INTEGRATED TERRESTRIAL–SATELLITE WIRELESS BACKHAULING

Resource Management and Benefits for 5G

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With the fifth generation (5G) of cellular communications around the corner, operators are searching for efficient solutions to accommodate the tremendous traffic increase with limited latency [1]. In the past few years, the satellite telecom industry has moved from traditional direct broadcasting and has been a solution in combination with the terrestrial 5G network [2]. Coverage extension, data offloading, and service continuity are the key complementary aspects that a satellite can offer, which demands more partnership and integration between terrestrial and satellite operators.

The most obvious application of satellite communication in a 5G delivery architecture is in the backhaul segment of the network. To improve the capacity of mobile wireless backhaul networks, the concept of a seamlessly integrated satellite–terrestrial backhaul network capable of jointly exploiting the terrestrial and satellite links depending on the traffic demands has been recently proposed [3]–[5]. However, spectrum management beyond the current fixed and exclusive licensed charts is one of the most important endeavors for backhaul operators to meet the ever-increasing traffic demand. A major impetus is to identify the spectrum bands that could be used to accelerate the hybrid backhaul network deployment. In this context, the European Conference of Postal and Telecommunications Administrations already allows uncoordinated satellite terminals to coexist with terrestrial wireless backhaul links in the 17.7–19.7-GHz band but without the right of protection [6]. The latter corresponds to the Space-to-Earth satellite downlink communication link. In the considered scenario, which is depicted in Figure 1(a), there are two types of interference that should be properly handled: 1) interference from terrestrial backhauling transmitters to the satellite backhauling terminals and 2) interference among the terrestrial nodes arising from the aggressive frequency reuse foreseen in future spectral-efficient backhaul networks. Therefore, effective interference mitigation is indispensable to leverage the full potential of such integrated terrestrial–satellite network. In addition, spectrum sharing between satellite and terrestrial systems have been investigated in the uplink 27.5–29.5-GHz band, which is illustrated in Figure 1(b), where the satellite terminals entail potential interference toward the terrestrial receivers.

Latency always stands at the forefront whenever satellite communications is discussed. A major physical constraint in geostationary Earth orbit-based satellite systems is the latency due to the long round-trip time of roughly 500 ms. While this delay is critical in certain use cases, such as real-time applications, there are definite situations where satellite can outnumber the benefits versus the delay disadvantage. The multicast nature of satellite enables the use of proactive caching for content placement to offload the terrestrial backhaul and reduce the communication delay. In this case, multigroup multicast is used as a means to efficiently update the local storage of the deployed caching servers at regular intervals (e.g., overnight). This caching use case is one of the most promising ones, which confirms the benefits of integrating the satellite segment for future 5G backhaul networks [7].

Radio Resource Management

Radio interference in wireless communication networks has long been a major research challenge that has been intensively addressed in the literature. There are several notable studies related to the use of multiantenna transceivers leveraging spatial division to mitigate interference. Nevertheless, the deployment of advanced antenna infrastructure implies significant hardware expenditure. A more affordable alternative is to tackle the interference problem from a simple radio resource management (RRM) point of view, where resources are exploited intelligently to reduce and mitigate interference. The latter requires relatively low investment on the backhaul network infrastructure and minimal operating cost, since it is based on software modules running in central controllers.

The future trend in integrated satellite–terrestrial wireless backhaul networks is to enable both systems to share the same spectrum to enhance the overall spectrum efficiency and meet the future capacity demands. These spectrum-sharing conditions force both systems to consider interference constraints during the resource-allocation process. As mentioned previously, two main sharing scenarios can be considered for satellites operating in the Ka-band: the satellite downlink and satellite uplink scenarios, as depicted in Figure 1. Figure 1 shows the terrestrial-to-terrestrial interference since this kind of interference is independent of the satellite transmission and appears because of the high-frequency reuse that is considered. Generally, the interference caused by the satellite toward Earth is neglected as the current satellite systems are usually in line with the predefined power-density limitations. On the contrary, the interference from the satellite terminal emitter to the terrestrial receiver in the uplink scenario is forming a main interference source.
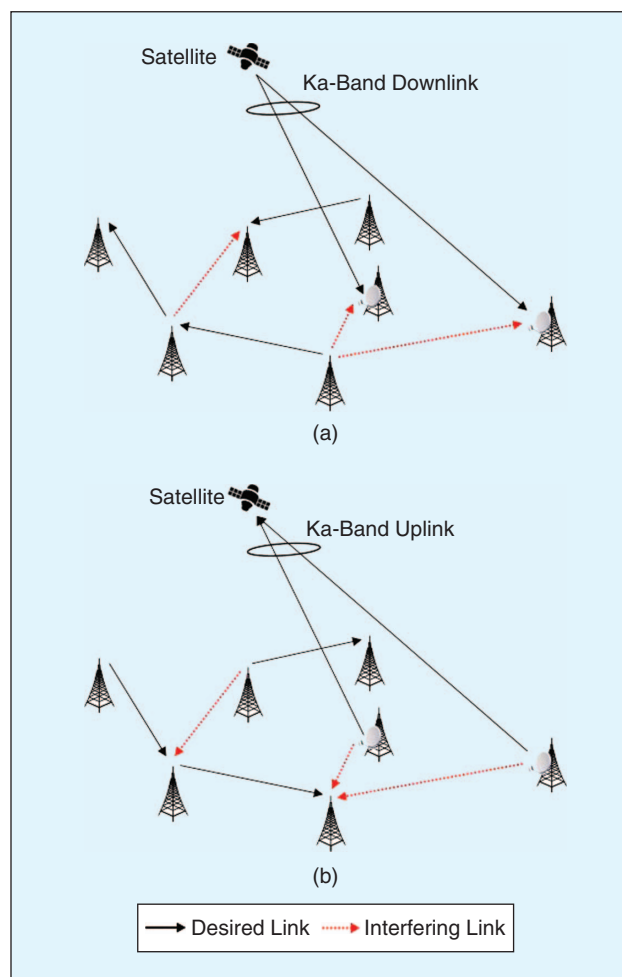

FIGURE 1 Integrated terrestrial–satellite wireless backhauling scenarios: (a) the forward link and (b) return link.

In general, resource allocation in integrated terrestrial and satellite networks is considered a rather new research area, and previous contributions are limited. Most of the published work has focused on the mobile satellite services (MSSs), which refer to satellite communication networks intended for use with mobile and portable wireless telephones [8]. Essentially, the literature has centered its attention on the coexistence of a terrestrial cellular system with MSSs. In this article, we focus the discussion on the scenarios where the satellite communications are adopted for backhaul deployment and coexist with the terrestrial backhauling network. This aligns with the vision that the space segment is expected to operate in the future in collaboration with the terrestrial component in a seamless interworking environment.

The most relevant work is related to the cognitive satellite communications in the presence of incumbent terrestrial links [9]. However, in [9], the satellite system adapts its carrier allocation to minimize the impact of interferences arising from the spectrum-sharing assumption. Here, we consider the RRM of both terrestrial and
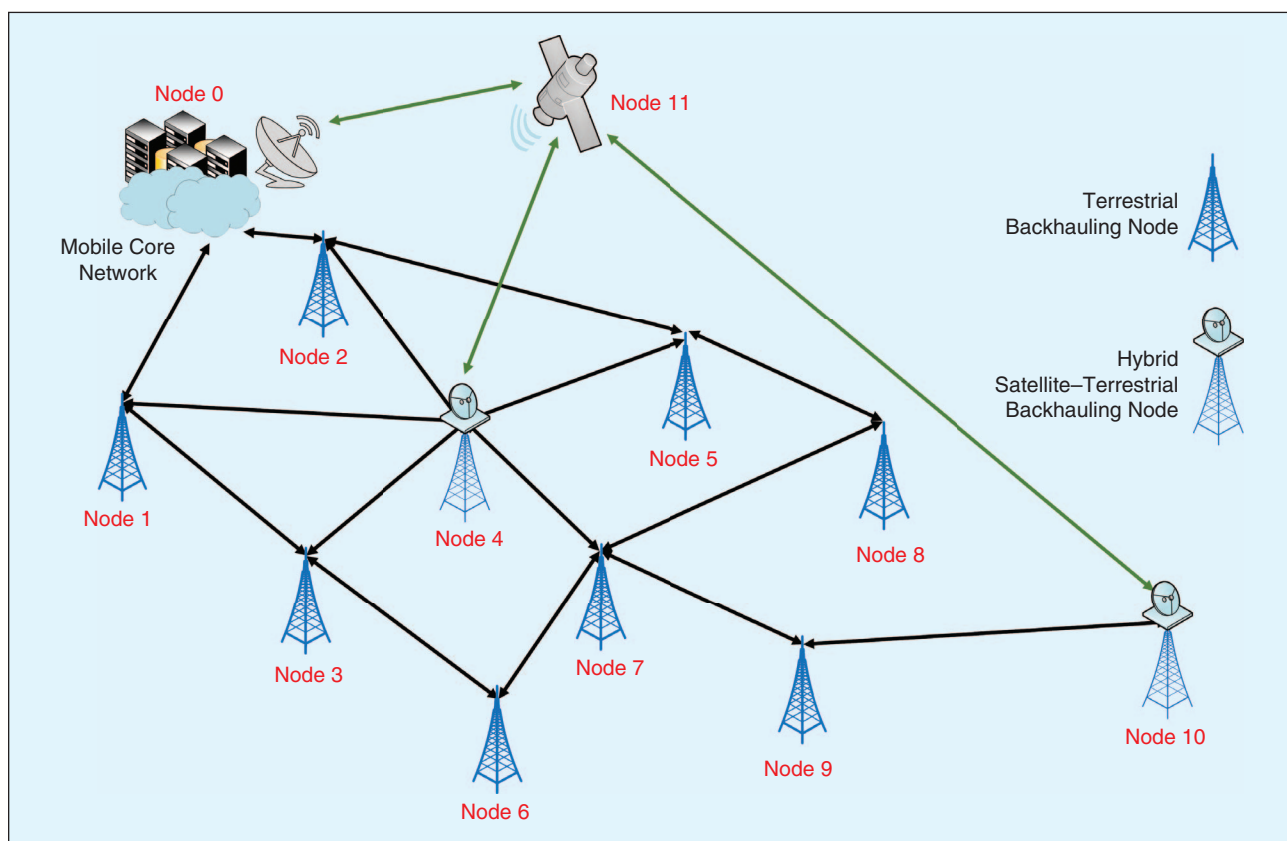
FIGURE 2 An example of an integrated terrestrial–satellite wireless backhauling network.

Links Establishment and Flow Control

In wireless backhauling systems, achieving the maximum throughput in the network is not an easy task, as it is not a question of optimizing only the transmission parameters, but it requires a cross-layer optimization of the different layers to intelligently handle the link-scheduling and traffic demand over the scheduled links. The backhauling nodes operate as a gateway access point to the associated access nodes and, at the same time, as a wireless router to other nodes' traffic.

We assume that there is a multihop wireless backhaul network where there are several base stations (BSs) that serve multiple users in a given geographical area. Not all the BSs have direct connection to the core network and, hence, some BSs reach the core network through multihop links. Additionally, some BSs have integrated terrestrial–satellite communication capabilities, which enable them to reach the core network through satellite. An example of such a network is depicted in Figure 2, which consists of N backhauling nodes. To activate links simultaneously, different radio and interference constraints should be considered. The radio constraints, which are usually called the *primary conflict*, can be the half-duplex constraint, where any backhauling node can either transmit or receive at the same time. A system with full-duplex frequency division duplexing capabilities can transmit and receive simultaneously, therefore, these radio constraints are not applied. This is also valid if the system uses any in-band half-duplex techniques. The activation of the links does not depend only on the radio limitations, but also on the level of interference between the neighboring nodes. Accordingly, two links that cause harmful interference to each other's should not be activated simultaneously. This type of conflict is called a *secondary conflict*. A scheduling configuration is the set of links that are free from both primary and secondary conflicts.

To decide which scheduling configuration should be used at a given time, as well as the amount of traffic that should be transmitted on each link, one can model the network as a multicommodity flow (MCF) [10], where the generated traffic at each node is considered a single commodity. For each backhauling node, the flow conservation law should be satisfied to ensure that the sum of incoming and outgoing flows belonging to a given commodity are equal in the event of a relaying node (i.e., the node that forwards other node's traffic). At the same time, the sum of the traffic in each source node (i.e., the node that transmits its own traffic in addition to other

node's traffic) should be equal to the amount of the traffic generated at this particular node. Additionally, the sum of flows belonging to different commodities, which are passing through a given link, should not exceed the capacity of that link.

Accordingly, considering the flow conservation law along with the capacity constraints, one possible utility function to optimize is the one that minimizes the scheduling time needed to deliver a generated amount of traffic in the networks as considered in [11]. The scheduling time is defined as the summation of the fractions of time in which the scheduling configurations are enabled. The satellite links should be used only when needed, therefore, one more term can be added to this utility function to count for the use of the satellite. This term can be the weighed sum of the flows scheduled on the satellite links. The optimization problem minimizes the objective function, which will force the network to use the satellite links only when it is necessary, such as terrestrial link failure or where traffic offloading is required when the terrestrial network is not capable of scheduling the generated traffic. The transmission over the satellite links may cause more propagation delay than the terrestrial delay, therefore, the utility function can be chosen in such a way to avoid transmitting delay-sensitive traffic over the satellite link, where the routing process should be combined with traffic-classification techniques.

To obtain the optimal solution for this problem, all scheduling configurations should be generated so that the problem is solved over all of them. However, generating all of the possible configurations is not practical as the number of configurations grows exponentially with the size of the network. Alternatively, the column generation technique can be used to solve the problem over a subset of the possible scheduling configurations. This approach is widely applied in large linear programming setups. In general, the column generation method has two main parts: the master problem and the pricing problem. The master problem consists of solving the original problem with restricted scheduling configurations while the pricing problem incorporates the dual variables found by the master problem to find the new scheduling configuration (i.e., column) to be added to the initial restricted scheduling configurations. The process continues until no new or better scheduling configurations are added. One possible initialization set of scheduling configurations can be a simple time-division multiple access scheme (i.e., only one link is active in every scheduling configuration).

Without the loss of generality, we consider that the two satellite links have capacities of 160 Mb/s, which is double the capacities of the terrestrial links. This assumption is for getting representative results; however, the proposed approach is applicable for any selected value. We are considering the upstreaming case where
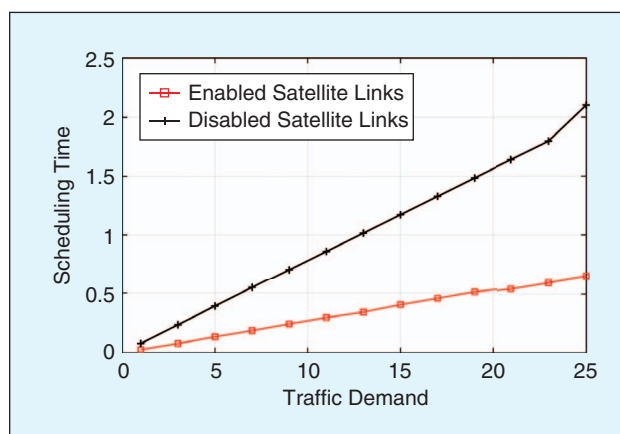

FIGURE 3 The scheduling time versus the traffic demand per node.

different nodes' traffic should be delivered to the core network.

Figure 3 depicts the scheduling time of the network against the traffic demand per node. It can be noted that the scheduling time increases with the increment of the traffic per node and the network with enabled satellite links always has a lower delivery time. As the scheduling time is the summation of fractions of time, the traffic is admissible if the scheduling time is less than one. In the case of not-admissible traffic, admission-control criterion should be applied to deliver the traffic.

Figure 4(a) depicts the flow assignment per link in normal conditions for the network shown in Figure 2 with traffic per node of 10 Mb/s. The thickness of the lines illustrates the amount of flow on that link. The red lines represent the generated traffic per node while the green line depicts the traffic received by the core network. The dashed line stands for the available links with zero traffic.

By assuming the failure of the links connecting both nodes 1 and 2 with the core network, the network has no option but to use the satellite links and reach the core network through satellite as depicted in Figure 4(b). The usefulness of the satellite link in the case of traffic congestion can be revealed by assuming that the traffic generated at node 4 is increased to 100 Mb/s due to an event. This increment in the traffic limits the ability of the terrestrial links to schedule the traffic and, hence, part of this traffic should reach the core network through the satellite link as depicted in Figure 4(c).

Carrier Allocation and Flow Control in Multifrequency Networks

While there is extensive literature on carrier allocation for terrestrial backhaul networks, this is not the case for integrated terrestrial–satellite backhaul networks, where interference coupling between both components exists. An early attempt to tackle the aforementioned scenario was presented in [12], where the sum-rate was taken as a
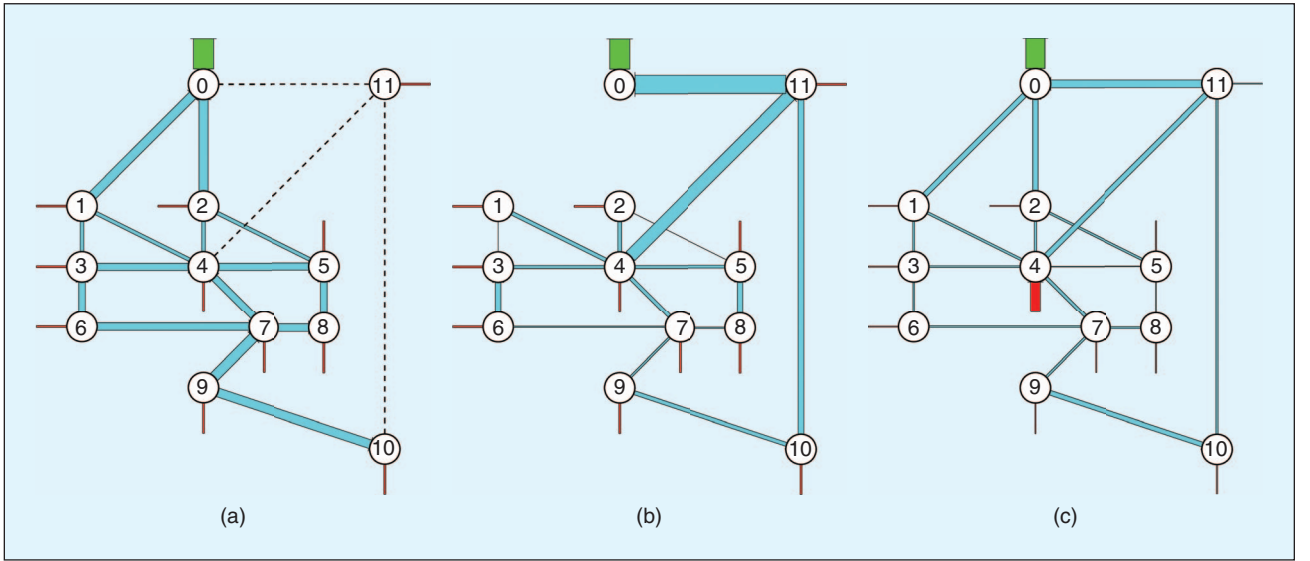
FIGURE 4 The flow assignment in the network (a) in normal conditions, (b) with link failure, and (c) with traffic congestion. The circled numbers represent the nodes in topology depicted in Figure 2.

utility function for the carrier allocation. However, the sum-rate is not a fair criterion, since a link severely affected by interference can hardly get a good channel assignment. To avoid this situation, here we focus on the maximum-minimum (max-min) carrier assignment problem. Assuming that we have K carrier frequencies available, $k = 1, ..., K$, the max-min problem can be formulated as follows:

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

where $R_t(j), R_s(i)$ stand for the rate at the terrestrial node j and the rate at the satellite node i, respectively. Variables $\boldsymbol{a}_t \in Z^L$ and $\boldsymbol{a}_s \in Z^M$ denote the terrestrial and satellite carrier allocation vector, respectively, whose elements $a_t(j), a_s(i) \in [1, K]$ contain the carrier identification number of the carrier that has been assigned to the jth and ith link. We use L and M to refer to terrestrial and satellite links, respectively, while N stands for the number of nodes in the network. The second constraint in (1) avoids possible full-duplex scenarios in which the same carrier is used for transmission and reception at the same terrestrial station. To express the latter, we use $O(n)$ and $I(n)$ representing a set of terrestrial links that are outgoing and incoming to and from node n. The third constraint in (1) accounts for the single-carrier communication mode of the satellite forward link, where one carrier frequency should be assigned to each satellite link and this cannot be shared with other satellite links.

The problem in (1) is nondeterministic polynomial-time (NP)-hard as it corresponds to a max-min assignment problem [13]. Moreover, the terrestrial carrier allocation is tightly coupled with the satellite backhaul link rates, making the problem intractable. Since testing all possible carrier permutations by brute force involves unpractical complexity, we propose a two-step sequential carrier allocation strategy specifically tailored to tackle the interference issues emerging from the spectral coexistence.

Given the conventional assumption that the number of satellite links is much smaller than the number of terrestrial links ($M \ll L$), we first focus on determining the carrier allocation for the satellite segment by assuming no terrestrial interference. The reason motivating this choice is that the terrestrial network is more flexible to adapt to the existing spectral environment. The satellite carrier assignment is thus done based on each satellite link budget and the corresponding achievable rate. However, unlike the sum-rate maximization, the max-min optimization cannot be casted as a classical assignment problem. Therefore, we use a suboptimal iterative algorithm that assigns the available carriers in a sequential order, where the link with the worst achievable rate is assigned to the best of the remaining empty channels. This procedure is repeated and, as a result, it takes the maximum among all solutions in terms of network throughput.

Second, assuming the previous satellite carrier assignment, we design the carrier allocation for the terrestrial part of the network. Again, this is a very challenging problem that requires analyzing the full search space. In addition, the terrestrial links interfere with each other due to the frequency reuse, usually $K \ll L$, which means that the problem becomes an interference-channel-like problem: intractable by nature. To circumvent
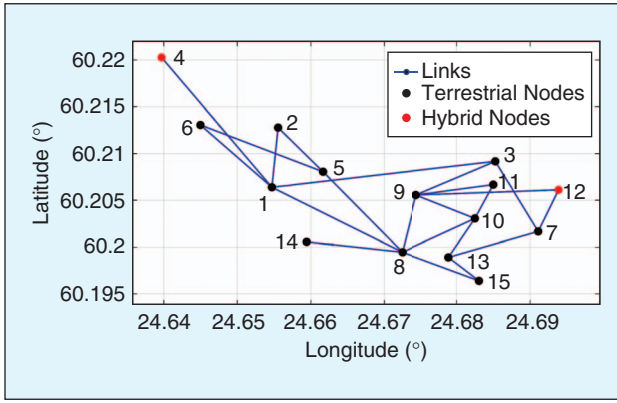
FIGURE 5 An example of a real network topology.

FIGURE 6 The spectral efficiency of the satellite segment.

$$SE\,[b/s/Hz] = \frac{SumRate}{Total\ bandwidth}. \qquad (2)$$

such tedious and unaffordable optimization, we follow a similar max-min sequential assignment approach to that used for the satellite links. However, here, we not only consider the achievable rate to decide the sequential order for the assignment, but also the interference caused at the satellite. Therefore, we take into account two types of rate: the terrestrial achievable rate, which depends on previous terrestrial carrier assignment decisions, and the satellite achievable rate, which is affected by the terrestrial interference, as well.

To illustrate the performance of the proposed carrier allocation approach, let us consider a multihop wireless backhaul network composed of several terrestrial stations. Some of them are equipped with a satellite dish antenna and, therefore, can receive backhaul traffic through the satellite network. Let us assume N terrestrial nodes indexed by $n = 1, \ldots, N$, which can send, receive, and relay backhaul traffic. We consider the terrestrial nodes to be interconnected through L unidirectional communication links, indexed by $l = 1, \ldots, L$, forming $L/2$ bidirectional links. Regarding the satellite segment, we consider $M \leq N$ terrestrial nodes equipped with satellite dish antennas.

An example of integrated terrestrial–satellite network topology is depicted in Figure 5, which consists of 15 terrestrial nodes, two of which are equipped with satellite transmission capabilities, interconnected via 22 bidirectional links and two satellite-to-Earth links. This makes $L = 44$ terrestrial unidirectional links and $M = 2$ satellite-forward links. The topology in Figure 5 is based on a true backhaul topology that is used in Finland, which has been taken as a main topology for validation within the Shared Access Terrestrial–Satellite Backhaul Network Enabled by Smart Antennas (SANSA) project [3]. As a benchmark for comparison, we will consider the carrier allocation illustrated in the database provided by the Finnish communications regulatory authority, which considers a block of eight carriers of 56 MHz each, reaching 95.67 b/s/Hz of spectral efficiency (SE). SE is defined as,
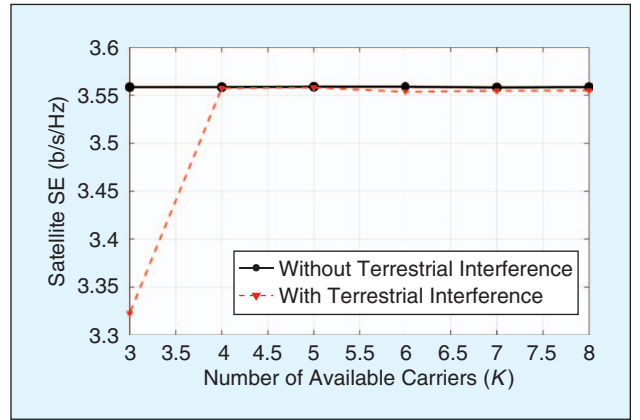
We assume a multibeam satellite located at the orbital position 13E provides coverage to the considered area. The beam pattern has been simulated as in [14].

Figure 6 illustrates the SE results obtained with the proposed algorithm for the satellite segment and for a different number of carriers. In Figure 6, we provide two results: 1) The ideal case where no terrestrial interference from the terrestrial links is received, noted as *w/o Terrestrial* and 2) the real case where the satellite links are affected by the terrestrial interference, noted as *w/ Terrestrial*.

The proposed algorithm is able to perfectly mitigate the interference when the number of available carriers is sufficiently large. Therefore, the satellite system is not affected by the spectral coexistence with the terrestrial backhauling network as the SE values achieved by the *w/ Terrestrial* and *w/o Terrestrial* are the same. By further reducing the number of carriers, the effect of the interference on the satellite link starts becoming visible on the satellite SE. The satellite SE drop is justified by the fact that, as the number of carriers reduces, higher-frequency reuse should be implemented, which translates into a higher-interference environment.

Figure 7 depicts the SE achieved by the proposed algorithm for the integrated terrestrial–satellite network with respect to the number of available carriers. The SE of the terrestrial segment is included in Figure 7 for comparison purposes. Clearly, the SE of the terrestrial network drives the SE of the integrated network, since the number of terrestrial links is much higher than the number of satellite links. Both SE increase as the number of carriers reduces, because the carrier allocation algorithm is able to efficiently manage the resulting terrestrial-to-terrestrial interference. This has a positive effect on the overall integrated network, whose SE increases as the spectrum reuse increases, reaching 200.28 b/s/Hz when $K = 3$. Compared to the 95.67 b/s/
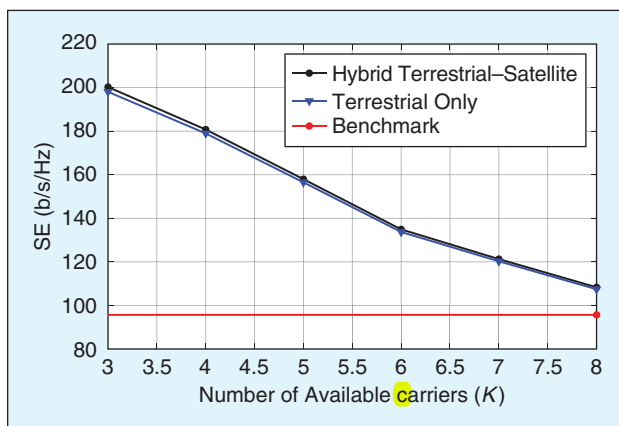
FIGURE 7 The SE of the terrestrial segment and SE of the overall integrated/hybrid network.
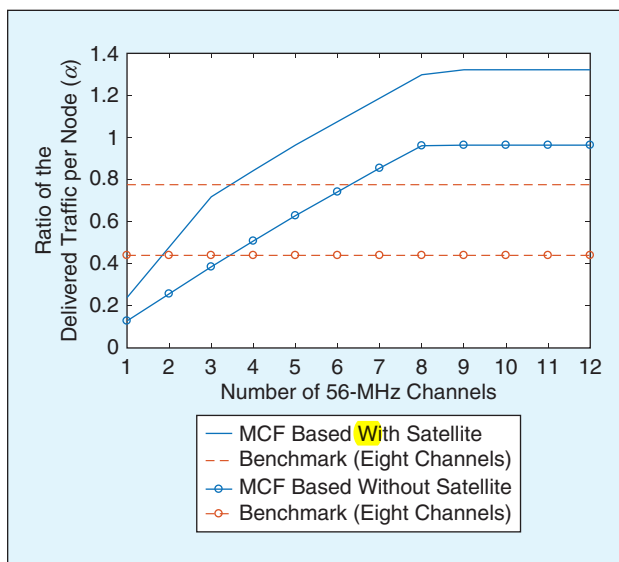

FIGURE 8 The ratio of the delivered traffic per node α against the number of used 56-MHz channels with/without satellite links.

Hz of the benchmark indicated with a red line in Figure 7, the proposed carrier allocation together with the satellite–terrestrial coexistence translates into 2.09 times SE increase.

Considering also the topology depicted in Figure 5, and assuming that both node $N = 8$ as well as the satellite are connected to the core network, we can again model the network using the MCF model. This model is adopted to find the amount of flow that should be scheduled in each link as well as the frequency that should be assigned to this link to maximize the net incoming traffic to the core network. The assignment process should respect the flow conservation laws as well as the capacity constraints. Additionally, the radio constraints should be considered where the half-duplex backhauling nodes do not have broadcasting and multicasting capabilities.

The capacity of the different links is highly dependent on the frequency assignment process as it determines the interfering links that are sharing the same frequency.

These unknown link capacities make the optimization problem nonlinear. To linearize the problem, there must be an estimate of the link capacities that share the same frequency, keeping in mind that the transmit power is fixed for the considered network. To estimate the capacity of the links, we start by evaluating the interference introduced by a given link to the rest of the links if all the links in the network are assumed to share the same frequency. Afterward, the links that generate high interference with each other are considered to be conflict links.

To this end, an additional constraint is added to the original formulation to count for this conflict, which enforces the system not to assign the same frequency to these links [15]. By assuming the worst-case scenario, where all the channels with no conflict to a given link are using the same frequency, the total interference introduced to a given link can be evaluated. Accordingly, the capacity for each link can be calculated and the nonlinear constraints can be converted into linear ones.

By solving the net flow maximization problem for the benchmark scheme for the case where the satellite links are enabled, the delivered data rate is equal to 4,888.10 Mb/s. Considering that the benchmark scheme uses eight channels, each with 56 MHz, the total used bandwidth is 448 MHz. Accordingly, the benchmark SE is 4,888.10/448 = 10.91 b/s/Hz. With disabled satellite links, the delivered data rate is equal to 2,772 Mb/s and the benchmark SE equals to 2,772/448 = 6.1875 b/s/Hz.

Figure 8 depicts the ratio of the delivered traffic per node α against the number of used 56-MHz channels with and without satellite links. Each node is assumed to generate 420-Mb/s traffic. The delivered rate increases as the channel number increases due to the additional transmission bands and reduced interference. For the enabled satellite link case, after nine channels, no increment is achieved by increasing the number of channels as the system is able to manage the link scheduling problem in the network. It can be noted that the proposed MCF-based solution can achieve the delivered rate by the benchmark network by using only four frequency bands. In particular, the SE gain that can be achieved corresponds to 2.47 times compared to the benchmark. Additionally, considering the same bandwidth for both system (i.e., eight channels) the SE improves to 1.6 times, approximately.

For the disabled satellite links case, it is observed that the link scheduling in the network with eight channels has no rate increment when using more channels. It is one channel less in the satellite links case as in this case, the interference and sharing constraints of the problem are reduced by removing the satellite links. In this case, the proposed MCF-based scheme can achieve the delivered rate by the benchmark network by using only four frequency bands, and the SE gain goes up to 2.34 times when considering only two channels. Additionally,

considering the same bandwidth for both systems (i.e., eight channels) the SE improves to two times, approximately. It should be noted that, as expected, disabling the satellite links would reduce the total amount of the delivered traffic as the number of links connecting the network to the core is reduced.

Conclusions

This article reviews the benefits of incorporating satellite links for the terrestrial wireless backhauling network as well as efficient RRM strategies to enable the coexistence between the two systems in the same frequency band, which, on average, double the overall spectral efficiency. Additionally, the article shows how the satellite links can speed the data delivery and how it can provide the system with the required resiliency against link failure or congestion. The advantages of having such an integrated/hybrid network to support the future demands of the wireless backhauling networks is revealed.

Acknowledgments

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