Spectrum Sharing in Hybrid Terrestrial-Satellite Backhaul Networks in the Ka Band

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***Abstract*—This work evaluates interference mitigation mechanisms to enable the operation of self-organizing hybrid terrestrial-satellite networks with aggressive frequency reuse between terrestrial and also satellite links. The objective is to take advantage of the improved capacity and resilience to congestion of such networks while assuring and efficient use of the spectrum. In particular, single- and multi-user hybrid analog-digital beamforming (HADB) techniques are considered as well as hybrid carrier allocation. The simulation results show network spectral efficiency improvements, with respect to conventional terrestrial backhaul systems, up to 2x when applying carrier allocation, and between 3.5x to 9x applying HADB in different environments.**

Keywords—Spectrum sharing; frequency reuse; interference mitigation; network spectral efficiency; hybrid-analog digital beamforming; carrier allocation

I. Introduction

The Fifth Generation of Mobile Communications (5G) is willing to provide an order of magnitude increase in performance metrics like network capacity, reliability and availability, among others. The direct solution for achieving the network capacity targets consists of increasing the utilized spectrum, what could lead to the so-called spectrum crunch. Therefore, recent socio-economic studies on 5G [1] defend the need of adopting spectrum sharing mechanisms. Usually, the studies on spectrum needs are focused on the Radio Access Network since optical fiber is considered for the Backhaul. However, wireless and even satellite communications may play an important role in backhaul networks for achieving reliability and availability targets, due to the large cost of deploying optical fiber which limit its coverage.

Focusing on backhaul, currently the 65% of fixed wireless links use a conservative licensing based on a link-by-link coordination [2], usually made under regulator's responsibility, resulting on a spectrum underutilization. In the last years, block spectrum licensing, in which the user of the license is usually free to use the block at best to deploy its network, has gained attraction in Point-to-Multipoint (PTMP) deployments, representing up to the 20.7% of license models in operation. However, the geographical exclusion of these block assignments still leaves room for spectrum reutilization.

In addition, the spectrum regulation among different systems tends to be also conservative, although some exceptions can be found for the terrestrial/satellite coexistence. This is the case of the satellite downlink at the extended Ka band (17.7-19.7GHz) in which uncoordinated satellite receivers are allowed but cannot claim for protection from terrestrial transmitters using the same frequencies [2]. However, in practice, this results again in underutilization since satellite operators tend to avoid using this band without protection.

In this work, we present an overview of the evaluation of multi-antenna and radio resource management (RRM) techniques for improving the spectrum usage in future backhaul networks, developed within the SANSA H2020 project [3, 4]. In particular, SANSA proposes a self-organizing hybrid terrestrial-satellite backhaul network in order to overcome the limitations of current networks in terms of capacity, resilience to congestion and failures, and coverage.

The remainder of the paper is organized as follows: Section II presents the SANSA concept; Section III introduces the scenario of evaluation and the main performance metric, Section IV evaluates multi-antenna techniques; Section V evaluates carrier allocation as the main RRM technique; and the conclusions are given in Section VI.

II. SANSA Concept

SANSA project proposes a backhaul network based on three main pillars. First, it considers the seamless integration of the satellite segment in terrestrial backhaul networks. A Hybrid Network Management (HNM) scheme has been proposed to make the most efficient use of all network resources being them terrestrial or satellite [4]. The use of the satellite not only provides coverage extension, but also a backup connection, the possibility of offloading data or the rapid placement of content to terrestrial caches through multicasting.

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The second pillar is a terrestrial network with self-organizing capabilities, i.e. capable of adapting its network topology according to the traffic demands, resulting in improved capacity and resilience to failures and congestion. This is accomplished through the HNM, which calculates new topologies according to the traffic events, and through equipping the terrestrial backhaul nodes with antenna arrays with beamforming capabilities. Therefore, the antenna arrays can perform single- or multi-beam steering to synthesize the topologies decided by the HNM.

The third pillar is the most efficient use of the spectrum. This translates in an aggressive frequency reuse between reconfigurable terrestrial backhaul links, but also between the terrestrial and satellite segments. The increase of interference levels due to the frequency reuse is coped by three kinds of techniques. Hybrid Analog-Digital Beamforming (HADB) in combination with the antenna arrays at the backhaul nodes are used not only to steer beams to the desired directions but also to steer nulls to unintended receivers, thus providing spatial interference mitigation. On top of this, RRM solutions such as carrier allocation, scheduling or joint carrier allocation, scheduling and flow assignment are proposed to deal with the remaining interference levels. Finally, in order to assure the compatibility of different SANSA systems, or of a SANSA systems with legacy deployments, database-assisted techniques are proposed for mitigating intra-system interference. This paper is focused on the HADB techniques, presented in Section IV, and on carrier allocation, presented in Section V, but the reader may refer to the SANSA public deliverables available at [3] for a complete description of all interference mitigation solutions. It is worth mentioning here that SANSA focuses on the extended Ka band for which the current regulation already considers terrestrial/satellite spectrum coexistence. In this case, the interference mitigation techniques enables the use of the satellite downlink band for providing backhaul services, which is underutilized otherwise.

III. Scenario and Performance metric

The benchmark scenario used to quantify the performance gains of the proposed approaches is based on real backhaul network topology, located close to Helsinki and depicted in Fig. 1. In this topology, each of the links is implemented via a SISO system, i.e. one highly directive antenna of 38dBi gain per end.

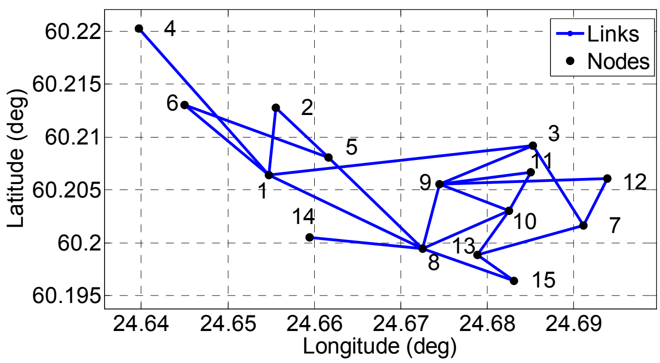

Fig 1. Helsinki topology

Then, eight carriers with 56 MHz channel bandwidths are shared and coordinated (usually by a regulation body) among the high directive links such that no interference is experienced among them. The objective of the multi-antenna and RRM techniques proposed in next Sections is to allow reducing the number of carriers while increasing the channel bandwidth of each link, thus keeping the total bandwidth used. This translates to a net network spectral efficiency (SE) improvement, which is used as the main performance metric and is defined as

$$SE = \frac{\sum_k R_k}{B_T}, \qquad (1)$$

where B_T is the total bandwidth employed by the topology and the achieved rate R_k is defined as

$$R_k = B \ \log_2 \det\left(\mathbf{I}_{L_s} + \mathbf{R}_n^{-1}\mathbf{W}^H\mathbf{H}\mathbf{F}\mathbf{F}^H\mathbf{H}^H\mathbf{W}\right), \qquad (2)$$

with B denoting the channel bandwidth of each link, $\mathbf{F}$ and $\mathbf{W}$ the precoding and postcoding matrices, respectively, $\mathbf{H}$ is the channel matrix and $\mathbf{I}_{L_s}$ is the identity matrix, L_S is the number of employed streams, and $\boldsymbol{R}_n$ is the interference-plus-noise matrix.

IV. Multi-antenna Techniques

Two sets of multi-antenna techniques are considered: (i) Point-to-Point (PTP) techniques consisting of a single link in presence of non-intended receivers; and (ii) Point-to-Multi-Point (PTMP) which considers a set of K legitimate transmissions whose signal-to-noise-plus-interference (SINR) ratios shall be balanced. In both cases, and attending to the cost performance trade-off, we focus on the design of hybrid analogue-digital beamformers where an analogue beamforming network (BN) processes the signals received by the Q antennas into a set of $N_{RF} \leq Q$ radiofrequency (RF) chains. Two types of analogue BN are considered: a fully-connected (FC) approach in which each antenna connects with each RF chain; and a simpler partially-connected (PC) one, in which each antenna connects to only one RF chain, resulting in analog subarrays. In both cases, the analog beamformer only performs phase control. In general, and otherwise stated, uniform planar arrays (UPAs) of 64x64 elements are used. For a fair comparison the EIRP of each case matches that of the benchmark.

A. PTP

In the PTP case, we try to optimize the gain in the direction of a single desired receiver while keeping the interference to multiple non-intended receivers below a certain threshold. The phase-only control of the analog BN leads to a non-convex optimization problem, thus novel convex relaxation techniques shall be introduced. We proposed a non-smooth method for dealing with the quadratic inequality constraints, which details can be found in [5]. The overall method consists of an alternating projection mechanism that iteratively solves the analog and digital beamforming parts. In this case the PC BN is selected.

Remarkably, this approach considers single-stream transmission, which is known to be efficient in low-rank MIMO channels. These channels are found in strong line-of-sight conditions such as in rural low-scattered environments or over-the-roof top communications. If the antennas are brought down to the street level in urban environments, as may happen with cell densification, the underlying channel model will support multi-stream transmission (channel matrix rank more than 1) [6]. In order to take advantage of this property we propose to design the optimal pre-coding matrix such that the mutual information of the corresponding link is maximized subject to the power and the interference constraints, that is

$$\max_{\mathbf{F}_{RF},\mathbf{F}_{BB}} \log_2 \det(\mathbf{I}_{L_s} + \widetilde{\mathbf{H}}\mathbf{F}_{RF}\mathbf{F}_{BB}\mathbf{F}_{BB}^H\mathbf{F}_{RF}^H\widetilde{\mathbf{H}}^H) \quad (3)$$
$$s.t. \mathbf{F}_{RF}\mathbf{F}_{BB} \in \mathsf{S} \;\&\; \mathbf{F}_{RF} \in \mathsf{F},$$

where $\widetilde{\mathbf{H}} = \mathbf{Q}^{-1}\mathbf{H}$, is the interference-plus-noise matrix, $\mathbf{F}_{BB}$ is the digital baseband precoder, $\mathbf{F}_{RF}$ is the analog RF one, S is the set defined by the power and interference constraints and F is the set related to the unit modulus constraints of the analog counterpart. At the receiver side, a linear postcoder based on the MMSE criterion is applied, given as a solution to the following optimization problem,

$$\min_{\mathbf{W}_{RB},\mathbf{W}_{BB}} \mathsf{E}\left\{\left\|\mathbf{x} - \mathbf{W}_{BB}^H\mathbf{W}_{RF}^H\mathbf{y}\right\|_F^2\right\} \quad (4)$$
$$s.t. \quad \mathbf{W}_{RF} \in \mathsf{F},$$

where $\mathbf{W}_{BB}$ is the digital baseband postcoder, $\mathbf{W}_{RF}$ is the analog counterpart, $\mathbf{x}$ is the transmitted signal and $\mathbf{y}$ is the received one. The solution to the aforementioned optimization problems is given in [7]. Let us remark here that in this case FC BN is assumed.

The performance of the proposed approaches is examined on the simulation setup described in Sec. III. There we assumed the full frequency re-use case were all the links are established via only two carriers due to the bidirectional nature of the links, instead of the eight considered in the benchmark. Table 1 compares the SE obtained by the single-stream PC and the multi-stream FC approach, with the benchmark (Ben) and the benchmark combined with full frequency reuse (F/R Ben.). An upper bound considering a fully digitally transceiver that experiences no interference is also shown.

TABLE 1. NETWORK SE (BPS/HZ) RESULTS ON THE HELSINKI TOPOLOGY

RF-Ch.	Ben.	F/R Ben.	Single-stream PC	Multi-stream FC	Upper bound
1	330.8	2.9	-	1078.0	1451.6
2	-	-	652.95	1787.3	2109.5
4	-	-	931.54	2959.8	3320.7

The application of the full frequency re-use on the benchmark has a severe impact on the network's spectral efficiency clearly motivating the need of the proposed beamforming/pre-coding techniques. For rank 1 channels, the single-stream technique provide SE gains of 3x-3.7x with respect to the benchmark, and performs slightly below the upper bound with only one RF chain (i.e. one stream). This difference is due to the use of the PC-BN, which on the contrary provides important savings in terms of cost and complexity. For channels with rank>1, the multi-stream FC solution performs very close to the upper bound, providing gains up to 9x as the number of parallel streams increases. For the single stream case the gains are bounded by the number of carriers present in the benchmark and reused here while the multi-stream overcomes this limitation exploiting the additional spatial degrees of freedom offered by the channel.

B. PTMP

The limitations of the channel rank can be partially overcome when transmitting different streams to multiple-receivers (Multi-user MIMO), due to its large separation. However, the hybrid analogue-digital MU-MIMO optimization is an open problem. Here we propose two similar methods, one based on the HADB architecture introduced before, and a very low cost alternative based on multi-active multi-parasitic antenna arrays [8]. As general statement, the use of iterative methods for beamforming limits its applicability to real systems as the computational complexity is high. In order to solve this problem, we propose in the following a low complexity approach for dealing with the multiuser interference.

We consider that the analog beamforming part only performs the operation of pointing to the intended users. In other words, no multiuser interference is mitigated in the analog domain. This substantially reduces the analog optimization which generally consists of the most computationally demanding operation. In particular, we adopt the analog-beamforming design described in [9, Section IV], for the HADB, and the realization of fixed beams for the parasitic arrays. Then, the digital part is designed for limiting the multiuser interference, based on the equivalent channel matrix obtained via the multiplication of the channel matrix and the analog beamforming. Here a zero-forcing and a regularized zero-forcing are considered for the HADB and the parasitic arrays, respectively.

In order to evaluate the proposed schemes, we consider the simulation setting depicted in Fig. 2. The benchmark consists of a system where the transmitting backhaul node uses disjoint carriers to multiplex the different symbols. In contrast, the proposed technique considers the case where the symbol multiplexing is done at the spatial domain so that all the intended backhaul nodes use the same carrier. For the sake of simplicity, we focus on a single case formed by the links that connect node 9 (assumed to be the transmitter) with nodes 3, 10, 11 and 12, in Fig. 1.

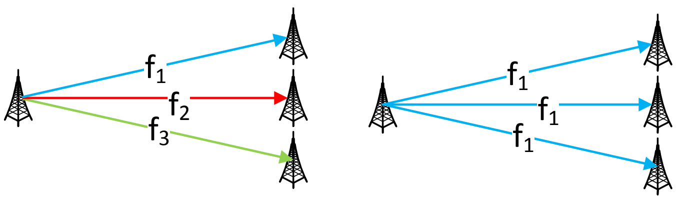

Fig. 2. In the left figure, we consider the benchmark scheme where FDMA is used for orthogonalizing the transmissions. The figure on the right describes the proposed technique.

Table 2 shows the numerical results considering HADB formed by a UPA with 400 elements with 4 N_{RF} chains with the different connectivity schemes [9], and the solution based on parasitic arrays. As a matter of fact, the FC solution provides gains close to the four carriers reused. Interestingly the PC localized does not perform far away from the FC while presenting a significant cost reduction. Finally, the gains are severely degraded when opting for parasitic arrays though the complexity/cost is also is extremely reduced, since these arrays make use of only 4 active elements (RF chains) and 40 parasitic elements in total.

TABLE 2. RESULTS PTMP

	Average Spectral Efficiency [bits/s/Hz]	Gain
Benchmark	22.71	-
UPA FC	80.76	3.55
UPA PC localized	65.25	2.87
UPA PC Interleaved	31.3	1.37
Parasitic Arrays	24.95	1.10

The PTMP case can be extended considering more than one transmitter (Tx) communicating to the same multiple receivers (Rx). This scenario can be understood as a multi-point to multi-point case (MPTTMP) and is referred as K-user MIMO X network in the literature [10]. Unlike the precoding schemes based on decomposing the K-user MIMO X network [11] , we first propose a simple yet efficient fully digital scheme based on dominant eigen-mode transmission (DET) and MMSE combining at each Tx and Rx, respectively. This scheme cancels interference at the Rx and is referred to as DET-MMSE in the following. With the aid of the SVD of the channel $\mathbf{H}_{k,l}$ of link(k,l), the precoder can be expressed as

$$\boldsymbol{B}_{kl} = \boldsymbol{V}_{kl}^{\parallel}[:,1:u], \tag{5}$$

where u denotes the number of streams on each link selected from the columns of the column space $\boldsymbol{V}_{kl}^{\parallel}$. Then, the MMSE combiner based on the received signal $\boldsymbol{r}_k$ is given by

$$\boldsymbol{Z}_k^H = \mathbb{E}\,[\boldsymbol{s}_k\boldsymbol{r}_k^H][\boldsymbol{r}_k\boldsymbol{r}_k^H]^{-1}. \tag{6}$$

We propose two alternative designs of hybrid precoders: dis-jointly and jointly. In the dis-joint approach, due to the severe coupling between the RF precoders and combiners of all Txs and Rxs, the design problem can be addressed in two steps and formulated as follows. In the first step, the RF combiner at each Rx is calculated such that it maximizes the frobenius norm

$$\max_{\boldsymbol{W}_k}\left\|\boldsymbol{W}_k^H[\boldsymbol{H}_{k,1}\ \dots\ \boldsymbol{H}_{k,L}]\right\|_F^2. \tag{7}$$

Given the RF combiners, the RF precoder at each Tx is calculated as

$$\max_{\boldsymbol{A}_l}\left\|[\boldsymbol{W}_1^H\boldsymbol{H}_{1,l}\ \dots\ \boldsymbol{W}_K^H\boldsymbol{H}_{K,l}]\boldsymbol{A}_l\right\|_F^2 \tag{8}$$

Addressing the problem in this manner may not lead to satisfactory results when a real channel is considered. Solving for the RF precoder using the above approach may lead to the selection of many steering vectors in the direction of the dominant channel which is closer to the Tx. Therefore, the steering vectors of the angle of departures (AODs) of the LOS paths on all links are chosen as the entries of RF precoder. Depending on the number of RF chains and performance, the steering vectors of the NLOS directions may be taken into consideration. Similar procedure is carried out at each Rx to design the RF combiners. Then, the aforementioned full-digital precoding is performed on the effective channel $\boldsymbol{G}_{k,l}$ to design the BB precoders and combiners.

In the joint scheme, the full digital precoders (combiners) calculated on the channel $\mathbf{H}_{k,l}$ are used to calculate the hybrid precoders (combiners) using the well-known OMP algorithm presented in [12]. The candidate vectors for the dictionaries are given by the steering vectors corresponding to the AOAs/AODs of all links at each Tx / Rx.

For the evaluation, we consider as Txs nodes 1 and 10 in Fig.1, and as Rxs nodes 2, 5, 8, 13. In total, the benchmark uses 8 different carriers that are reduced to 1 with the proposed scheme. The results are shown in Table 3. Since, the dis-joint is very sub-optimal, a huge performance gap can be observed. On the other hand, the joint scheme achieves satisfactory results compared to the full-digital benchmark resulting in gains of 7.56x with respect to the benchmark.

TABLE 3. SE (BPS(HZ) RESULTS IN MPTMP

Scheme	**benchmark**	**Full-digital**	**Hybrid joint**	**Hybrid disjoint**
DET-MMSE	21.99	173.92	166.40	139.52

V. HYBRID CARRIER ALLOCATION

Complementary or alternatively to multi-antenna techniques, carrier allocation techniques more aggressive than the traditional ones used by the regulation bodies, permit also increasing the network spectral efficiency. The goal here is then to design jointly the terrestrial and satellite carrier assignment for which the interference impact on both the terrestrial and satellite link performance is minimal. To be more specific, in this section, we will focus on the maximization of the worst link in terms of interference. We discarded the sum-rate utility function because, although it was proposed as one of the key performance indicators identified in Section III, it might end up sacrificing some links in detriment of others with good rate performance.

Let us assume the availability of K equally sized frequency carriers, each of bandwidth size B_t . For the sake of clarity, we assign a carrier identification number to each of the K frequency carriers, namely $k=1,\ldots,K$. Let $\mathrm{a}_t \in R^L$ be the terrestrial carrier allocation vector, where L denotes the number of terrestrial links, whose elements $\mathbf{a}_t(i)\in[1,K]$ contain the terrestrial carrier identification number of the carrier that has been assigned to the i-th terrestrial link. Similarly, for the satellite we assume the availability of C equally sized frequency carriers, each of bandwidth size B_s , with identification number $c=1,\ldots,C$. The satellite carrier allocation is determined by $\mathrm{a}_s \in R^M$ with elements $\mathbf{a}_s(j)\in[1,C]$, where M denotes the number of satellite links.

Therefore, the corresponding max-min problem is formulated as follows:

$$\begin{aligned}\max_{a_t,a_s} \quad \min_{j,i} \quad & \{R_t(j), R_s(i)\} \\ s.t. \quad & a_t(j) \in [1, K], \quad j = 1,\ldots,L \\ & a_s(i) \in [1, C], \quad i = 1,\ldots,M \\ & a_t(i) \neq a_t(j), \quad j \in I(n), i \in O(n), \quad n = 1,\ldots,N \\ & a_s(i) \neq a_s(j), \quad i,j = 1,\ldots,M, \quad i \neq j \end{aligned} \tag{9}$$

where $R_t(j)$ and $R_s(i)$ denote the rate of the j-th terrestrial link and the i-th satellite link, respectively; N is the number of terrestrial nodes; and $I(n)$ and $O(n)$ denote the set of terrestrial links that are incoming and outgoing to/from node *n*, respectively. The last constraint ensures that a single carrier is not assigned to multiple satellite links, while the second-to-last constraint prevents full-duplex scenarios in which the same carrier is used for transmission and reception at the same terrestrial station.

Clearly, the considered joint carrier allocation problem of terrestrial and satellite segment is intractable due to the non-linear coupling between each other caused by interference links between terrestrial and satellite segments. To handle the problem, we follow the approach described in [13], where first the carrier assignment for the satellite backhaul network is solved and, on a second step and assuming the resulting satellite segment allocation, we design a sub-optimal and iterative carrier assignment for the terrestrial part of the network.

Fig. 3 illustrates the achieved SE values as a function of the carrier bandwidth (assuming $B_t = B_s$). In particular, the total bandwidth is fixed to 448 MHz, so that higher values of carrier bandwidth imply higher frequency reuse. The proposed carrier allocation is able to handle the interference by reaching a maximum SE value of 181.43 bps/Hz, which compared to the 95.67 bps/Hz of the benchmark (indicated with a red dot Fig. 3) translates into 1.90x SE increase.

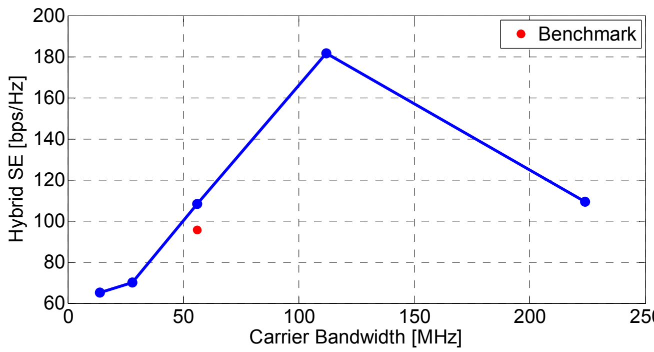

Fig 3. SE achieved with carrier allocation

VI. Conclusions

In this paper, we have proposed and evaluated different multi-antenna techniques and a carrier allocation solution specifically designed to be applied in hybrid terrestrial-satellite backhaul networks with the aim of improving the network spectral efficiency. Each technique has been verified in several different setups considering realistic and modeled parameters but always keeping a true Helsinki network topology as a benchmark for comparison purposes.

Results show that hybrid carrier allocation can reach SE gains of the order of 2x when compared to the conventional terrestrial-only backhaul networks, without the need of a significant investment for deploying antenna arrays in the terrestrial nodes. However, if such a deployment is available, motivated by the self-organizing operation of the network, the SE improvements can be enlarged. In particular, it is shown that the proposed HADB techniques in low scattered backhaul channels (e.g. rural or urban over-roof-top) are able to provide performance gains close to the number of carriers used in the conventional system and reused in the proposed system. Therefore, conventional systems with denser deployments would need more carriers to assure no interference, which would translate in higher SE gains after applying the proposed techniques. Numerically, gains between 3.5x to 7.5x have been observed for the different evaluated cases. In a rich scattered urban channel with antennas at street levels, the additional degrees of freedom offered by the channel can be used to multiplex different streams increasing the 3.5x SE gains obtained with only frequency reuse to 9x.

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