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Load-Efficiency-Balance Cell Selection Policy for IAB Networks

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Abstract— The 3rd Generation Partnership Project (3GPP) has proposed recently the Integrated Access and Backhaul (IAB) to simplify the deployment of new base stations, where the connection between the User Equipment (UE) and the Core Network (CN) is provided by a multi-hop 5G wireless connection between the IAB nodes. The main contribution of this paper is to propose a cell selection policy specific to IAB, that aims to guarantee the lowest possible total transmission bandwidth cost (including the backhaul cost which is a significant factor in an IAB context) while respecting the base stations capacities, in order to boost IAB network capacity. In this context, a comparative performance study is performed between our proposed policy and state-of-the-art policies. System level simulation results show that our solution provides the best system capacity via a trade-off between spectral efficiency and load balancing.

Index Terms—5G, IAB, wireless connection, cell selection, capacity.

I. INTRODUCTION

Fifth-generation wireless networks present a great challenge in terms of massive number of users with very high data demands, which requires dense deployment of base stations, especially when deployed using Frequency Range 2 (FR2). However, base station densification requires expensive wired infrastructure. To cope with this issue, the Integrated Access and Backhaul (IAB) architecture and its radio protocols have recently been standardized by the 3rd Generation Partnership Project (3GPP) in Release 16 [1]. IAB provides a valuable alternative for the densification of cellular networks that avoids the higher cost of a wired backhaul network deployment [2]. In addition to the traditional 5G-based macro cell generally connected with fiber to the Core Network (CN), the IAB architecture allows the operator to easily deploy micro Base Stations (BSs) wirelessly connected to the macro cell. In other words, two types of nodes are defined in an IAB network: the IAB donor, which is a macro cell connected to the CN using wired backhaul, and the IAB node, which is a micro cell

using wireless backhaul to its parent node or to the donor. Wireless backhaul links share the same frequency band as access links, which is called inband backhaul. The reuse of the same frequency in IAB allows the operator to avoid paying for a new frequency.

The IAB topology offers the possibility for the User Equipment (UE) to connect to the core network either directly through the IAB donor, or indirectly by multi-hop relaying connections through IAB nodes. The direct connection is represented via a direct link between the UE and the IAB donor. The indirect connection is represented via an access link between the UE and a IAB-node and one or more backhaul links between a IAB-node and the IAB donor depending on the number of hops. Even though we can assume better propagation conditions on the backhauling links with respect to the access link, the extra resource cost of transmitting backhaul data in IAB is significant. Consequently, if we go through an IAB-node, the throughput depends on two links, moreover, the IAB donor-IAB node link is shared between several users and the load on this link has an influence. Thus, several strategies for cell selection can be employed, but until now there is no standardized policy. In this paper, we propose a new cell selection policy specific to IAB networks based on a information broadcast between BSs and UEs, that aims to guarantee the lowest possible total transmission bandwidth cost while respecting the base stations capacities.

The rest of the paper is organized as follows. In section II, the state of the art is presented. Section III describes our proposal. Sections IV and V include the description of our system model and performance comparison results of our policy with existing policies, respectively. Finally, Section VI concludes the paper and discusses possible extensions of this work.

II. STATE OF ART

The Reference Signal Received Power (RSRP) based cell selection policy [3] is classically used in 5G networks. With

this policy, the UE compares the strength of signals from neighboring BSs and selects the cell corresponding to the maximal RSRP. The implementation of this policy in an IAB network can result in unbalanced network topology and lower performance [4]. As shown in the example of Fig. 1, if user 4 selects his parent based on RSRP, he will associate with micro 2, which offers the best RSRP value -110 dBm but is also the furthest from the CN in terms of number of hops, which requires more radio resources and increase the latency. The implementation of RSRP-based policy is straightforward since users can measure the quality of the link using the synchronization signals transmitted by the base stations, but has limited performance in an IAB network. For this reason, additional criteria must also be taken into account during the selection of cells to improve performance.

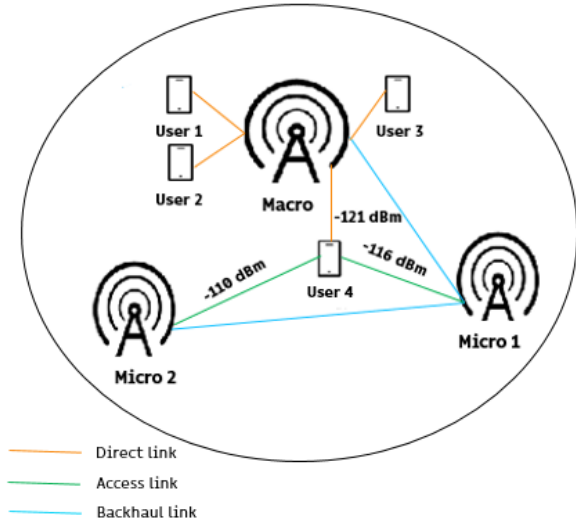


Fig. 1 – An example of RSRP-based policy operation

In [4], authors are looking for path selection policies that decreases the number of hops without affecting the bottleneck SNR. For this reason, several policies have been studied in this paper:

- 1) Highest-quality-first (HQF) policy: This policy is based on the calculation of the Signal-to-noise ratio (SNR) offered on link to each parent candidate at each hop in order to select the next Generation Node B (gNB) that offers the highest SNR.
- 2) Wired-first (WF) policy: This policy is designed to minimize the number of hops required to reach a wired gNB. At each hop, if there is a available link to a wired gNB from the current IAB node with an SNR higher than a threshold Γ_{th} , then the wired gNB is selected, else the HQF policy is applied.
- 3) Position-aware (PA) policy: This policy is based on the use of IAB nodes and gNB position information. First, the IAB node splits into two half-planes the neighboring region, identified by the line, which is perpendicular to the one that passes through the IAB and the wired gNB positions. Then, for the selection only the parents candidate, which are in the half-plane with also the wired

gNB are considered. Finally, the one with the highest SNR is selected.

- 4) Maximum-local-rate (MLR) policy: This policy is based on the calculation of the achievable rate. At each hop, the user selects the parent candidate with the highest achievable Shannon rate.

In [5] authors propose two basic policies that are not specifically dedicated to a backhaul context but can be used as reference policies like the RSRP-based policy :

- 1) Maximum Signal-to-interference-plus-noise ratio (SINR) association strategy: This policy is based on the calculation of the SINR. Each user is associated to the parent candidate for which it has the highest preliminary SINR.
- 2) Maximum receive power association strategy: This policy is based on the calculation of the receive power. Each user is associated to the parent candidate for which it has the highest receive power.

The policies proposed in [4] and [5], do not take into account the network state in terms of capacity of the base stations, which can introduce an overload on stations and therefore packet losses while there are stations that have the capacity to support these packets. The successful exploitation of the network capacity requires taking into account the network state at the moment of cell selection.

In [6], authors propose several cell selection strategies. For the operation of the proposed strategies, the authors propose that the following information will be broadcast by the parent candidate nodes to assist UEs in the cell selection process:

- SNR Γ_{im} offered on the link between the parent candidate i and the user m , refers to the link quality.
- The number of hops between the parent candidate node i and the CN h_i , refers to the latency.
- The number of associated UEs to the parent candidate node i n_i , refers to the load.

Achievable Rate of Path (ARP) policies: Each UE m has a parent node BS i , it encounter a set P_i of radio links along its path to the CN. A radio link between a child node j (including the UE m) and its potential parent node k , the link normalized capacity is determined by $C_j = \log_2(1 + \Gamma_{kj})$. The calculating of the normalized capacity rate of each radio link along the path allows to the UE m to identify the achievable rate of the path R_i . The UE will associate with the station that offers him the best R_i :

$$i^* = \operatorname{argmax}_i R_i \quad (1)$$

Several ways for the calculation of R_i have been proposed:

- ARP using Minimum rate (AM) policy:

$$R_i = \frac{1}{1 + h_i} \min_{j \in P_i} \{C_j\} \quad (2)$$

- ARP using Harmonic mean of rates (AH) policy:

$$R_i = \frac{1}{1 + h_i} HM_{j \in P_i} \{C_j\} \quad (3)$$

- ARP using Scaled Minimum rate (ASM) policy (extension of the AM policy):

$$R_i = \frac{1}{1 + h_i} \min_{j \in P_i} \left\{ \frac{C_j}{n_k} \right\} \quad (4)$$

- ARP using Scaled Harmonic mean of rate (ASH) policy (extension of the AH policy):

$$R_i = \frac{1}{1 + h_i} \text{HM}_{j \in P_i} \left\{ \frac{C_j}{n_k} \right\} \quad (5)$$

In [6], the authors show that taking into account the network state information at the cell selection moment introduces a significant improvement on the network performances. However, the author's consideration of gNB load in terms of the number of associations has the potential to degrade the quality of the decision making. First, the number of associations does not reflect the real load of a parent candidate, i.e. two candidates with the same number of associations do not necessarily have the same load. Second, if the UE has two parent candidates, the first with a very good link capacity and a large number of associations (knowing that it still has the capacity to serve new user) and the second with a low link capacity but it is empty. In this case we can choose to associate with the second candidate, hence the policies ASH and ASM do not always guarantee the best quality of link when it is feasible. Third, there is no guarantee that the selected parent is not saturated.

III. LOAD-EFFICIENCY-BALANCE POLICY

Load-Efficiency-Balance (LEB) is our proposed cell selection policy for IAB networks. LEB aims to achieve a trade-off between spectral efficiency and load balancing in the IAB context defined in the 3GPP standards. This policy allows each new user joining an IAB network to determine its suitable parent by applying the algorithm summarized by the flow chart presented on Fig. 2.

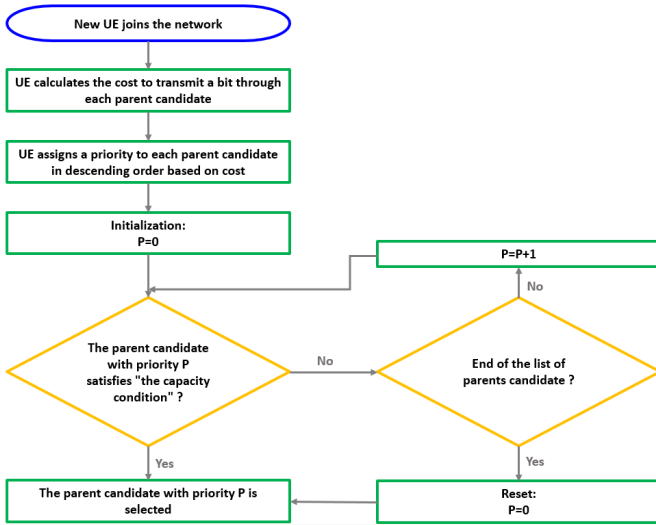


Fig. 2 – LEB algorithm flow chart

Using LEB, each new user joining the network will first calculate the cost of transmitting a bit through each parent

candidate i . This transmission cost is determined by the following formula (expressed in terms of resource block (RB)):

$$Cost_i = \sum_{j \in P_i} \frac{1}{W_{rb} \times SE_j} \quad (6)$$

where P_i refers to the set of radio links (access and backhaul links) along the path of the parent node i to the CN, W_{rb} is bandwidth of a RB (expressed in Hz/RB) and SE_j is the spectral efficiency of the link j (expressed in Bit/s/Hz) determined by Shannon capacity: $\log_2(1 + SNR)$.

SNR is a measure that compares the level of a desired signal to the level of background noise:

$$SNR = \frac{P_r}{N_0 \times W \times NF} \quad (7)$$

where P_r is the received signal power (expressed in W), W is the bandwidth (expressed in Hz), N_0 is the noise spectral density and NF is the receiver noise figure.

SINR is a measure of the signal quality: the strength of the wanted signal compared to the unwanted interference and noise.

$$SINR = \frac{P_r}{N_0 \times W \times NF + \sum_{j \in N} P_{rj}} \quad (8)$$

where N is the set of UEs share one or more resources with the current UE.

RX_{PWR} represent the received signal power (expressed in dBm) and can be expressed as (see in [7]-section 4.5):

$$RX_{PWR} = TX_{PWR} - \max(\text{pathloss} - G_{TX} - G_{RX}, MCL) \quad (9)$$

where TX_{PWR} is the transmitted signal power, G_{TX} is the transmitter antenna gain = $G_{ant} + A(\theta)$ where G_{ant} is the antenna gain and $A(\theta)$ is the antenna gain per sector defined in [7]-section 4.2, G_{RX} is the receiver antenna gain and MCL refers to the minimum coupling loss, which is the parameter describing the minimum loss in signal between BS and UE or between two UEs in the worst case. MCL is defined as the minimum distance loss including antenna gains measured between antenna connectors.

The "capacity condition" in the algorithm, consists in checking whether or not the parent candidate has the capacity to support a new UE m :

$$\forall j \in P_i, B_j(1 - BO_j) > \frac{R_m \times T_f}{T_s \times W_{rb} \times SE_j} \quad (10)$$

where B_j is the total number of resource blocks available in a 10-ms frame at the parent node of link j (expressed in RB), BO_j is the bandwidth occupancy rate i.e the ratio of allocated RBs to the total available RBs, R_m represents the desired rate that has to be transmitted for the user m (expressed in Bit/s), T_f is frame duration (expressed in s) and T_s is slot duration (expressed in s), considering the allocation of one RB per slot to the same UE. For the operation of the LEB policy, we propose a diffusion of information on the load from BSs to UEs, expressed by a value BO_j between 0 and 1. This value will limit the load on the BSs, by preventing overuse of the bandwidth.

IV. SYSTEM MODEL

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

A. Simulation scenario

As a test scenario, a heterogeneous scenario (dense urban) extension as shown in Fig. 3 proposed by 3GPP [2] is adopted. In our scenario an IAB donor is surrounded by 3 hexagonal sectors where each sector contains 3 IAB nodes. The IAB nodes have the IAB donor as a parent. The IAB donor is equipped with 3 antennas, one in each sector. Table I summarizes the main parameters used in this scenario. The

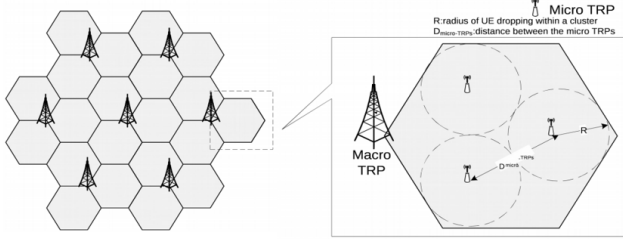


Fig. 3 – 3GPP heterogeneous scenario [8]

TABLE I
Scenario parameters

Number of macro BS	1
Number of micro BS	3/sector
Inter-Macro Distance	500
Min distance between Micro-UE [m]	10
Min distance between Macro-UE [m]	35
Min distance between Macro-Micro and Micros [m]	40
Number of UEs	Several values
Percentage of the number of UEs/sector	[50,20,30]
Position of UEs	Random
Message size [Mbit]	2
Frame size [ms]	10

simulation results discussed in the next section are obtained by 1000 independent runs, where each execution is running for 100 iterations to reduce interference's impact. Table II summarizes the main system level parameters derived from [2] [9] [10] [7]. To model the path loss, we used the Umi-NLOS model [9] on the direct and backhaul links and the Umi-NLOS model [10] on the access link.

B. Half-duplex implementation

In IAB networks, a base station cannot receive and transmit at the same time due to the half-duplex constraint, to avoid intra-site interference as direct, access and backhaul links share the same spectrum. In the standards there are several techniques to respect this constraint. In our simulations, we considered the Time-division multiplexing (TDM) technique that allows a strict time-domain separation between transmission and reception phases. With this technique, we will have two phases for the downlink and two phases for the uplink as shown in Fig. 4. To classify the macro-UE traffic between phases 1 and 2 we use SNR as criteria. The macro-UE communications with the best SNR are assigned to phase

2 in order to ensure that UEs far from micros are managed on phase 2 to minimize interference during this phase.

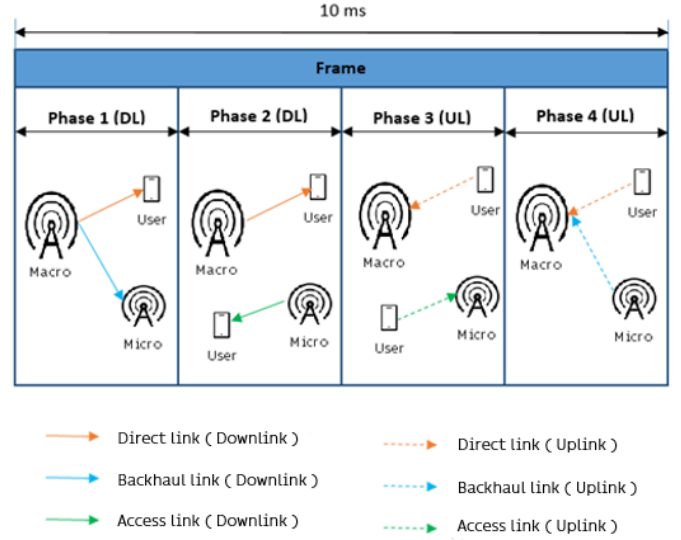


Fig. 4 – Downlink and uplink communication phases

V. SIMULATION RESULTS

To evaluate the performance of the proposed policy, we also implemented two policies from the literature presented in the section II: the HQF policy as a simple benchmark policy and the ASH policy since in [6] the authors showed that, among their proposed policies, ASH has the best performance. This section represents the main performance evaluation results of the comparison between the LEB and these two policies.

Fig. 5 shows the achievable rate as a function of the number of users, considering the packet losses due to interference and capacity. The results show that, at low loads below 160 users, there is a slight difference between the three policies in terms of the achievable rate due to the impact of interference. This impact increases as the number of users grows. Past 160 users, the LEB policy outperforms the HQF and ASH and achieves the best system rate. LEB is more resistant to packet loss due to capacity. This is due to the fact that with LEB, the user chooses the best parent candidate only if the "capacity condition" is validated, if not, another worse parent is chosen instead of losing the packets. Unlike with HQF and ASH, where only the best parent calculated by the policy is directly chosen. Therefore, they assign users to congested cells at high load, which does not allow to take advantage of the residual capacities of the surrounding cells.

Fig. 6a indicates the necessary consumption of resource block to reach the total transmission of data that the system aims to transmit as a function of the number of users. Fig. 6b is a zoomed-in view of the hatched sections in Fig. 6a. The results show that, LEB offers always the best resource consumption. LEB consumes less resources than HQF, because HQF ignores the backhauling cost, unlike LEB. At the same time, less than ASH because ASH takes into account the number of associations of the stations at the decision time as a load. So it

TABLE II
Simulation parameters

Parameters	Direct link	Access link	Backhaul link
Path loss model	Uma-NLOS	Umi-Non-line-of-sight (NLOS)	Uma-NLOS
Emission power (P_{tx}) [dBm]	44	33	44
Frequency (f) [MHz]	2600	2600	2600
Bandwidth (B) [MHz]	100	100	100
Height of BS1 (h_{BS1}) [m]	25	10	25
Height of BS2 (h_{BS2}) [m]	-	-	10
Height of UE (h_{UE}) [m]	1.5	1.5	-
Transmitter antenna gain (G_{ant}) [dBi]	15	8	15
Receiver antenna gain (G_{RX}) [dBi]	-	-	8

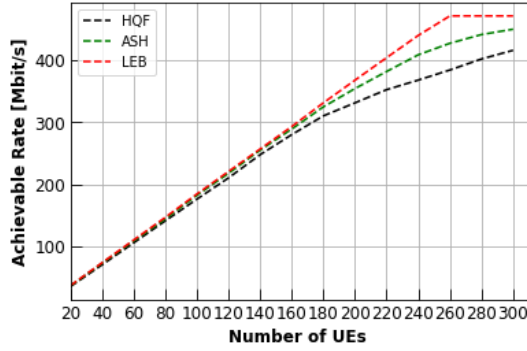
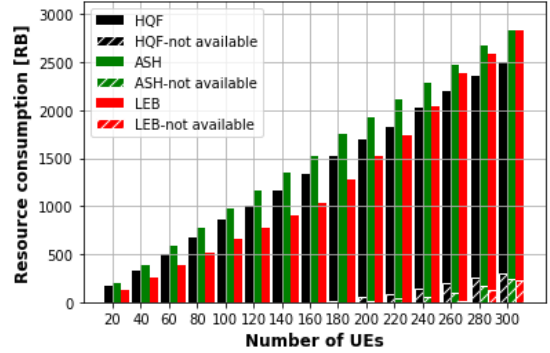


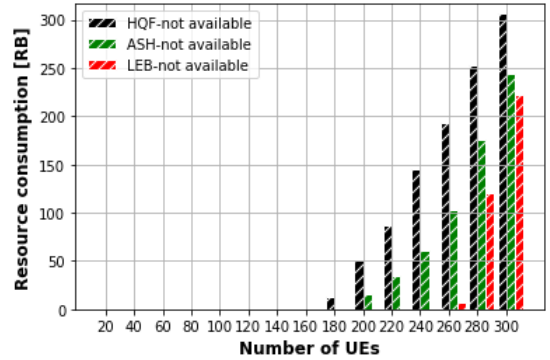
Fig. 5 – Achievable Rate as a function of number of users

possible to avoid, in certain cases, to choose the parent, which offers the best cost if it has many associations even if it still has the capacity to serve a new user. At the same time, LEB allows, as needed, choosing the parent who offers the lowest cost in terms of consumed resources. At a heavy load, above 220 users, LEB starts to consume resources greater or equal than HQF and ASH among the available resources. On the other hand, it needs less additional resources than HQF and ASH. Indeed, after 220 users, some cells are full and LEB makes users assignments to second choice with lower spectral efficiency but with available resources.

Fig. 7a and Fig. 7b present the number of associations of users to parents (macro or micro node) and the total cost of bit transmission given by (6) (on the direct link for a macro parent and on the access plus backhaul links for a micro parent) with these associations as a function of the distance between parent and user, respectively. The results show that, at 160 users, when all three policies provide the same total number of associations (no packet loss due to capacity) LEB always chooses the associations with the lowest cost compared to HQF and ASH, even if it means longer distance in some cases. For example, by choosing to associate with the macro, which is a bit far rather than with the micro, since the cost of the direct link is lower than the cost of the access link plus the cost of the backhaul link. HQF chooses the micro, which is closer and thus offers a better SNR without taking into account the cost of the backhaul. ASH chooses the micro,



(a) Total required resources

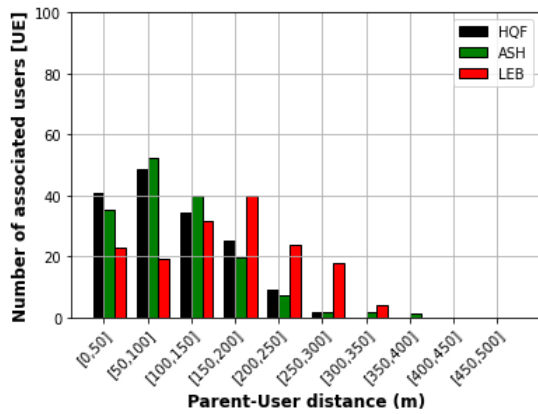


(b) Missing resources

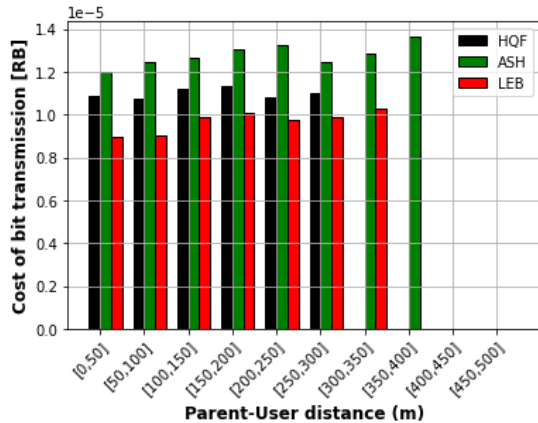
Fig. 6 – RBs consumption as a function of number of users

which is closer and less loaded than the macro.

Fig. 8a and Fig. 8b illustrate the percentage of requested macro resources during phases 1 and 2 as a function of sector number at 280 users (when the system is losing data due to capacity with all policies), respectively. The results show that, first, LEB requires much more resources for downlink communications on the direct link between phases 1 and 2 than HQF and ASH. This means that LEB did more direct associations with the macro than HQF and ASH. In some cases for example, due to the backhauling cost, the cost of associating with the macro, that is a bit further away and more loaded than micros is lower than the cost of associating with a empty micro, that is closer and offers a better link



(a) Number of association



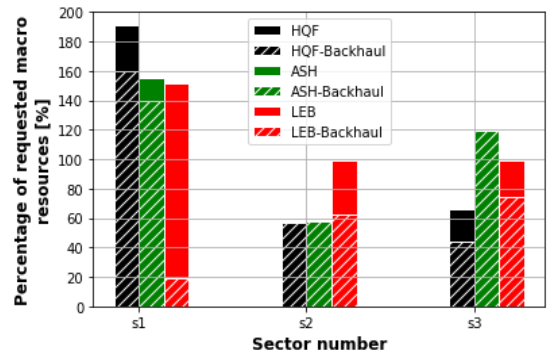
(b) Cost of bit transmission

Fig. 7 – The functioning of policies at 160 users

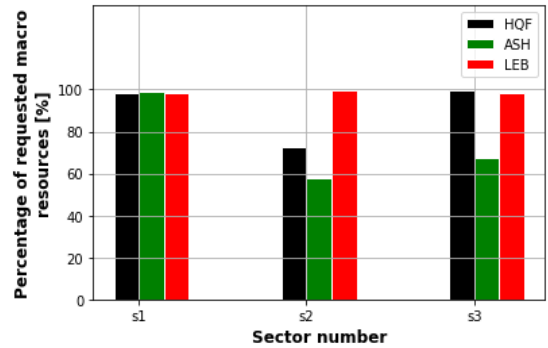
quality. Second, the results show that with LEB the macro is almost saturated on the 3 sectors. When with HQF and ASH, there are still resources available on sectors 2 and 3 (in our scenario sectors 2 and 3 are less loaded than sector 1 see table I). With LEB on sector 1 the most loaded when the macro is saturated, the rest of the users of this sector choose to associate with micros on sectors 2 and 3 as long as the macro has free resources for the backhaul on sectors 2 and 3 unlike HQF and ASH.

VI. CONCLUSION

In this work, a new cell selection strategy, LEB, for IAB networks was proposed. LEB aims to guarantee the lowest possible total transmission cost (including the backhaul cost, which is a significant factor in an IAB context) while respecting the base stations capacities. In order to validate the performance of LEB, a comparative study with two state-of-the-art policies using different metrics was performed. The results show that, on the one hand, LEB guarantees the best total transmission cost in terms of consumed resources. On the other hand, at high network load, it offers the best system capacity in terms of served users thanks to a good management of the resource usage. To conclude, LEB ensures a trade-off between spectral efficiency and load balancing, which gives the advantage over other policies to achieve our main goal,



(a) phase 1



(b) phase 2

Fig. 8 – Percentage of requested macro resources as a function of sector number at 280 users

boosting IAB network capacity. As a continuation of this work, we envisage enhancing LEB by optimizing its load balancing feature and, possibly, by managing energy at low load.

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