Cooperative spectrum sharing in 5G access and backhaul networks

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Abstract—Stringent demands for a continuous evolution of cellular networks push today academic and industrial researchers to re-think backhaul solutions for 5G. In one hand, wireless backhaul solutions are cost effective and easy to deploy but suffer from limited capacity. On the other hand, wired solutions have the potential to meet bandwidth requirements but usually involve higher costs. Thus, adoption of heterogeneous technologies will be necessary. Moreover, in 5G, access and backhaul networks will work closely, and therefore, total separation of their resources may not be possible anymore; rather, cooperation between the two portions of the cellular network is desirable. Subsequently, cooperative access-backhaul mechanisms become necessary to ensure the best use of the scarce resources, i.e. bandwidth. Hence, in this paper we present the idea of spectrum sharing among different links from a cooperative access-backhaul mechanism point of view. We present simulation results for different approaches of such sharing from a common spectrum pool. The results show that traffic-aware approaches show increased fairness thus re-inforcing the idea of cooperative access-backhaul mechanisms as essential strategies in current and future networks.

I. INTRODUCTION

Mobile data traffic is experiencing multi-fold growth with the increasing popularity of mobile devices (e.g. smartphones, tablets). Thus, future mobile networks are expected to carry large traffic while ensuring ubiquitous coverage. It is also anticipated that a large portion of the future data traffic will be due to data-rich Internet content (e.g. video related services), which demands higher capacity and very low latency. According to [1], 5G should support peak data rates up to 10Gbps in some scenarios and, for latency-critical applications, the end-to-end latency has to be as low as 1ms. Moreover, according to the International Mobile Telecommunications for 2020 (IMT-2020) [2], support for connection density up to $10^6/km^2$ is expected. With this in mind, 5G is aiming to provide ubiquitous, high speed, low latency mobile broadband coverage, where any device can benefit from being connected.

To support the anticipated traffic, enhancement of the system capacity is required and, therefore, future mobile networks are expected to employ different small cell (SC) paradigms connecting very large amount of devices requiring high data rates. Moreover, low power Internet of Things (IoT) devices are getting popular with its positive impact on our daily life, yet increasing the device density. To support the aforementioned Ultra Dense Network (UDN), a s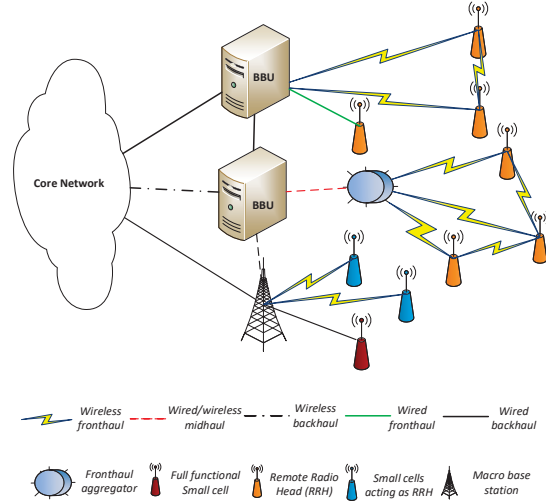uitable backhaul solution is necessary to make the best use of scarce resources. As discussed throughout the paper, no single backhaul technology can meet the requirements of such UDN. Therefore, 5G will be deployed employing heterogeneous backhaul networks, facilitating both wired and wireless solutions. From the architectural point of view, the complex 5G transport network can be decomposed into backhaul, midhaul and fronthaul.

Traditionally, the links connecting Base Stations (BS)/evolved-NodeB (eNB) to the Core Network (CN) and inter-connecting BSs/eNBs are referred to as backhaul (BH). On the other hand, in Centralized Radio Access Network (CRAN), all the processing is centralized in Baseband Units (BBU), and Access Points (AP) are defined as Remote Radio Heads (RRH) performing only radio functionalities. The links connecting BBUs to CN are referred to as BH, whereas, the links connecting RRHs to BBUs and inter-connecting different RRHs are considered fronthaul (FH). Additionally, connecting links between eNB and the SCs acting as RRH, with eNB assuming few functionalities of the SCs centralized into a co-located processing unit with eNB, can also be considered as FH. According to [3], the links between an aggregated fronthaul point (where few nearby FH links are merged

Fig. 1. Heterogeneous backhaul in 5G networks.

together benefiting from multiplexing gain) and BBUs are called midhaul (Figure 1). Additionally, data compression techniques can be adopted in the fronthaul aggregator to relax the requirements for the subsequent transport network. Note that the term backhaul is used hereafter to refer to the entire transport network (including fronthaul and midhaul) although, in few cases, they are also used separately when required.

To meet the expected Quality of Service (QoS), several wired and wireless technologies are being considered as potential backhaul solutions for 5G. Among wired solutions, optical fibre utilizing different access technologies, such as Gigabit Passive Optical Network (GPON), Ethernet PON (EPON), Point-to-Point (PtP), Point-to-multipoint (PtmP), Next Generation PON (NGPON), NGPON2, Wavelength Division Multiplexing (WDM) PON, provides the highest capacity and very low latency. However, wired options lack scalability and are costly for new deployments.

On the other hand, wireless backhaul options are less costly and their deployment is faster and easier. However, they are very vulnerable to environmental effects and often lack from capacity. An attractive option for future wireless backhaul is mmWave, that operates in three different bands, 60GHz (V-band), 70/80GHz and 90GHz (E-band), offering data rates up to 10Gbps [3] [4]. Additionally, European Telecommunication Standards Institution (ETSI) recently started to work into D-band (141-174.8 GHz) for higher capacity. Advanced technologies, such as spatial multiplexing and beamforming can be used to improve the overall performance of mmWave.

From the previous discussion, it is clear that the transport network depicted in Figure 1 will be a dominant element of 5G networks, which needs to be cost and resource-efficient. Acknowledging this condition, cooperative access-backhaul mechanisms ensure the efficient use of precious resources, where both networks are dependent on each other's requirements and constraints. Moreover, cooperative access-backhaul mechanisms have the potential to minimize network Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) [5]. Therefore, in this paper, we first provide a discussion on the benefits of cooperative access-backhaul resource management and present cooperative spectrum sharing as one promising cooperative access-backhaul mechanism. Subsequently, we discuss the related works of cooperative spectrum sharing, where access and backahul network share the same spectrum. Finally, we evaluate different spectrum sharing approaches through simulation. This article is concluded identifying respective benefits and future challenges.

II. RELATED WORK

With the multiple use cases (e.g. coverage expansion, indoor coverage, SC deployed on lamp posts, roof-top, walls mounted to buildings, etc.) that the 5G APs will serve, despite of the benefits of wired solutions, a purely wired backhaul network will be intractable. Thus, it is anticipated that wireless-based BH solutions will be dominant in future networks. Thus, in UDN, a large amount of base stations and wireless backhaul links will likely have to compete for a limited frequency spectrum. In this scenario, to ensure the best use of the limited backhaul resources, it is foreseen that access and backhaul networks become dependent on each other, pushing towards their cooperative design and management. For example, in future UDN, considering a scenario where the User Equipment (UE) receives service from several APs, a large collection of parameters characterizing both access and backhaul (i.e. state of access and backhaul portions of the network) should be considered to ensure the best possible Quality of Experience (QoE), thus encouraging its cooperative operation. Additionally, in 5G, access and backhaul cannot be seen as separate entities since they may employ same basic wireless technology and operate using a common spectrum pool [1]. Hence, solo optimization should be abandoned in favor of cooperative operation.

Different approaches to perform such cooperative operation are mentioned in [5], however, in this work we focus on cooperative **spectrum sharing**, where a spectrum pool is shared by both networks to use the available resources in an efficient way. There are some popular techniques to perform such sharing. In-band full duplex (IBFD) [6] is a technique whereby SCs can work in full duplex (FD) mode, backhauling themselves wirelessly with the anchor eNB and communicating simultaneously over access and backhaul using the same frequency band. In reference [6], employing FD mode, the entire available bandwidth is used simultaneously by both eNB and SCs, and later the bandwidth is proportionally divided to be used for uplink (UL) and downlink (DL) communication at both eNB and SCs. Subsequently, the bandwidth dedicated for eNB UL/DL transmissions is further divided for backhaul and access communications. On the other hand, in half duplex (HD) mode, Frequency Division Duplexing (FDD) is used to proportionally divide the entire bandwidth among eNB and SCs. Similar to the previous technique, allocated bandwidth, is further divided for UL and DL communication , and bandwidth for eNB UL/DL is further splitted for backhaul and access communications. Authors illustrate that, despite the higher interference in the network, IBFD capability improves the average achievable rate by a factor close to double, however the coverage is limited to half of the obtained through FDD approach. In IBFD mode, additional interference is experienced by the BH links, named as self-interference (SI), which occurs due to the leakage of transmitted signal to the receiver channel at SCs. SI cancellation technique is proposed for such interference-limited scenario in [7] [8]. In reference [9], authors consider a two-tier network, i.e. macro cell (MC)/eNB tier and SCs tier, and partition the resources employing active and silent modes. During the silent periods, MC/eNB shuts down the transmission, and thus, SCs serve UEs associated to them. However, in this work, the main focus has been to perform offloading from MC to SCs given that without proactive

offloading, the gain from SCs deployments is very limited [9].

Two more approaches are mentioned in [9] for resource partitioning in such multi-tier networks. A straightforward approach consists in a process to search all possible UE-AP associations and allocate the time/frequency resources accordingly, which is very inefficient and computationally daunting. Another approach is the probabilistic analytical approach, where the partitioning and configuration is performed on an assumption following a certain distribution. Additionally, according to [10], by performing disjoint spectrum partitioning, the cross-tier interference can be avoided, however appropriate partitioning mechanism remains an open issue.

In [11], authors consider an heterogeneous network, where SCs are connected to a Wireless Backhaul Hub (WBH). The available spectrum is composed of frequency channels for both access and backhaul links of the SCs. Accordingly, the SC rate, defined as the minimum among backhaul and access link rate, is mostly governed by the backhaul rate. With a small number of backhaul frequency channels, access networks having more channels cause low interference and obtain high rate availability at the access links. However, the high rate in the access links may not be supported by the small number of backhaul channels, acting as the bottleneck. On the other hand, with a large number of backhaul channels, access networks get less number of channels resulting into higher interference and lower rate at the access links. Subsequently, high proportion of the backhaul channels are wasted, as low rate in the access network does not require from many channels in the backhaul links. Thus, optimal partitioning is required.

To perform the optimal partitioning of spectrum, reference [8] proposes and compares the performance of three different approaches: Out of Band Full Duplex (OBFD), IBFD and the hybrid mode. Employing OBFD, access and backhaul transmissions use orthogonal spectrum bands, i.e. the dedicated spectrum for each SC is further partitioned orthogonally to be used by access and backhaul links. On the other hand, in IBFD, the same spectrum is used by access and backhaul links in full duplex mode. Finally, the hybrid approach provides a flexible allocation scheme, where SC can operate completely in OBFD or IBFD mode. In this scheme, the spectrum allocated to each SC is partitioned optimally into three portions, i.e. one portion for IBFD mode, one portion for OBFD backhaul transmissions and one portion for OBFD access transmissions.

III. ACCESS-AWARE COOPERATIVE SPECTRUM SHARING

The related works discussed in Section II propose spectrum partitioning either in a two-tier network, i.e. among MCs and SCs, or between access and backhaul links of SCs. Considering the later, few works suggest that resources to build the backhaul links can be partitioned either from the ones dedicated for SCs or from the corresponding to MCs. Focusing towards 5G dense networks, we consider
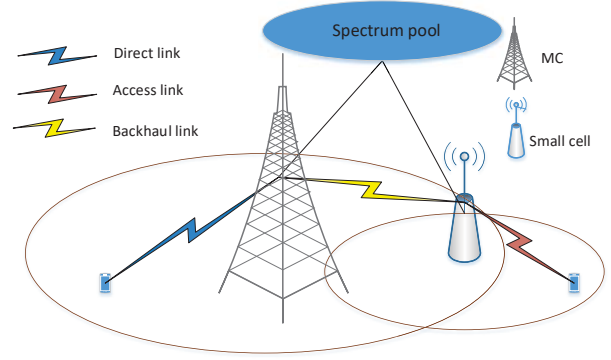

Fig. 2. Considered three DL links under a common spectrum pool in a two-tier network.

three types of DL links: (i) **Direct link**, the link connecting UE to MC, (ii) **Access link**, the link connecting UE to SC, (iii) **BH link**, the link connecting SC to anchoring MC. This scenario requires flexible partitioning from a common spectrum pool, as shown in Figure 2. Reference [12] also considers three types of link to share spectrum, but employing HD-capable SCs, i.e. SCs can either transmit data to its UEs or receive data from corresponding anchor MC in a given time-frequency resource. That approach does not allow the full utilization of resources; rather, FD operation is preferred, although it might require intelligent techniques to take care of SI in the network. Hence, we consider both MC and SC are FD-enabled. Subsequently, we evaluate different spectrum partitioning approaches among the aforementioned three different DL links, where five possible scenarios, depicted in Figure 3, are identified according to the state-of-the-art. Note that, in the following, we use α as the proportion of the bandwidth dedicated for direct links, β for the BH links, and γ for the access links.

Spectrum Sharing Approach-1 (SSA-1): Each AP (MC and SCs) in the network can access the full bandwidth from the spectrum pool. MC treats the BH links in the same way as UE links [12], and allocates the bandwidth accordingly. Thus, total bandwidth allocated for MC is distributed among BH links and direct links.

Spectrum Sharing Approach-2 (SSA-2): In this approach, all the links, i.e. direct links, BH links and access links, operate in an out-of-band fashion. Thus, 50% (assuming a typical deployment, where α is equal to 0.5) of the total bandwidth is used for direct links, and 50% is for SC networks. As this is a fully out-of-band approach, the dedicated bandwidth for SC network is further equally shared among the access links and BH links without spectrum reuse. Thus, $\alpha = 0.5$, $\beta = 0.5/(\text{Number of SC (NSC)*2})$ and $\gamma = 0.5/(\text{NSC*2})$. A great benefit of this approach is that there are no interferences in the network.

Spectrum Sharing Approach-3 (SSA-3): We consider that 50% of the bandwidth is dedicated for direct links, and that each SC reuses the 50% of the bandwidth dedicated to SCs. Thus, all SCs' access networks are in-band, hence interfering
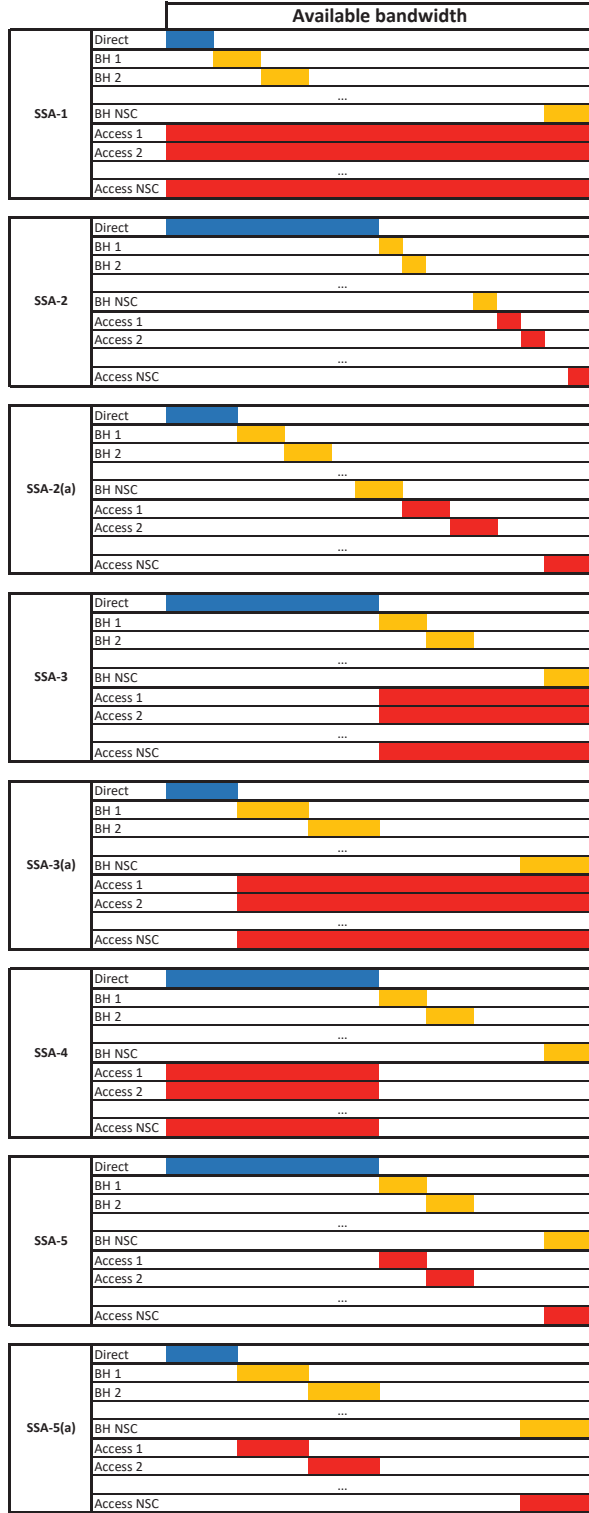
Fig. 3. Set of Spectrum Sharing Approaches considered.

to each other. The same 50% of the bandwidth is also used in the BH links, yet managed by the MC and hence shared in a 50%/NSC fashion. Thus, $\alpha = 0.5$, $\beta = 0.5$/NSC and γ = 0.5. In SSA-3, spectrum re-use allows higher bandwidth in SC's access links than in SSA-2. On the other hand, in this approach, access links interfere to each-other, and additionally, self-interference also affects the BH links.

Spectrum Sharing Approach-4 (SSA-4): Here, 50% of the total bandwidth is dedicated to BH network, and the remaining 50% is re-used by all APs, (i.e. MC's direct links and SCs' access links). Hence, BH network is totally out-of-band and does not experience any interference. On the other hand, all access networks (i.e. direct links and access links) are in-band, and thus, interfere to each other. Using this approach, we have, $\alpha = 0.5$, $\beta = 0.5$/NSC and $\gamma = 0.5$, being the values of α, β and γ values the same as in SSA-3, but showing a different interference scenario.

Spectrum Sharing Approach-5 (SSA-5): Similar to SSA-3, 50% of the total bandwidth is dedicated for SCs' network and remaining 50% is dedicated for direct links. However, unlike SSA-3, in SSA-5 all the SCs are out-of-band. Hence, dedicated 50% of the spectrum is distributed among the SCs, and each SC re-uses the same spectrum in both BH link and access link. In this approach, access links of different SCs do not interfere to each other, but, for each SC, corresponding BH link interferes with access link. BH links also experience SI. Thus, the distribution is $\alpha = 0.5$, $\beta = 0.5$/NSC and $\gamma = 0.5$/NSC.

IV. EVALUATION AND RESULTS

To evaluate different spectrum sharing approaches, we consider a dense urban scenario wherein a two-tier 5G network is deployed; one MC and several SCs cover the area (e.g. Figure 2). In such network, a spectrum pool is managed and controlled by the central controller, which distributes the frequency resources among the potential links. The simulation assumptions summarized in Table I follow the use cases defined in [13] and the 5G deployment scenarios as predicted by METIS-II project [14].

As discussed in Section II, resources are scarce, and thus, more efficient and fair distribution is required thereof. According to METIS-II recommendation for system level simulation, MC will serve 10 UEs, there will be 8 SCs per MC and each SC will serve 5 UEs (cf. Table I). Taking this into account, SCs will carry 80% of the UE traffic, whereas MC (direct link) will serve around 20%. With this in mind, we propose three additional SSAs.

Spectrum Sharing Approach-2(a) (SSA-2(a)): This is an access-aware version of SSA-2, where MC gets 20% of the bandwidth and SCs' network 80%, according to aforementioned traffic requirements. Thus, $\alpha = 0.2$, $\beta = 0.8$/(NSC*2) and $\gamma = 0.8$/(NSC*2).

Spectrum Sharing Approach-3(a) (SSA-3(a)): This approach consists in an access-aware version of SSA-3, following the same idea as for SSA-2(a). Thus, $\alpha = 0.2$, $\beta = 0.8$/NSC and $\gamma = 0.8$.

TABLE I
SIMULATION ASSUMPTIONS

Parameters	Value
Carrier Bandwidth (B)	100 MHz
Carrier frequency	3.5 GHz
Number of SCs	8 per MC
MC coverage radius	150m
SC coverage radius	15m
Minimum distance between MC and SC	20m
Minimum distance between adjacent SCs	15m
MC transmit power	49dBm in 20 MHz band
SC transmit power	30 dBm in 20 MHz band
Thermal noise level	-174 dBm/Hz
MC and SC noise figure	9 dB in 20 MHz band
Antenna gain	MC: 17 dBi; SC: 5dBi
Antenna height	MC: 25m; SC: 10m; UE; 1.5m
Channel model	3D model from [13]
Number of UEs	10 per MC; 5 per SC
SI cancellation factor (C_{SI})	100 dB [7]
Propagation type	BH link: LoS; Direct links: NLoS; Access links: LoS; Interferer links: NLoS
Number of simulations	1000 simulations, each with a random deployment of UEs and SCs

Fig. 4. BH link throughput vs C_{SI} value.

Spectrum Sharing Approach-5(a) (SSA-5(a)): Similar to SSA-2(a) and SSA-3(a), SSA-5(a) provides an access-aware version of SSA-5. Hence, α = 0.2, β = 0.8/NSC and γ = 0.8/NSC.

The aforementioned eight SSAs are illustrated in Figure 3. We performed a large number of random simulations using Matlab tool for the eight different approaches presented, and according to the simulation assumptions exposed in Table -I. The achievable throughput for each link has been computed utilizing the Shannon - Hartley theorem (Eq. 1), where C is the channel capacity in bps, B corresponds to the channel bandwidth in Hz, and S is the received signal power in W. For in-band backhaul solutions, SI power (R_{SI}) in W has been considered in addition to the sum of co-channel interference power (I), and the sum of thermal noise and noise figure at the receiver (N) in W (Eq. 2). R_{SI} depends on C_{SI} value as R_{SI} = P_{SC}/C_{SI} [8], where P_{SC} corresponds to SC transmitted power.

$$C = B * \log_2(1 + \frac{S}{N+I})bits/s \qquad (1)$$

$$C = B * \log_2(1 + \frac{S}{N+I+R_{SI}})bits/s \qquad (2)$$

Firstly, we show the impact of C_{SI} values on BH link throughput (Figure 4). As illustrated, SSA-2, SSA-2(a) and SSA-4 do not experience any dependency on C_{SI} value as these approaches use different band for BH and access links, thus not experiencing any SI.

On the other hand, for in-band approaches, the maximum achievable throughput improves with the increment of C_{SI}
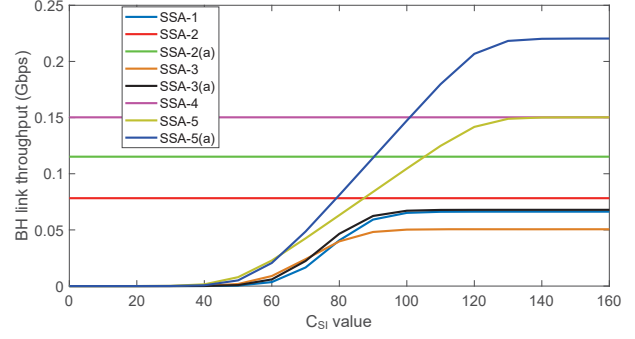
value. Obviously, with low C_{SI} values, in-band approaches perform worse than out-of-band solutions, even using a higher bandwidth share for BH links. Additionally, after certain C_{SI} values (between 80 and 120 dB), BH link achieve its maximum capacity. As suggested in [7], a value of C_{SI} = 100 dB is used hereinafter in those BH links experiencing SI.

Figure 5(A) provides average BH and access link capacity for the different SSAs. Maximum achievable capacity for SC's UE consist in the minimum value between access and BH link throughput. From the figure, it can be observed that, BH links are acting as the bottleneck in most of the cases (BH link throughput is lower than access link throughput). On the other hand, for SSA-5 and SSA-5(a), BH link achieves higher average throughput in comparison to access link, due to the higher power received from the MC in BH interfering links (access links and BH links are in-band). Figure 5(B) illustrates maximum achievable throughput per UE for both MC and SC (note that, for SC UE, value corresponds to the minimum between BH and access link divided by the number of UEs per cell). Boxplot for 1000 simulations in Figure 5(C) depicts the system spectral efficiency (SE), which corresponds to the ratio between aggregated UE throughput in bps and total bandwidth in Hz. Boxplot (1000 simulations) in Figure 5(D) represents *Jain's fairness index* calculated utilizing Eq. 3, where n is the number of UEs and X_i consist in the individual throughput of each UE [15]. In the presented boxes, the lower bound and the upper bound of the boxes represent 25th and 75th percentile of the data, and the line inside each box represents the median of 1000 simulations. The whiskers are extended to the maximum and minimum values inside the simulation tests.

$$F_j(w) = \frac{(\sum_{n=i}^{n} X_i)^2}{n * \sum_{n=i}^{n} X_i^2} \qquad (3)$$

Evidently, proposed SSA-2(a), SSA-3(a) and SSA-5(a) show higher fairness than corresponding legacy approaches
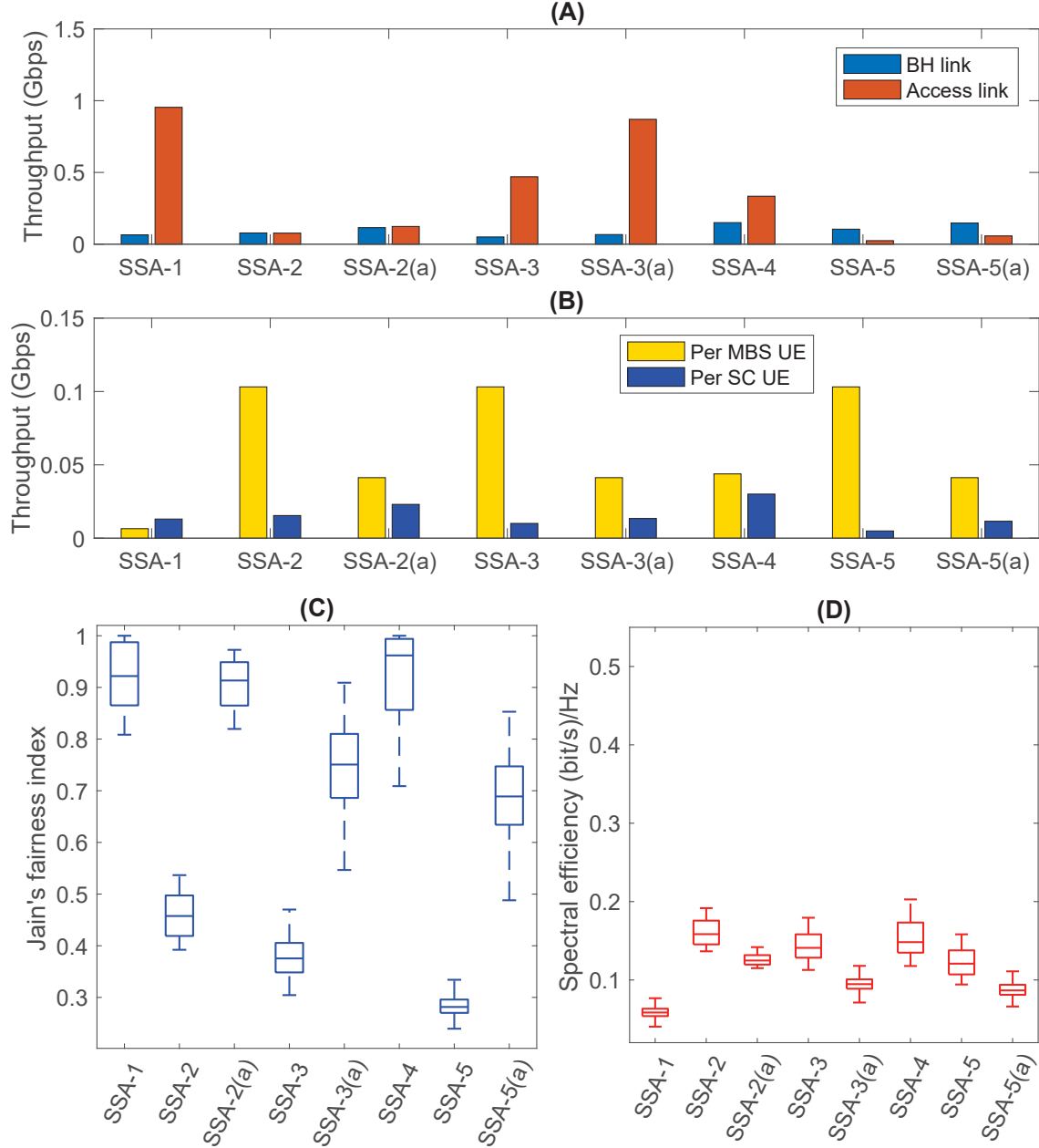
Fig. 5. Performance evaluation of different SSAs: A) BH and access link achievable throughput; B) Per UE throughput of MC and SC; C) Jain's Fairness index; D) Spectral efficiency.

(SSA-2, SSA-3 and SSA-5, respectively). Although, in some cases, the whiskers show a larger window for the access-aware approaches, they always provide higher values, thus being fairer than their legacy counterparts. Allocating more resources into the SC networks, which suffer from bottleneck in the BH link, allows more room for improvement, and thus, additional variability in the fairness enhancement is observed. On the other hand, SE in the fairest approaches is slightly lower. This is due to the fact that direct link gets less portion of bandwidth, whereas the larger bandwidth assigned to SCs is shared among eight BH links, and thus, the

throughput increment in each SC's UE, does not compensate the loss of capacity experienced in direct link UEs.

As already discussed, BH links become the bottleneck in most of the cases and thus, maximum throughput for SC's UE is limited, although higher throughput is achievable in the access link. To tackle this problem, we study the effect of Multiple Input Multiple Output (MIMO) in the BH network. Eight transmitter antennas and eight receiver antennas (8 x 8 MIMO) is considered to perform the MIMO operation. We use capacity computation from [16] (Eq. 4) to calculate the MIMO capacity in the BH links:
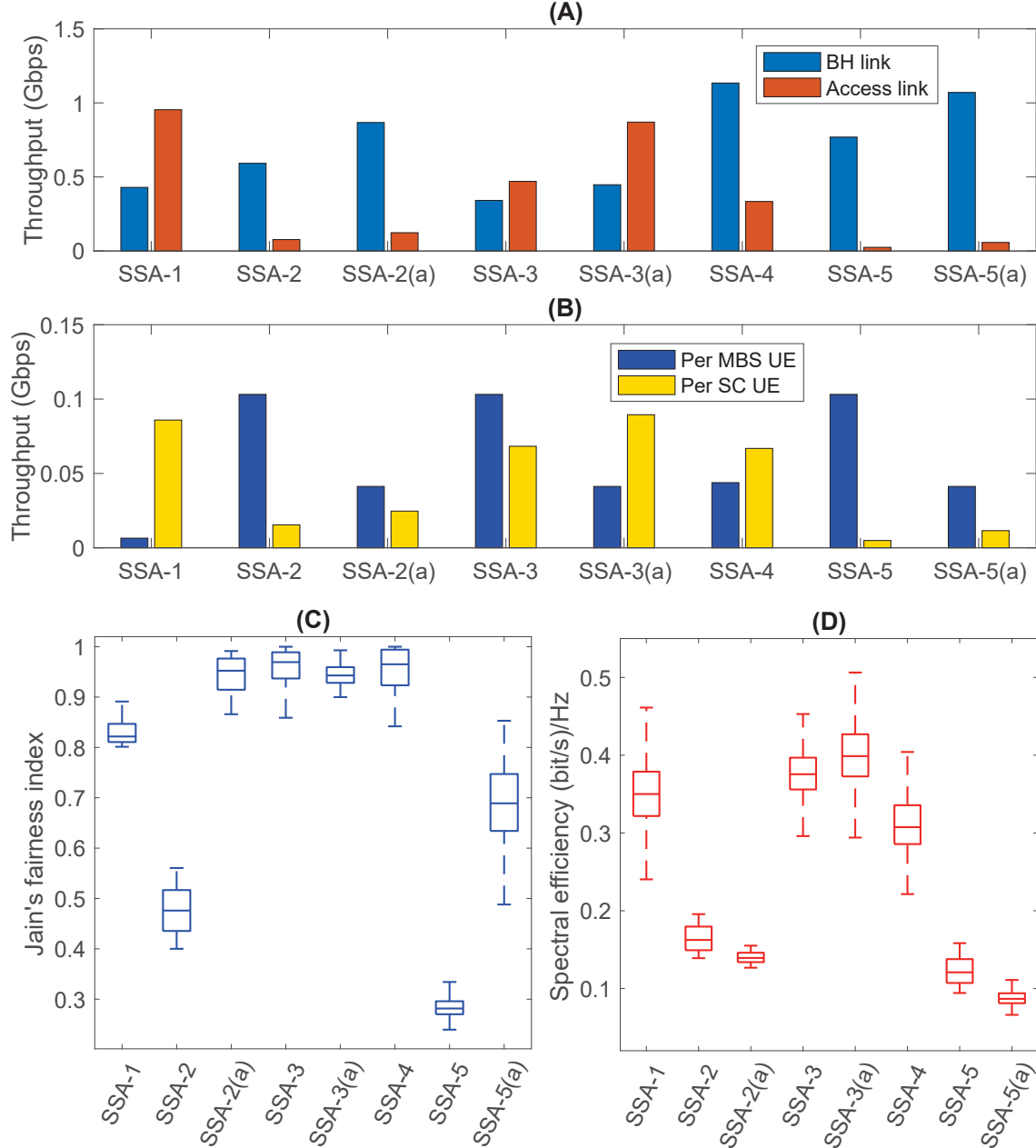
Fig. 6. Performance evaluation of different SSAs with MIMO enabled in BH link: A) BH and access link achievable throughput; B) Per UE throughput of MC and SC; C) Jain's Fairness index; D) Spectral efficiency.

$$C = B * \log_2 \det(\mathbf{I} + (\frac{SINR}{n}) * \mathbf{H}.\mathbf{H^+}) bits/sec \quad (4)$$

where n is the number of transmitter/receiver antennas, $\mathbf{I}$ corresponds to the $n \times n$ identity matrix, $\mathbf{H}$[1] is the normalized channel matrix, which is frequency independent over the signal bandwidth, and $\mathbf{H^+}$ is the transpose conjugate of $\mathbf{H}$.

Figure 6 (A, B, C, D) represents the corresponding results with MIMO enabled in BH links, which shows that

[1] For the sake of simplicity, we build $\mathbf{H}$ is as an $n \times n$ random matrix following a complex normal distribution.

MIMO technology can be efficiently used to overcome the bottleneck situation in BH links. Unlike Figure 5(A), Figure 6(A) shows that, with MIMO enabled, the bottleneck has been moved towards the access link in most of the cases. As mentioned earlier, for approaches SSA-5 and SSA-5(a), BH is not the bottleneck, even without MIMO enabled (Figure 5(A)) and hence, enabling MIMO in the BH link does not have any impact on the presented results for these two approaches. This is due to the fact that, for these approaches, access link of SC limits the achievable data rate, and thus, requires MIMO operation in the access link to improve

performance.

Note that when the capacity of the BH links is larger than the capacity of the access links, part of the resources granted to the BH will be wasted. Therefore, it makes sense to share BH resources with access links to increase efficiency (cf. SSA-3 and SSA-3(a)). When BH is the bottleneck, the highest efficiency is obtained when BH is isolated (SSA-4). However, when BH is not the bottleneck (e.g. because of MIMO), reuse in the SCs (i.e. SSA-3(a)) outperforms other approaches.

With MIMO enabled in the BH links, we present preliminary results, which can be further exploited considering other potential benefits of MIMO, such as interference mitigation. Additionally, MIMO can be also useful in the access link in order to increase corresponding capacity. However, if perfect balance between BH and access links is not achieved, resources can be wasted in either link, as throughput experienced by SC's UE is always limited by the minimum value between BH and access link capacity. And thus, to achieve the perfect balance, intelligent cooperative optimization of access and BH is essential.

V. CONCLUSION

This article discusses the requirements, heterogeneity and complexity of future 5G wireless-based BH networks, which will be very challenging to design. Cooperative access-backhaul mechanism, a key enabler of 5G, comes up with alluring solutions, which makes the future networks more feasible, flexible, resource and cost efficient. Discussed results puts additional weight to the aforementioned statement. Moreover, cooperative access-backhaul design and optimization allow to relax BH requirements and validates the idea of offering an on-demand BH service.

There are some additional lessons learnt from the presented results. Firstly, the value of C_{SI} has a great impact on the performances of in-band solutions. Thus, to benefit from the idea of in-band allocation of spectrum, self-interference has to be taken carefully into account. Secondly, access-aware spectrum allocation of SCs and MBSs provides a fair distribution of resources among different UEs at the cost, in some cases, of reducing spectral efficiency. Finally, depending on the location of the bottleneck (access or BH), different spectrum sharing strategies should be chosen.

In this way, the possibility that both BH and access networks share spectrum resources, brings the need of cooperative spectrum sharing. We believe, the characterization and understanding of different spectrum sharing alternatives provided in this article are useful for the development of optimization algorithms that will make the most of those scarce resources.

REFERENCES

[1] Ericsson, "5G Radio Access What is 5G ?" *White Pap.*, no. February, p. 10, 2015. [Online]. Available: http://www.ericsson.com/res/docs/whitepapers/wp-5g.pdf

[2] ITU, "IMT Vision Framework and overall objectives of the future development of IMT for 2020 and beyond, M Series, Recommendation ITU-R M.2083-0," vol. 0, p. 21, 2015. [Online]. Available: https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf

[3] M. Jaber, M. A. Imran, R. Tafazolli, and A. Tukmanov, "5G Backhaul Challenges and Emerging Research Directions: A Survey," *IEEE Access*, vol. 4, pp. 1743–1766, 2016.

[4] J. Bartelt, G. Fettweis, D. Wübben, M. Boldi, and B. Melis, "Heterogeneous backhaul for cloud-Based mobile networks," *IEEE VTC*, 2013.

[5] R. I. Rony, A. Jain, E. Lopez, E. Garcia, and I. Demirkol, "Joint Access-Backhaul Perspective on Mobility Management in 5G Networks," *IEEE CSCN 2017*.

[6] A. Sharma, R. K. Ganti, and J. K. Milleth, "Joint backhaul-access analysis of full duplex self-backhauling heterogeneous networks," *IEEE TWC*, vol. 16, no. 3, pp. 1727–1740, March 2017.

[7] R. A. Pitaval, O. Tirkkonen, R. Wichman, K. Pajukoski, E. Lähetkangas, and E. Tiirola, "Full-duplex self-backhauling for small-cell 5G networks," *IEEE Wirel. Commun.*, vol. 22, no. 5, pp. 83–89, 2015.

[8] U. Siddique, H. Tabassum, and E. Hossain, "Downlink spectrum allocation for in-band and out-band wireless backhauling of full-duplex small cells," *IEEE Transactions on Communications*, vol. 65, no. 8, pp. 3538–3554, Aug 2017.

[9] S. Singh and J. G. Andrews, "Joint resource partitioning and offloading in heterogeneous cellular networks," *IEEE TWC*, vol. 13, no. 2, pp. 888–901, February 2014.

[10] Y. Lin and W. Yu, "Joint spectrum partition and user association in multi-tier heterogeneous networks," in *48th CISS*, March 2014, pp. 1–6.

[11] U. Siddique and H. Tabassum and E. Hossain, "Spectrum allocation for wireless backhauling of 5g small cells," in *Communications Workshops (ICC), 2016 IEEE International Conference on*. IEEE, 2016, pp. 122–127.

[12] R. Gupta and S. Kalyanasundaram, "Resource allocation for self-backhauled networks with half-duplex small cells," in *ICC Workshops*, May 2017, pp. 198–204.

[13] 5G-PPP, "5G PPP use cases and performance evaluation models," *Living document on*, no. March, p. 10, 2016. [Online]. Available: https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-use-cases-and-performance-evaluation-modeling_v1.0.pdf

[14] METIS-II, "Performance evaluation framework," *Deliverable D2.1*, no. January, p. 10, 2016. [Online]. Available: https://metis-ii.5g-ppp.eu/wp-content/uploads/deliverables/METIS-II_D2.1_v1.0.pdf

[15] R. Jain, D.-M. Chiu, and W. R. Hawe, *A quantitative measure of fairness and discrimination for resource allocation in shared computer system*. Eastern Research Laboratory, Digital Equipment Corporation Hudson, MA, 1984, vol. 38.

[16] S. L. Loyka, "Channel capacity of mimo architecture using the exponential correlation matrix," *IEEE Communications letters*, vol. 5, no. 9, pp. 369–371, 2001.