by temporal blockage (Fig. 17). Also, the introduction of GA to optimize the dedicated non-IAB backhaul connections has brought further resilience in the network to temporal blockage. Finally, the sensitivity to temporal blockage increases slightly at low SBS

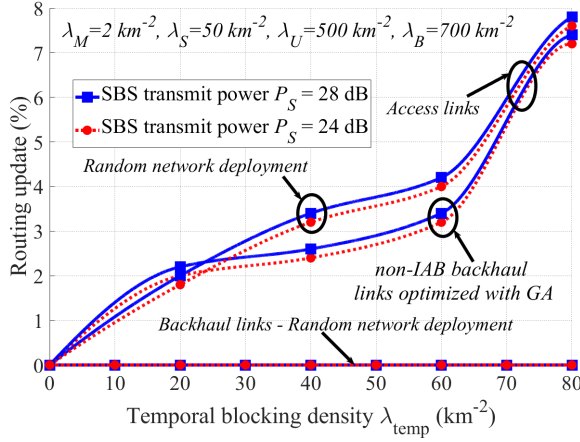


Figure 18: Percentage of routing updating of the IAB network as a function of the temporal blocking density λ_{temp} with $P_m, P_u = (40, 0)$. The parameters are set to $\lambda_M = 2 \text{ km}^{-2}$, $\lambda_S = 50 \text{ km}^{-2}$, $\lambda_U = 500 \text{ km}^{-2}$ and $\lambda_B = 700 \text{ km}^{-2}$

transmit powers (Fig. 17).

- As demonstrated in Fig. 18, with temporal blockage, the routing scheme may update the access links of the UEs to the IAB nodes. However, 1) for a broad of temporal blockage densities for both non-IAB backhaul connection-optimized and random deployments, the access links updates are less than 10%. Also, 2) in all considered cases, the backhaul links do not need to be updated due to temporal blockage. This is intuitively because the IAB donor-IAB backhaul links are strong to support the required rates and the presence of temporal blockage does not affect their efficiency much unless for high temporal blockage densities. Finally, compared to random network deployment, optimizing the non-IAB backhaul link distribution among 10% of the SBSs with GA has slightly reduced the percentage of routing update with the addition of temporal blockings. For instance, with the parameter settings of Fig. 18, $\lambda_{\text{temp}} = 50 \text{ km}^{-2}$, and $P_s = 28 \text{ dBm}$, in random network deployment one may need a routing update of 3.6%, while in the GA-optimized network it is only 2.9%.

In this way, the results indicate that, while deployment optimization can well robustify the network to static blockages, with a well-planned network the system performance is almost insensitive to low/moderate temporal blockages, and routing may not be required unless for high temporal blockage densities/severe coverage probability requirements. On the other hand, depending on the data traffic variation and the number of hops in the IAB network, the routing may be of interest in load balancing.

7 Conclusion

We studied the problem of deployment optimization and routing in IAB networks to guarantee high coverage probability in the presence of tree foliage/blockage. Moreover, we reviewed the recent 3GPP agreements on IAB-based routing, as well as the key challenges to enable meshed IAB.

As we showed, machine-learning techniques can be effectively utilized for deployment optimization, with no need for mathematical analysis and with the capability to be adapted for different channel models/constraints/metrics of interest. Particularly, the proposed algorithm reduces the complexity compared to exhaustive search significantly because with typical network area our proposed scheme requires orders of magnitude less solution checkings compared to exhaustive search. Also, while deployment planning boosts the coverage probability of IAB networks, compared to random deployment, significantly, for a broad range of coverage constraints/blockage densities, the impact of routing to increase redundancy may be negligible. Indeed, routing may be of interest in the cases with severe availability constraints/high blockage densities as well as for load balancing. Finally, in practice, deployment planning may be affected by, e.g., the availability of non-IAB backhaul connection in specific areas, and the designer may consider, e.g., seasonal tree foliage variations, rental costs and/or foreseen infrastructure changes.

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**Constrained Deployment Optimization in Integrated Access and
Backhaul Networks**

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The layout has been revised.

Abstract

Integrated access and backhaul (IAB) is one of the promising techniques for 5G networks and beyond (6G), in which the same node/hardware is used to provide both backhaul and cellular services in a multi-hop fashion. Due to the sensitivity of the backhaul links with high rate/reliability demands, proper network planning is needed to make the IAB network performing appropriately and as good as possible. In this paper, we study the effect of deployment optimization on the coverage of IAB networks. We concentrate on the cases where, due to either geographical or interference management limitations, unconstrained IAB node placement is not feasible in some areas. To that end, we propose various millimeter wave (mmWave) blocking-aware constrained deployment optimization approaches. Our results indicate that, even with limitations on deployment optimization, network planning boosts the coverage of IAB networks considerably.

Integrated access and backhaul, IAB, Topology optimization, Densification, millimeter wave (mmWave) communications, 3GPP, Coverage, Wireless backhaul, 5G NR, 6G, Blockage, Machine learning, Network planning.

1 Introduction

The data traffic and the users' rate/reliability demands continue to steadily increase in 5G and beyond (6G) [1]. In order to meet such demands, network densification, i.e., the deployment of many base stations (BSs) of different types is one of the key enablers. These increasing number of BSs, however, need to be connected to the core network using the transport network.

According to [2], the backhaul technology varies across different regions. However, optical fiber and microwave links have been globally the dominating media for the backhaul. Recently, fiber deployments have increased due to their reliability, and have demonstrated Tbps-level data rates. On the other hand, due to low initial investment and installation time, wireless backhaul comes with considerably lower price, flexibility and time-to-market, at the cost of low peak rate.

Typical wireless backhaul technologies are mainly based on 1) point-to-point line-of-sight (LoS) communications in the range of 10-80 GHz, 2) non-standardized solutions, and 3) accurate network planning such that the interference to/from the backhaul transceivers is minimized. With 5G, however, access communication, i.e., the communication between the gNB and the user equipments (UEs), moves to the millimeter wave (mmWave) band, i.e., the band which was previously used for back-

hauling. Thus, there will be conflict of interest between access and backhaul, which requires coordination. Also, considering small access points on, e.g., lamppost, one needs to support NLoS (N: non) communication in (possibly, unplanned) backhaul networks. These are the main motivations for the so called integrated access and backhaul (IAB) where the operators can use portion of the radio network resources for wireless backhaul. That is, IAB provides not only access link cellular service but also backhaul using the same node. IAB has been standardized for 5G NR in 3GPP Release-16, Release-17 [3], [4] and, the standardization will be continued in Release-18 [5]–[7].

IAB network supports multi-hop communication in which an IAB donor, connected to the core network via, e.g., a fiber link, includes a central unit (CU) for the following concatenated IAB nodes which are connected to IAB donor in a multi-hop fashion (see Fig. 1). Each IAB node consists of two modules, namely, mobile termination (MT) and distributed unit (DU). The DU part of an IAB node is used to serve UEs or the MT part of *child* IAB nodes. The MT part of the IAB is used to connect the IAB node to its *parent* IAB-DU in the multi-hop chain towards the IAB donor. In general, the DU part has similar gNB functionalities, although there may be IAB-specific differences. The IAB-MT part, on the other hand, may have different capabilities, although in general it acts not differently from a UE from the point-of-view of its parent IAB.

In practice, IAB networks may face deployment constraints, where the nodes can not be deployed in some locations. Such constraints may come from two reasons: On one hand, depending on the location and regulatory restrictions in protected areas, it may not be possible/allowed to have the IAB nodes in, e.g., some areas. Although these restrictions vary based on the country and locality, all provinces have their own building and landscape protection laws. Additionally, federal laws have to be obeyed and permissions under these laws, if applicable, have to be obtained (e.g. air traffic safety, forest protection, listed buildings etc.). On the other hand, network planning may impose constraints on IAB nodes placement, e.g., to limit the interference. For instance, 3GPP has defined two categories of IAB nodes, namely, wide- and local-area IAB, with distinct properties [8], [9]. The main differences between these two categories are in the nodes capabilities and the level of required network planning.

Wide-area IAB-node can be seen as an independent IAB-node providing its own coverage, with possibly long backhaul link to connect to its parent IAB-node. Here, the goal is to extend the coverage. Due to radio frequency properties, wide-area IAB-node deployment are *well-planned*, by operators. For these type of IAB-nodes, the MT part of the IAB node looks like a normal gNB, in terms of, e.g., high transmit power, beamforming or antenna gains. In wide-area IAB networks, one may consider a minimum distance between the nodes with, e.g., LOS connections. On the other hand, the use-case for the local-area IAB-node is to boost the capacity within an already existing cell served by an IAB donor or parent IAB-node. With local-area

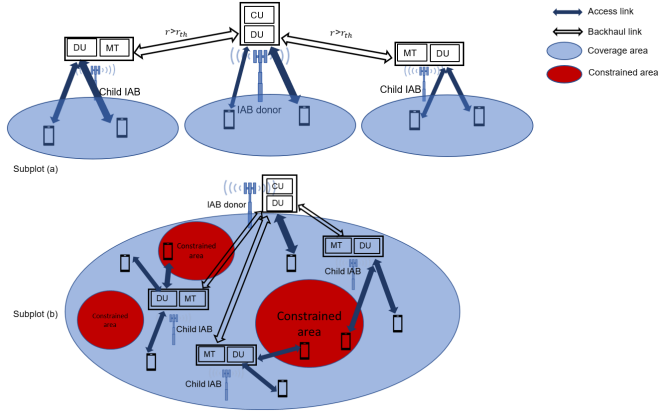


Figure 1: An illustration of the IAB network. Subplot (a): An IAB network with a minimum required distance between the IAB nodes and the IAB-MTs having gNB-like capabilities. Subplot (b): An IAB network with geographical constraints on node placement and the IAB-MT being less capable compared to an gNB.

IAB networks, the transmit power of the MT part may range between those of UEs and gNBs. Also, the network may be fairly unplanned, while geographical-based constraints may still prevent unconstrained IAB installation in different places.

In this paper, we study the effect of network planning on the service coverage of IAB networks. We present different algorithms for constrained deployment optimization, with the constraints coming from either inter-IAB distance limitations or geographical restrictions. Moreover, we study the effect of different parameters on the network performance. As we show, even with constraints on deployment optimization, the coverage of IAB networks can be considerably improved via proper network planning.

Note that the problem of topology optimization in different IAB or non-IAB networks have been previously studied in, e.g., [10]–[15]. However, compared to the literature, we present different algorithms for deployment optimization, consider different types of constraints and study the performance of IAB networks with various parameter settings, which makes our paper different from the previous works.

2 System Model

Consider downlink communication in a two-hop IAB network, where the IAB donor and its child IAB nodes serve multiple UEs [16]–[20] (see Fig. 1). Since in-band communication offers proper flexibility for resource allocation, at the cost of coordination complexity, we consider an in-band setup where both access and backhaul links operate over the same mmWave band.

In one scenario as shown in Fig. 1a, the IAB nodes with gNB-like IAB-MT capabilities maintain a minimum distance r_{th} between each other, i.e., the distance between every two node s should be $s > r_{\text{th}}$ where r_{th} is a threshold distance considered by the network designer, when there is no blockage in the links between IAB nodes. In another scenario shown in Fig. 1b, while the IAB nodes can be in different distances to each other, due to geographical or regulatory restrictions, it may not be possible to have the nodes in some specific areas.

We use the germ grain model [21, Chapter 14] to model the blockings which provides accurate blind spot prediction. Particularly, a finite homogeneous poisson point process (FHPPP) is used to model the blockings in an area with the blocking density λ_{bl} . The blockings are considered to be walls of length l_{bl} and orientation θ_{bl} .

Using the state-of-the-art mmWave channel model, e.g., [22], [23], the received power at each node can be described as

$$P_r = P_t h_{t,r} G_{t,r} L_{t,r} (||x_t - x_r||)^{-1}. \quad (\text{C.1})$$

Here, P_t stands for the transmit power, $h_{t,r}$ denotes the small-scale fading of the link, $L_{t,r}(\cdot)$ is the path loss according to 5GCM UMa close-in model described in **ref3**, and its path loss exponent is dependant on the LoS and NLoS state of the link which is determined by the germ grain blocking model. Particularly, the antenna gain is characterized according to sectored-pattern antenna array model by

$$G_{t,r}(\alpha) = \begin{cases} G_m & -\frac{\alpha_{\text{HP}}}{2} \leq \alpha \leq \frac{\alpha_{\text{HP}}}{2} \\ G_s & \text{otherwise,} \end{cases} \quad (\text{C.2})$$

where G_m denotes the main lobe antenna gain and G_s represents the side lobe antenna gain. Furthermore, in our two-hop setup, each of the UEs can be connected to either the IAB donor or a child IAB, depending on the received power at the UE. Thereby, the interference observed by UE u , caused by the neighbouring interferers, is expressed as

$$I_u = \sum_{i \in \chi_{i,u} \setminus \{w_u\}} P_i h_{i,u} G_{i,u} L_{t,r} (||\mathbf{x}_i - \mathbf{x}_u||)^{-1}, \quad (\text{C.3})$$

where i represents the nodes excluding the associated node w_u of UE u . Moreover, for child IAB node c , the aggregated interference on the backhaul links is given by

$$I_c = \sum_{j \in \chi_{j,c} \setminus \{w_c\}} P_j h_{j,c} G_{j,c} L_{j,c} (||\mathbf{x}_j - \mathbf{x}_c||)^{-1}, \quad (\text{C.4})$$

where j represents transmitting nodes with the exclusion of associated node w_c of child node c . The available mmWave spectrum is partitioned into access and backhaul links such that

$$\begin{cases} W_{\text{Backhaul}} = \beta W \\ W_{\text{Access}} = (1 - \beta)W, \end{cases} \quad (\text{C.5})$$

where W denotes the bandwidth and $\beta \in [0, 1]$ represents the bandwidth partitioning factor. With our implementation, the network may have two types of access links, i.e., IAB donor-UE or child IAB-UE, and the individual UE data rate depends on the type of the access link. In particular, the UE data rates in access links that are connected to the IAB donor or to the child IAB nodes are given by

$$R_u = \begin{cases} \frac{(1-\beta)W}{N_d} \log(1 + \text{SINR}(x_u)), & \text{if } \mathbf{w}_u \in \chi_d, \\ \min \left(\frac{(1-\beta)WN}{\sum_{\forall u} N_{j,u}} \log(1 + \text{SINR}(x_u)), \right. \\ \left. \frac{\beta WN}{\sum_{\forall j} N_j} \log(1 + \text{SINR}(x_b)) \right), & \text{if } \mathbf{w}_u \in \chi_c, \end{cases} \quad (\text{C.6})$$

where j denotes each child IAB node connected to the IAB donor d , which shares some of its bandwidth with child IAB nodes. Moreover, c denotes the child node, and u identifies the UE. Thereby, χ_d , χ_c , χ_u denote the set of IAB donors, child IAB nodes and UEs, respectively. In particular, using the rates (C.6), our goal is to perform constrained deployment optimization such that service coverage given by

$$\text{CP} = \Pr(R_U \geq \rho), \quad (\text{C.7})$$

is maximized. Here, ρ denotes a minimum rate threshold requirement considered by the network designer.

In Algorithms 1 and 2, we propose greedy-based methods for IAB placement with minimum inter-IAB distance and geographical constraints, respectively. The algorithms are based on rejection-sampling method where multiple possible solutions are checked such that, satisfying the constraints, the service coverage is maximized.

Note that we present the algorithms for the general case where the position of both the IAB donors and the IAB nodes are optimized. However, in practice, the position of the IAB donor may be pre-determined based on, e.g., the fiber availability. Moreover, we present the algorithms for the simplest cases where each of the N_{it} possible set of locations is determined independently. However, one can use, e.g., genetic algorithms to generate the new set of possible solutions based on, e.g., mutation of the previously obtained solutions [12], [19]. Such more complex algorithms may also be of interest in the cases with a large number of nodes. Finally, we present the setup for the cases finding a given number of possible solutions N_{it} . Alternatively, one can run the algorithms until no further improvement is observed in a window of

Algorithm 7 IAB placement with minimum inter-IAB distance requirement

With N_d IAB donors, N_c IAB child nodes inside the network area, do the followings:

- I. Place the 1st node, $i = 1$, randomly in the considered network area.
- II. Place the next node $i + 1$ where $i = 1, 2, 3, \dots, (N_c + N_d - 1)$.
- III. Find the minimum inter-node distances s_i between $(i + 1)$ th node and each of other nodes.
- IV. If any $s_i < r_{th}$, redistribute the last node $(i + 1)$ th by repeating Steps II-IV until $s_i > r_{th}$.
- V. For the obtained node locations, calculated the coverage. Then, proceed to Step I and continue the process for N_{it} iterations pre-considered by the network designer, saving the best set of node locations L_b among the considered solutions $L_j, \forall j, j = 1, 2, 3, \dots, N_{it}$, which gives in the best value of the service coverage.

Return the set of the node locations in Step V as the optimal node location set.

Algorithm 8 IAB placement in the presence of constrained areas restricting IAB node placement

With N_d IAB donors, N_c IAB child nodes and a set of constrained areas inside the network area, do the followings:

- I. Place the IAB donors/IAB nodes randomly in the considered network area.
- II. Identify the IAB node(s) falling inside the constrained areas.
- III. For each of the nodes identified in Step II, redistribute the nodes.
- IV. Proceed to Step II and continue the process until all IAB nodes fall outside the constrained areas. Save the set of locations as L_i .
- V. For the saved set of node locations L_i , compute the utility function, i.e., the service coverage given by (C.7). Proceed to Step I and continue the process for N_{it} iterations pre-considered by the network designer, saving the best set of node locations L_b among the considered solutions $L_i, \forall i, i = 1, \dots, N_{it}$ which gives in the best value of the utility function, e.g., service coverage.

Return the set of the node locations in V as the optimal node location set.

the obtained solutions.

3 Simulation Results and Discussion

In this section, we evaluate the effect of inter-node distance and the effect of constrained deployment optimization on the service coverage (C.7) of the IAB networks.

Figure 2b demonstrates the service coverage as a function of the distance between the IAB donor and child IAB nodes, s as of the symmetric setup shown in Fig. 2a of which the donor is located at the center and child IAB nodes are placed symmetrically besides. As shown, the service coverage improves as the IAB nodes are well distributed in the area up to certain distance. Intuitively, this is supported by the decreased interference among the nodes and also better coverage in the area. However, the coverage later starts to drop at large values of s , due to the low coverage experienced by the UEs in the middle of the IAB donor and child IAB nodes.

In Fig. 3, we study the cumulative distribution function (CDF) of the UEs achievable data rates in the cases with different antenna gains and inter-node distances, $s = 100$ m and $s = 400$ m. Here, the parameters are set to UE density = 100 km^{-2} , $P_m, P_s = 24$ dBm, and the IAB-donor is located at the center. As can be seen in Fig. 3, higher antenna gain gives the opportunity to support higher access data rates depending on the inter-node distances. For instance, with $G_m, G_s = 28$ dBi and $s = 400$ m around 20% of UEs may experience > 200 Mbps access rates, compared to the 13%, when $G_m, G_s = 24$ dBi. Moreover, the effect of the antennas gain increases with the inter-node distance (Figs. 2 and 3).

Figure 4b demonstrates the service coverage as a function of the distance between the IAB donor and child IAB nodes, s as of the symmetric setup shown in Fig. 4a of which the IAB donor is located at the center and child IAB nodes are placed symmetrically with equal distance from the donor. As shown, the service coverage increases with the node separation s , up to a point around 550 m, which is due to the decreased interference between the nodes and at the same time properly covering the area. Then, the coverage starts to slightly drop due to the coverage reduction for the UEs in between too far nodes. In this way, there is an optimal distance between the nodes maximizing the coverage. Finally, the coverage decreases significantly with increased UEs minimum rate requirements, to compensate of which one needs more resources/IAB nodes.

In Fig. 5, we study the effect of deployment optimization. Particularly, considering a minimum inter-node distance constraint, we compare the coverage of the IAB networks in the cases with optimized deployment, optimized by Algorithm 1, and the cases with hexagonal IAB deployment.

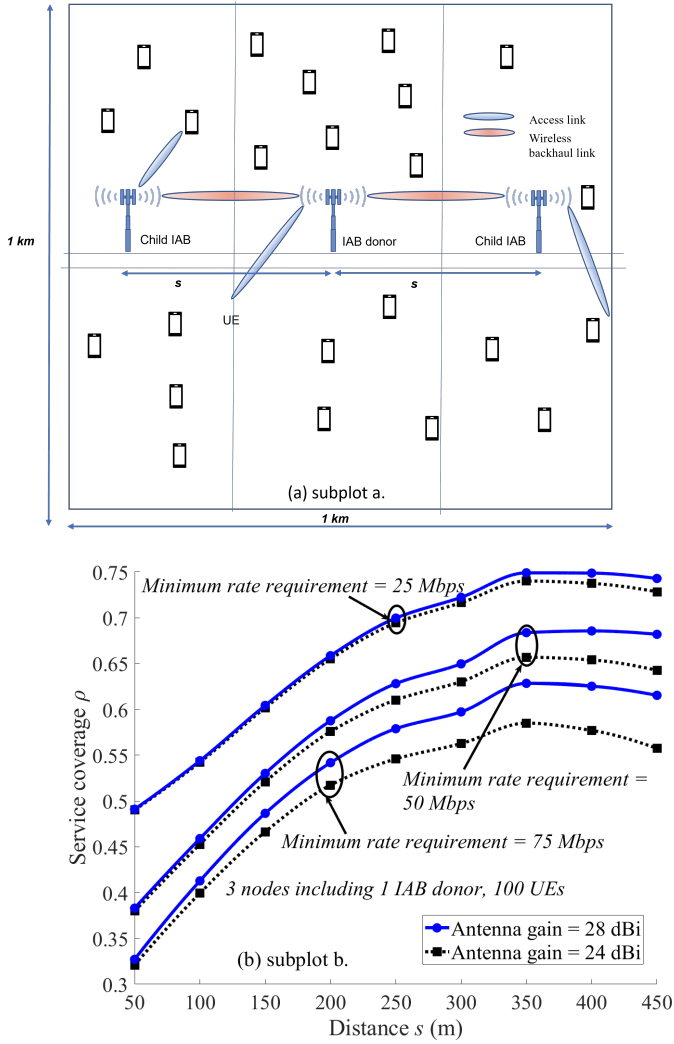


Figure 2: Service coverage as a function of the distance from IAB donor to child IAB s in subplot a with blockage $\lambda_{bl} = 500 \text{ km}^{-2}$.

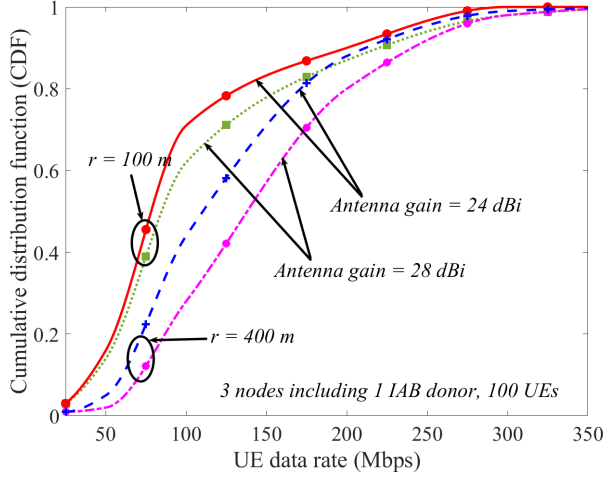


Figure 3: CDF of the achievable rates with blockage density $\lambda_{bl} = 500 \text{ km}^{-2}$, and 100 UEs.

Here, the results are presented for the cases where the IAB donor has $G_m = 24$ dBi and child IAB nodes have a gain of $G_s = 18$ dBi for IAB nodes density of 20 km^{-2} . Moreover, the figure presents the results for the cases where the nodes locations are obtained only by considering the minimum distance between them or when the blockages and the backhaul links' qualities are also taken into account in the optimization. As we see, the service coverage drops when the constraint becomes tighter, however, for all considered range of constraints, compared to hexagonal deployment, constrained deployment optimization increases the network coverage significantly. Indeed, knowing the blockages locations helps in improving the deployment optimization, specially when the UE density increases. Finally, the effect of inter-node distance constraint on the coverage increases with the UE density.

Figure 6 verifies the effect of geographical constraints, on the coverage of IAB networks. Particularly, we study the coverage of the deployment-optimized IAB networks in the cases where, following Fig. 1b, the IAB nodes can not be placed in constrained areas. Here, the results are presented for a network consisting of five circular constrained areas of radius c , with blockage density $\lambda_{bl} = 500 \text{ km}^{-2}$, child IAB node density $\lambda_{child} = 50 \text{ km}^{-2}$, and minimum rate requirement $R_U = 75$ Mbps. The results are presented for the radius of each constrained areas ranging from 100 m to 200 m which corresponds from 10% to 40% of the total disk area, respectively.

As demonstrated in Fig. 6, with low geographical constraints, network performance is not affected by the deployment constraints. However, with large area constraints, the service coverage decreases. This is intuitively because, with larger constraints for IAB placement, there is an increased chance of low coverage for users within the

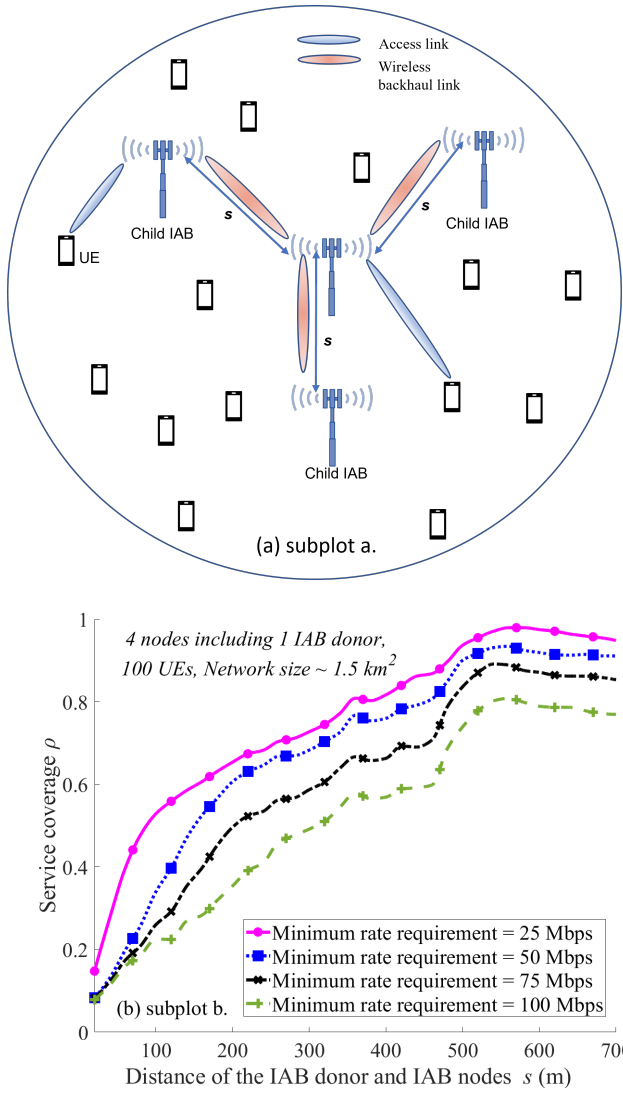


Figure 4: Service coverage as a function of the minimum distance constraint between the nodes, blockage density $\lambda_{bl} = 500 \text{ km}^{-2}$, child IAB node density $\lambda_{child} = 20 \text{ km}^{-2}$.

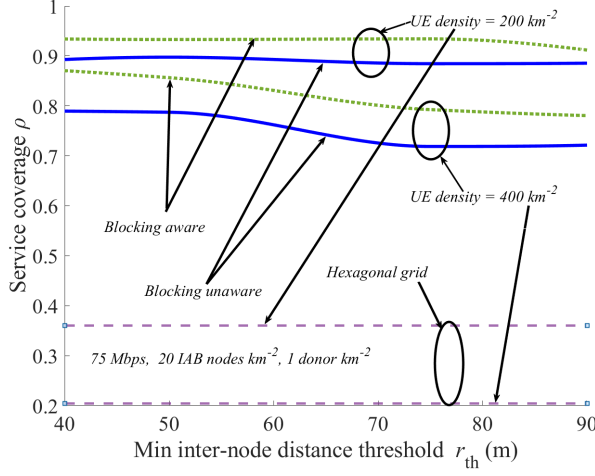


Figure 5: Service coverage as a function of the minimum distance constraint between the nodes, blockage density $\lambda_{bl} = 500 \text{ km}^{-2}$, child IAB node density $\lambda_{child} = 20 \text{ km}^{-2}$.

constrained areas. Also, since the IAB nodes get packed outside the constrained areas, interference levels for the UEs outside the constrained areas increases resulting in a further decrease in coverage. It can be seen in Fig. 6, where the optimized IAB network in the presence of UE density = 200 km^{-2} increases the coverage to 90.5% from the case with UE density = 400 km^{-2} with coverage of 77%. Finally, compared to random deployment, proper network planning boosts the coverage significantly. Also, compared to the case with child IAB nodes distributed randomly in the unconstrained areas, the coverage is less severely affected by geographical constraints when optimized by Algorithm 8.

4 Conclusion

We studied the problem of IAB network deployment optimization in the cases with different deployment constraints. We proposed iterative constrained deployment optimization methods with no need for mathematical analysis and with the capability to be adapted for different channel models/constraints/metrics of interest. As demonstrated, with different geographical and inter-node distance constraints, compared to random or hexagonal deployments, proper network planning can boost the coverage of the IAB networks significantly. Finally, in practice, deployment planning may be affected by, e.g., the availability of non-IAB backhaul connection in specific areas, local authority regulations, and the designer may consider, e.g., the planned

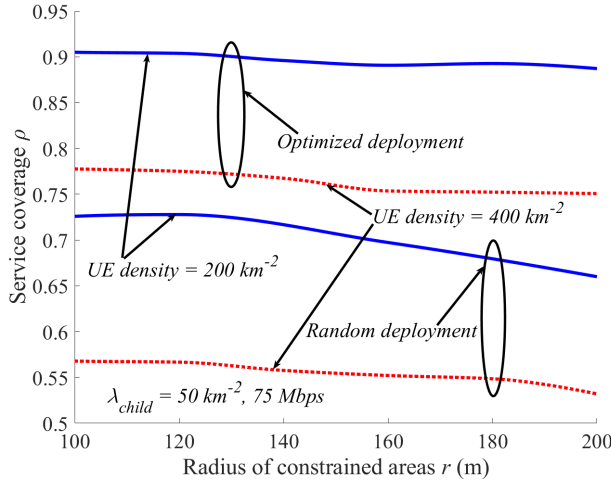


Figure 6: Service coverage as a function of the radius of the constrained areas (c), blockage density $\lambda_{\text{bl}} = 500 \text{ km}^{-2}$, $\lambda_{\text{child}} = 50 \text{ km}^{-2}$.

infrastructure changes, cost, seasonal variations.

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