D3.2

MAC layer mechanisms and adaptations for Hybrid Terrestrial-Satellite Backhauling

<table>
<thead>
<tr>
<th>Grant Agreement nº:</th>
<th>645047</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Acronym:</td>
<td>SANSA</td>
</tr>
<tr>
<td>Project Title:</td>
<td>Shared Access Terrestrial-Satellite Backhaul Network enabled by Smart Antennas</td>
</tr>
<tr>
<td>Contractual delivery date:</td>
<td>31/07/2016</td>
</tr>
<tr>
<td>Actual delivery date:</td>
<td>04/08/2016</td>
</tr>
<tr>
<td>Contributing WP</td>
<td>WP3</td>
</tr>
<tr>
<td>Dissemination level:</td>
<td>Public</td>
</tr>
<tr>
<td>Editors:</td>
<td>CTTC</td>
</tr>
<tr>
<td>Contributors:</td>
<td>CTTC, AIT</td>
</tr>
</tbody>
</table>

Abstract:

This deliverable contains studies and results of Task 3.4 MAC Layer Mechanisms and Adaptations which intends to describe the MAC layer mechanisms that enable the hybrid terrestrial-satellite system. The deliverable focuses on investigating an efficient random access technique for access request at the satellite link based on Direct Sequence Spread Spectrum (DSSS) together with Slotted Aloha scheme and also focuses on the cross-layer design of the flow control and link scheduling for the hybrid backhauling network. The benefits of applying the different proposed schemes are analyzed and exploited in this report.
# Document History

<table>
<thead>
<tr>
<th>Version</th>
<th>Date</th>
<th>Editor</th>
<th>Modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>14/03/2016</td>
<td>CTTC</td>
<td>Initial ToC, assignment of responsibilities, short description of awaited contributions.</td>
</tr>
<tr>
<td>0.1</td>
<td>15/07/2016</td>
<td>CTTC</td>
<td>Input by CTTC to the chapter of joint flow control and link scheduling.</td>
</tr>
<tr>
<td>0.2</td>
<td>21/07/2016</td>
<td>CTTC</td>
<td>Simulation result section added and text revised.</td>
</tr>
<tr>
<td>0.3</td>
<td>26/07/2016</td>
<td>AIT</td>
<td>Input by AIT to the chapter of 2 Combination of DSSS and Aloha for The Return Link.</td>
</tr>
<tr>
<td>0.4</td>
<td>27/07/2016</td>
<td>CTTC</td>
<td>Integration of the received input, adding abstract, executive summary, introduction and conclusion sections.</td>
</tr>
<tr>
<td>0.5</td>
<td>01/08/2016</td>
<td>AVA</td>
<td>QA review.</td>
</tr>
<tr>
<td>0.6</td>
<td>02/08/2016</td>
<td>ULUX</td>
<td>QA review.</td>
</tr>
<tr>
<td>0.7</td>
<td>02/08/2016</td>
<td>CTTC</td>
<td>QA Comments addressed and clean version drafted.</td>
</tr>
<tr>
<td>0.8</td>
<td>03/08/2016</td>
<td>AIT</td>
<td>Chapter 2 revised and minor corrections are added.</td>
</tr>
<tr>
<td>0.9</td>
<td>04/08/2016</td>
<td>CTTC</td>
<td>Document revised and minor corrections are added.</td>
</tr>
<tr>
<td>1</td>
<td>04/08/2016</td>
<td>CTTC</td>
<td>Document ready.</td>
</tr>
</tbody>
</table>
Contributors

<table>
<thead>
<tr>
<th>Name</th>
<th>Partner</th>
<th>Contributions include</th>
</tr>
</thead>
<tbody>
<tr>
<td>Musbah Shaat</td>
<td>CTTC</td>
<td>All document</td>
</tr>
<tr>
<td>Kostas Voulgaris</td>
<td>AIT</td>
<td>Chapter 2</td>
</tr>
<tr>
<td>Georgios Ziaragkas</td>
<td>AVA</td>
<td>QA</td>
</tr>
<tr>
<td>Georgia Poziopoulou</td>
<td>AVA</td>
<td>QA</td>
</tr>
<tr>
<td>Christos Tsinos</td>
<td>ULUX</td>
<td>QA</td>
</tr>
</tbody>
</table>
Table of Contents

List of Figures .......................................................................................................................... 6
List of Acronyms ......................................................................................................................... 7
Executive Summary ...................................................................................................................... 8
1 Introduction .................................................................................................................................. 9
2 Combination of DSSS and Aloha for The Return Link .............................................................. 9
  2.1 Introduction .......................................................................................................................... 9
  2.2 Random Access protocols for Satellite Access ................................................................. 10
    2.2.1 Adaptations to Slotted Aloha for Satellite communications ......................................... 11
    2.2.2 DSSS-Slotted Aloha encompassing Polarization Interference Cancellation ................. 13
    2.2.3 Simulation considerations, parameters, and results ....................................................... 13
3 Joint Flow Control and Link Scheduling in Hybrid Terrestrial-Satellite Wireless Backhauling Network ................................................................................................................................. 18
  3.1 Introduction .......................................................................................................................... 18
  3.2 Related Work ......................................................................................................................... 19
  3.3 System Model ....................................................................................................................... 20
    3.3.1 Radio Constraints ........................................................................................................ 22
    3.3.2 Interference Constraints .............................................................................................. 23
    3.3.3 Maximum Hop Count Consideration ........................................................................ 24
  3.4 Mathematical Formulation of the Joint Flow Control and Link Scheduling Problem ........ 25
    3.4.1 Multi-commodity Flow Model and Flow Conservation Constraints ............................. 25
    3.4.2 Link Capacity Constraints ........................................................................................... 25
    3.4.3 Optimization Problem Formulation ............................................................................ 26
  3.5 Solution of the Joint Flow Control and Scheduling problem .............................................. 27
  3.6 Simulation Results ................................................................................................................. 31
    3.6.1 Convergence of the Columns Generation Method ....................................................... 32
    3.6.2 Understanding the Effect of \( \Delta \) ............................................................................ 32
    3.6.3 Link Failure Simulation ............................................................................................... 35
List of Figures

Figure 2-1 Illustration of the CR-DSA algorithm. Collided packets can be recovered through iterative SIC. .................................................................................................................. 12
Figure 2-2 Illustration of DSSS-Aloha with Polarization IC. Up to two collisions in the code and time domains can be resolved using the polarization degree of freedom. ................................................. 13
Figure 2-3 Packet Loss Ratio for the two protocols considered, CR-DSA and DSSS-Aloha with Interference Cancellation ($M = 100, s = 10, c = 2$). .............................................................. 14
Figure 2-4 The expected number of retransmission before an access request packet is successfully received by the satellite ($M = 100, s = 10, c = 2$).................................................................................. 15
Figure 2-5 The effect from the choice of orthogonal codes on the Packet Loss Ration and the Expected number of retransmissions ($M=100,s=5,c=2$) ................................................................................ 16
Figure 2-6 Throughput comparison between the two MAC protocols ($M = 100, s = 10, c = 2$)....... 17
Figure 3-1 Wireless Backhauling Network ................................................................................. 21
Figure 3-2 The simulated wireless backhauling network ............................................................. 31
Figure 3-3 Convergence of the column generation algorithm..................................................... 32
Figure 3-4 Scheduling time vs. traffic demand per node with high $\Delta = 1.$ ............................... 33
Figure 3-5 Scheduling time vs. traffic demand per node with medium $\Delta = 0.016.$ .................. 34
Figure 3-6 Scheduling time vs. traffic demand per node with low $\Delta \approx 0.$ ............................ 34
Figure 3-7 Flow assignment before links failure between nodes 1,2 and the core and before congestion, $\sum \lambda = 0.8750.$ .............................................................................................................. 36
Figure 3-8 Flow assignment after links failure between nodes 1,2 and the core, $\sum \lambda = 0.4250.$ .. 37
Figure 3-9 Flow assignment after links failure between nodes 9 and 10, $\sum \lambda = 0.8222.$ ........... 38
Figure 3-10 Flow assignment after links congestion, $\sum \lambda = 1.$ ........................................... 40
### List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>CR-DSA</td>
<td>Collision Resolution Diversity Slotted Aloha</td>
</tr>
<tr>
<td>CSMA</td>
<td>Carrier Sensing Multiple Access</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>Carrier Sensing Multiple Access with Collision Avoidance</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree of Freedom</td>
</tr>
<tr>
<td>DSA</td>
<td>Diversity Slotted Aloha</td>
</tr>
<tr>
<td>DSSS</td>
<td>Direct Sequence Spread Spectrum</td>
</tr>
<tr>
<td>FDM</td>
<td>Frequency Division Multiplexing</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>GoE</td>
<td>Grade of Experience</td>
</tr>
<tr>
<td>IBFD</td>
<td>In-band full-duplex</td>
</tr>
<tr>
<td>IC</td>
<td>Interference Cancellation</td>
</tr>
<tr>
<td>MCF</td>
<td>Multi-Commodity Flow</td>
</tr>
<tr>
<td>MF-TDMA</td>
<td>Multi Frequency TDMA</td>
</tr>
<tr>
<td>MMSE</td>
<td>Minimum Mean Square Error</td>
</tr>
<tr>
<td>PLR</td>
<td>Packet Loss Ratio</td>
</tr>
<tr>
<td>QoE</td>
<td>Quality of Experience</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RTS/CTS</td>
<td>Request-To-Send and Clear-To-Send</td>
</tr>
<tr>
<td>SIC</td>
<td>Successive Interference Cancellation</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference plus Noise Ratio</td>
</tr>
<tr>
<td>STDMA</td>
<td>Spatial Time Division Multiple Access</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
</tbody>
</table>
Executive Summary

This is Deliverable D3.2 of the SANSA “Shared Access Terrestrial-Satellite Backhaul Network enabled by Smart Antennas” project which forms part of the technical outcome of Task 3.4 “MAC layer mechanisms and adaptations”. The main objective is to tackle the problems of the MAC layer mechanisms and adaptations for Hybrid Terrestrial-Satellite Backhauling. The work related to the state of the art review of the MAC mechanisms in both terrestrial and satellite networks are already anticipated and reported in D3.1 along with the performance curves of the terrestrial and satellite links.

In this deliverable, the problem of satellite link access request is considered first. As the access request is done currently over random access channels, Direct Sequence Spread Spectrum (DSSS) together with Slotted Aloha scheme is developed to take advantage of the Interference Cancellation (IC) based on the polarization. The proposed scheme achieves lower Packet Loss Ratio (PLR) than Collision Resolution Diversity Slotted Aloha (CR-DSA) and also achieves lower estimated number of retransmissions. Additionally, the proposed scheme increases the total throughput that can be carried over the link. In the second part of the deliverable, the problem of cross-layer design of the link scheduling and flow control is studied. Based on the network topology, the proposed scheme decides the links to be activated simultaneously considering network limitations and requirements. Additionally, the proposed scheme provides a way to utilize the satellite links efficiently in order to provide the required link failure resiliency and traffic off-loading capability. As the work in this deliverable considers the different problems from a MAC layer perspective, the work will be continued in the radio resource management task to consider efficient utilization of the network resources and take advantages of the proposed MAC schemes.
1 Introduction

This deliverable aims at providing MAC layer mechanisms and adaptation required to enable the SANSA hybrid terrestrial-satellite backhauling solution. SANSA as a backhauling system treats the MAC problems differently compared to normal multi-user cellular systems scenarios. SANSA system deals with static—in terms of mobility—backhauling nodes. Part of these nodes have terrestrial only transmission capabilities while others have both satellite and terrestrial ones. Accordingly, access control is required to organize the simultaneous/scheduled access to both terrestrial and satellite links. On that track, this deliverable tackles two different problems. In Chapter 2, the problem dealing with the satellite link access requests is tackled. As the access request is currently done by random access techniques, a Direct Sequence Spread Spectrum (DSSS) with Slotted Aloha is developed with the objective of achieving lower packet lost ratio and lower number of required retransmission. In Chapter 3, the problem of cross-layer design of flow control and link scheduling is examined. The target is to decide the active backhauling links that can transmit simultaneously and define a proper way to decide when the satellite links should be used. The deliverable treats the topology as the set of links that can be used in the network. It is worth mentioning that this work deals with the problem from a MAC layer perspective assuming that resources are utilized efficiently. The ongoing work in the resource management task T3.2 is studying the effective way to take advantage of the available resources in the network. The conclusions drawn from the work carried out in this deliverable are summarized in Chapter 4.

2 Combination of DSSS and Aloha for Return Link

2.1 Introduction

SANSA satellite backhauling system offers alternative satellite backhauling for base stations (BSs) in cases where the available terrestrial backhaul network is not available or sufficient. Mobile backhaul is dimensioned to satisfy usual traffic levels, including traffic over busy hours. However, there are cases where the traffic demand exceeds the expected levels. Depending on the extent of unexpected spikes in traffic demand, the Quality of Experience (QoE) and Grade of Experience (GoE) targets may not be met, while in more severe cases the communication may be interrupted altogether.

Cases of high traffic demand can occur in unforeseen circumstances, such as disasters and accidents, when people are interested to find out information about their loved ones, receive security-related information, etc. In the era of ubiquitous and instant information, severe events may affect traffic conditions in geographically uncorrelated areas. For example, terrorist actions have had a significant effect on global mobile traffic with people trying to download information and videos.
In addition to severe circumstances, traffic surges may happen during popular events such as football matches and music concerts. This is further aggravated by the use of social media and new, demand hungry, applications. In many cases new applications can increase traffic faster than the operators’ ability to react by providing additional backhaul capacity. In other cases, upgrading the backhaul capacity to be able to react to unexpected traffic surges is not financially justified.

In addition to traffic surges, fixed backhaul may become unavailable, completely cutting off communication from one or more mobile base stations. This can happen, for example, due to civil works damaging the fiber backhaul infrastructure. The ramifications of this catastrophic break in communications can be severe as services as important as access to lifeline services can be interrupted for hours or days.

Among the aims of SANSA is that of providing a quick backhaul backup solution for cases where installed capacity is inadequate, or completely unavailable through the use of satellite communication links. An important part in setting up a communication link is that of requesting access to the satellite network. Typically, in multiuser systems, access request is done over random access channels as there are not enough resources to allow scheduled access for all users. The DVB-RCS2 protocol for satellite communications defines random access slots which are used for capacity requests and low traffic transmissions where the allocation of dedicated resources would be wasteful. The use of Slotted Aloha and Contention Resolution Diversity Slotted Aloha (CR-DSA) is defined for return channel transmissions in these slots. It is important to note that following the initial capacity request over the RA channels, dedicated resources may be allocated to the terrestrial terminals. Access to these resources is done by using the Multi Frequency TDMA (MF-TDMA) MAC layer protocol, which is very efficient for dedicated, scheduled, transmissions.

In the remaining of this section we propose a new random access MAC protocol for capacity request from the SANSA base stations. The proposed protocol uses Direct Sequence Spread Spectrum (DSSS) and Aloha, along with Interference Cancellation using polarization. We compare our proposition against the CR-DSA and show that our protocol reduces the Packet Loss Ratio, and therefore the expected packet delay, minimizing the time to request satellite backhaul resources.

### 2.2 Random Access protocols for Satellite Access

Satellite communications are a particularly challenging environment for un-scheduled access. This is because of (i) the isolation between terrestrial nodes competing for access and, (ii) the very long propagation delays. Because of (i), Terrestrial Satellite stations cannot hear other stations contending for access which makes Carrier-Sense-Multiple-Access- (CSMA-) type access techniques unusable [1]. Furthermore, (ii) renders signaling-based collision resolution techniques, such as those used in CSMA with Collision Avoidance (CSMA/CA), impractical since they introduce very long delays, reducing the efficiency in utilizing the available radio resources [2].
Due to the limitations above, the established Random Access MAC protocols in satellite applications rely on modified versions of the Aloha protocol [3]. Aloha is widely known in the computer networking field as it was the first random access MAC protocol designed for packet communication. In its most basic form there is no attempt to avoid collisions and every ready station transmits its packet. The peak normalized throughput rate achieved by the Aloha protocol is only ~0.18, meaning that only about 18% of the time the channel is used for successful transmissions. A slight modification of the protocol led to Slotted-Aloha where stations are synchronized and are only allowed to start transmitting at specific, delimited, instances which mark the beginning of the “slots”. The addition of slots reduces the collision vulnerable time (the time during which collided packets may be occupying the shared channel) and doubles the achievable throughput.

Despite the low throughput performance of Aloha, its simplicity and the fact that it does not rely on carrier sensing for scheduling transmissions, make it suitable for resource (capacity) request applications in both cellular and satellite communications. As a result, Slotted Aloha has been adopted as a mandatory feature in the DVB-RCS2 standard [4].

### 2.2.1 Adaptations to Slotted Aloha for Satellite communications

Aloha is the basis for a number of Satellite-tailored MAC protocols. The general idea is to use Aloha to minimize scheduling overheads and introduce redundancy at the PHY or Radio Link layers to resolve collisions. Of particular interest is CR-DSA which is also adopted in the DVB-RCS2 standards.

#### 2.2.1.1 Diversity Slotted Aloha (DSA)

DSA extends Slotted Aloha by requiring each terrestrial satellite terminal to transmit its packets twice. The protocol relies on the lower probability of multiple collisions to effectively double the probability that a packet is received successfully, or halve the probability of collision.

#### 2.2.1.2 Contention Resolution DSA (CR-DSA)

The CR-DSA [5] extends the DSA protocol to further improve the probability of successful reception and, as a result, the packet transmission delay in satellite networks. The idea is that the collided packets can be recovered through iterative Successive Interference Cancellation (SIC) at the receiver [6].

First of all, each terrestrial satellite station chooses two slots from the Random Access slots available in the Return Channel super-frame and transmits a copy of its packet in each of them. The header in each packet includes information on where the receiver can find the other copy of the packet. This information is critical for the protocol and is therefore protected using a pseudo-random sequence at the preamble [5]. Figure 2-1 illustrates the operation of the CR-DSA algorithm. Each column represents a slot, while each row represents transmissions from each of the contending users. Suppose User 1 chooses to transmit in slots 1 and 5 and that the transmission in slot 1 is collision free, while the transmission in slot 5 collides with second transmission attempt from User
2. The receiver uses the “clean” baseband signal received from User 1 to cancel the interference in slot 5 and therefore recover the packet transmitted by User 2. In the second iteration, the receiver uses the recovered baseband signal from User 2 to cancel the interference in slot 2 and recover the transmission from User 3. Finally, the recovered baseband signal from User 3 is used to cancel the interference in slot 4 and recover the packet transmitted by User 4. In this way, the receiver manages to successfully decode all the four packets transmitted, despite the fact that only one packet had not collided.

![Figure 2-1 Illustration of the CR-DSA algorithm. Collided packets can be recovered through iterative SIC.](image)

While CR-DSA improves significantly the maximum achievable throughput for the Random Access Return Channel, it comes with significant requirements:

(i) At least one packet has to be received without suffering collision for the SIC process to begin. If all the packets collide with some other packets, then none of the packets can be received.

(ii) The complete frame has to be received before the SIC processing can begin, which could cause additional delay compared to a scheme where each packet can be processed autonomously.

(iii) Iterative decoding is necessary which adds processing and memory requirements. In practice this means that the processing has to take place at the Satellite Gateway, potentially causing additional delay.

These requirements affect the probability of collision, particularly at high levels of offered traffic load, introduce delays in packet delivery, and due to the heavy processing require that the resource allocation request is forwarded to the Satellite Gateway in order to be processed.
2.2.2 DSSS-Slotted Aloha encompassing Polarization Interference Cancellation

To serve the specific requirements of the SANSA project, we propose the use of DSSS together with Slotted Aloha and to take advantage of Interference Cancellation (IC) based on the polarization of the colliding signals from two separate base stations. Cross-polarization IC is typically used in microwave and earth-satellite links [6]. Using interference cancellation techniques, it is possible to distinguish between two signals that arrive at a random polarization angle at the satellite receiver.

Error! Reference source not found. illustrates the transmission of packets using our proposed access method. Different colors correspond to different orthogonal codes. IC allows up to two transmissions using the same time slot and code to be successfully received. However, if more than three users choose to transmit using the same code, in the same time slot, all three transmissions are considered lost, increasing the Packet Loss Ratio.

![Diagram](image)

*Figure 2-2 Illustration of DSSS-Aloha with Polarization IC. Up to two collisions in the code and time domains can be resolved using the polarization degree of freedom.*

2.2.3 Simulation considerations, parameters, and results

We have implemented MAC-layer simulators for both CR-DSA and DSSS-Aloha with polarization interference cancellation to compare their performance under the same system parameters. We assume ‘M’ BSs compete for random access slots. We further denote the number of timeslots by ‘s’ and the number of orthogonal codes by ‘c’. To make fair comparison between the two protocols we assume that the CR-DSA users can choose between $s \times c$ slots. This is the equivalent of having $c$ parallel channels that can carry the access request packets.
The SIC used in CR-DSA does not always lead to successfully recovering all the transmitted packets. Consider, for example, the case where two base stations have picked the same slots to transmit the two copies of their respective access request packets. It is not possible to recover either of them since there is no clean copy of any of the packets to allow recovery of the colliding one. Similarly, there can exist combinations of packet collisions that cannot be resolved. In addition, depending on the number of contending users and the available slots, the number of SIC iterations (\(i\)) can vary, being larger when more packets are likely to collide. In practical implementations the maximum number of iterations is limited. In [7], a maximum of 10 iterations is suggested, which is the value we used for our simulations.

### 2.2.3.1 Packet Loss Ratio

![Figure 2-3 Packet Loss Ratio](image)

*Figure 2-3 Packet Loss Ratio for the two protocols considered, CR-DSA and DSSS-Aloha with Interference Cancellation (\(M = 100, s = 10, c = 2\)).*

Figure 2-3 compares the Packet Loss Ratio (PLR) for the two protocols against the normalized offered traffic (\(G\)). It can be clearly seen that our proposed approach constantly achieves lower PLR for all the values of offered traffic, and particularly for low values of the offered traffic, which is likely to be the case with base station backhaul access requests.
2.2.3.2 Expected Delay calculations
The total delay from the time that a base station requests satellite backhaul access until it is granted the requested resources is dominated by the propagation delay of the satellite link. For the Geostationary satellites considered in SANSA the propagation delay is in the region of 250ms. Considering further that, currently, the access granting response is provided by the Satellite Gateway, the expected backhaul setup delay is at least 1sec and scales linearly with the number of retransmissions before an access request is successfully received.

The number of retransmissions $K$ before an access request message is successfully received is given by a geometric probability distribution so that $\Pr[K = k] = PLR^k \cdot (1 - PLR)$. The expected number of retransmissions is therefore given by $E[K] = \frac{1}{1-PLR}$. Using the PLR measured for the two protocols in Figure 2-3, we can compute the estimated number of retransmissions, which is shown in Figure 2-4.

![Figure 2-4](image)

*Figure 2-4 The expected number of retransmission before an access request packet is successfully received by the satellite ($M = 100, s = 10, c = 2$).*

2.2.3.3 Effect of the number of orthogonal codes
As expected, the number of orthogonal codes $c$ that is available to the base stations affects the PLR and the expected number of retransmissions before a packet is successfully received, which is shown in Figure 2-5.
Figure 2-5 The effect from the choice of orthogonal codes on the Packet Loss Ratio and the Expected number of retransmissions ($M=100, s=5, c=2$)

(a) Packet Loss Ratio

(b) Expected number of retransmissions ($K$)
While we propose the use of DSSS-Aloha with Polarization Interference Cancellation as MAC layer protocol to be used by the SANSA base stations for requesting satellite backhaul connection, the use of orthogonal codes, along with interference cancellation can increase the total throughput that can be carried over the satellite link. This is demonstrated in Figure 2-6, below. The maximum achievable throughput for DSSS-Aloha is approximately 1.66. This is because interference cancellation using polarization allows for more than one packets to be received over the same time and code resources.

*Figure 2-6 Throughput comparison between the two MAC protocols (M = 100, s = 10, c = 2).*
3 Joint Flow Control and Link Scheduling in Hybrid Terrestrial-Satellite Wireless Backhauling Network

3.1 Introduction

Wireless backhauling provides an alternative efficient solution to complement the wired backhauling solution of leasing bundled copper wires or using optical fiber cables due to their easy and low cost deployment and maintenance. The wireless backhauling should provide high throughput and reliable service to the end users as the wired backhauling does. Additionally, the different data applications which may contain a large volume of traffic should be supported. Accordingly, appropriate protocols as well as advanced radio technologies should be applied to boost the capacity of these wireless links.

SANSA backhauling system utilizes smart antennas to provide high capacity wireless backhauling links and incorporates satellite backhauling links additionally. The smart antennas improve the network throughput and reduce the interference by utilizing the transmitter and receiver Degrees of Freedom (DoFs) to transmit/receive parallel streams, to suppress the interference from other active links as well as combat the channel fading. Additionally, antenna directivity provides longer transmission range and lower power consumption. The satellite links can provide additional capability to the wireless backhauling network to serve higher user demands. Accordingly, satellite links are not only used to increase the terrestrial links fault tolerance, but also in cases where traffic offloading is needed or in zones where terrestrial links have no coverage.

In wireless backhauling system, achieving maximum throughput in the network is not an easy task as it is not a question of optimizing the transmission parameters only, but it also requires a cross-layer optimization between the different layers to handle intelligently the link scheduling and traffic demand over the scheduled links. The backhauling nodes operate as a gateway access point to its associated access nodes and in the same time as a wireless router to other nodes’ traffic. By an adequate link activation policy, concurrent transmission of links that are geographically separated can be achieved in the network while maintaining the Signal to Interference plus Noise Ratio (SINR) above the expected receiving threshold, which increases the spectral efficiency and exploit the flexibility of the wireless network. On top of that, SANSA backhauling network introduces additional satellite links to the conventional terrestrial wireless backhauling network, which offers additional DoFs that should be explored by the network.

This chapter tackles the problem of cross-layer design of flow control and link scheduling policy in hybrid terrestrial-satellite wireless backhaul network. By the flow control, the amount of data that
belongs to the traffic generated in the network on the different links is decided. The decision is taken based on the different links capacities and the volume of the generated traffic. On the other hand, the link scheduling determines the links that should be activated concurrently considering the network limitations and requirements. The overall target is to deliver the traffic demand efficiently taking into account the different characteristics of the terrestrial and satellite links.

3.2 Related Work
The problem of joint routing and scheduling in wireless mesh network is NP-complete problem [8], [9].

MAC protocol design for ad-hoc multi-antenna network is studied widely in the literature, e.g. see [10]-[13] and references therein. The schemes are based mainly on suboptimal heuristic algorithms. The techniques developed for ad-hoc networks are not suitable for backhaul mesh networks.

Cross physical and MAC layers design for multi-hop wireless mesh network using heuristic schemes are proposed in [14]-[16] while the design with MIMO equipped nodes is tackled in [17]-[20].

In relation with the scheduling problem in wireless mesh networks, centralized scheduling and routing tree construction algorithms to provide per flow Quality of Service (QoS) is investigated in [21] with no spatial reuse. The scheme is developed in [22] to consider the spatial reuse. A scheduling algorithm is developed in [23] to maximize the system utilization and achieve a proposed fairness objective that is linked with the actual traffic demand. In [24], the interference impact and the available DoFs in each node are considered using an interference aware tree construction routing algorithm. The scheduling is performed via heuristic algorithms.

The cross routing and link scheduling problem has been considered widely, e.g. see [19],[25]-[31] and references therein. [32] showed that routing using shortest path without any consideration of interference can lead to significant performance degradation. In [25], cross layer design of wireless network with MIMO enabled nodes under power constraints is studied. The non-linear problem is solved by decomposing the problem into several sub-problems that solved in a distributed manner. Afterwards, Heuristic algorithm is proposed to solve the same problem with lower computational complexity. In [26], Joint optimal design of routing and MAC scheduling with beamforming at the physical layer is considered. The dual decomposition method is used to decouple the routing and scheduling sub-problems. In [19], the cross-layer optimization in Time Division Multiple Access (TDMA)-based multi-hop wireless network with MIMO link is investigated. A constant factor approximation and heuristic algorithms are proposed. Distributed link scheduling and power control algorithm based on decomposing the system into multiple isolated MIMO broadcast subsystems is proposed in [27]. In [28], joint optimization of routing and scheduling is considered where the interfering links are determined according to the distance between the nodes. In [29], two different problems are considered, the first problem evaluates the amount of flow on each link considering
the interference between the different links while the second problem decides the link scheduling given the known amounts of flow per link. In [30], the routing and scheduling scheme is proposed to handle the traffic dynamics and traffic uncertainty. In [31], Interference aware joint routing and link scheduling for static wireless networks is studied. The links are scheduled either in Request-To-Send and Clear-To-Send (RTS/CTS) interference model or protocol interference model with fixed transmission power.

For the Carrier Sensing Multiple Access (CSMA) based mesh networks, CSMA- based distributed scheduling in multi-hop MIMO networks under Signal to Interference plus Noise Ratio (SINR) model is proposed in [32]. Capacity region of wireless mesh network over Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) MAC is investigated in [34]. Upper and lower bounds of the network throughput are also derived. Two link scheduling schemes based on interference cancellation techniques are proposed in [34] to exploit the spatial multiplexing and to overcome the limitations of CSMA/CA scheme.

The work in this chapter is different from the already mentioned papers in that it considers the joint flow control and link scheduling in Spatial Time Division Multiple Access (STDMA) based wireless backhaul network where both terrestrial and satellite links are available in the system. The problem is solved by taking into account the use of the satellite links only in cases of traffic offloading, link failure and remote access. However, the system is able to use satellite links all the time in case the cost is not a concern.

3.3 System Model
The system considered in this work is a multi-hop 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 reach the core network through multi-hop links. Additionally, some BSs have hybrid terrestrial-satellite communication capabilities which enable them to reach the core network through satellite. The considered multi-hop network is depicted in Figure 3-1.
The network is modelled as a directed graph $G = \{N, L\}$ where $N = \{0, 1, \ldots, N\}$ is the set of all backhauling nodes (vertices) $n$ equipped with multiple antennas with $D_n$ DOFs. The zero node represents the core network and $L$ is the set of all available links (edges). A link exists between two nodes if they are in the transmission range of each other, i.e. $L = \{l, d_{t(l),r(l)} \leq T_{t(l)}, t(l) \in N, r(l) \in N, l(l) \neq r(l)\}$ where $d_{t(l),r(l)}$ is the distance between the transmitter on the $l^{th}$ link, $t(l)$, and the receiver on the $l^{th}$ link, $r(l)$. $T_{t(l)}$ is the transmission range of the transmitting node $t(l)$. The incidence matrix of the graph $G$ is defined as follows

$$I(n,l) = \begin{cases} 1, & \text{if the node } n \text{ is transmitting on } l, \\ -1, & \text{if the node } n \text{ is receiving on } l, \\ 0, & \text{otherwise} \end{cases} \quad (3-1)$$

Additionally, to indicate whether a given link is active or not in a given scheduling configuration, the following binary variable is defined

$$a_i^c = \begin{cases} 1, & \text{if the link } l \text{ is active in } c \\ 0, & \text{otherwise} \end{cases} \quad (3-2)$$
where $c$ is a possible link scheduling configuration that includes all the active links, i.e. $c = \{a^c_l, \forall l \in \mathcal{L}\}$.

We are considering the uplink scenario, where the traffic generated at the different BSs is transmitted to the core network. However, a similar approach can be used for the downlink case. Not all the links in the system can be active in the same time due to radio or interference constraints. Accordingly, the objective is to decide which link scheduling configuration should be active at a given time scheduling interval and decide in the same time the amount of flow that should be transmitted on the different active links of the selected scheduling configuration. Accordingly, STDMA is employed to the time slots to be shared by simultaneous transmission once possible. In the following subsections, details of the radio and interference constraints are discussed. An additional constraint on the maximum number of hops that can be used to reach the destination is also reviewed.

### 3.3.1 Radio Constraints

The transceivers in the backhauling nodes are assumed to be working in half-duplex mode. Accordingly, any backhauling node can either transmit, or receive and suppress interference at the same time. This is usually called the primary conflict. Define $\mathcal{L}_n = \{O^n_+ \cup O^n_\}$ to be the set of the links that are connected to the node $n$ where $O^n_+$ is the set of ongoing links of node $n$, i.e. $O^n_+ = \{l: I(n,l) = 1\}$ while $O^n_-$ is the set of ingoing links to node $n$, i.e. $O^n_- = \{l: I(n,l) = -1\}$. To satisfy the radio constraint, the links with no primary conflict in a given scheduling configuration $c$ should satisfy the following constraint

$$a^c_j + a^c_k \leq 1 \ \forall n \in \mathcal{N}, j \in O^n_+, k \in O^n_-$$

(3-3)

Or equivalently

$$\sum_{j \in O^n_+, k \in O^n_-} a^c_j a^c_k = 0, \ \forall n \in \mathcal{N}. \quad (3-4)$$

When multiple link transmission is not allowed, i.e. single transmission link per node, the half-duplex transmission constraint becomes

$$\sum_{l \in \mathcal{L}_n} a^c_l \leq 1 \ \forall n \in \mathcal{N}$$

(3-5)

A system with a full duplex Frequency Division Duplexing (FDD) capabilities can transmit and receive simultaneously and hence, this radio constraint is not applied. This is also valid if the system uses any In-band full-duplex (IBFD) techniques.
3.3.2 Interference Constraints

The activation of the links does not depend only on the radio limitation, but also on the level of interference between the neighboring nodes. Accordingly, two interfering links should not be activated simultaneously. This type of conflict is called the secondary conflict. A scheduling configuration is the set of links that are free from both primary and secondary conflicts. As the interference cannot be eliminated completely while sharing network resources, minimum SINR guarantee on every active link is a possible way to decide the active links. Two different formulations have been followed in the literature to decide the links that should be eliminated due to secondary conflicts.

The first formulation is depending on the number of DOFs available for the different nodes in the network. By the transmit DoFs, we refer to the number of independent data streams that can be transmitted by a given backhauling node either over one link or multiple links. Additionally, the receiving DoFs refers to the number of independent streams that can be received simultaneously by a given backhauling node over one or multiple links. Moreover, Part of the receiving DoFs can be utilized by the receiver to suppress interfering transmissions. The used DoFs are similar to the number of the interfering streams. As discussed in [19]-[36], assume that \( t_n \) and \( r_n \) represent the effective transmit and receive DOFs and \( \hat{L} \) be the set that includes the interfering links free of primary conflict. Define \( \hat{L}_t^+ \) to be the set of links whose correct reception is affected from transmit on the link \( l \) and \( \hat{L}_t^- \) the set of links whose transmission affects the reception on the link \( l \). Additionally, we define the binary variables \( \alpha_{j,k}^f \) and \( \beta_{j,k}^f \) that have a nonzero value when both the links \( j \) and \( k \) are active and the interference is nullified at the transmitter in the former or suppressed at the receiver in the latter binary variable. Accordingly, the following set of constraints should be satisfied to resolve secondary conflicts of the links:

\[
\begin{align*}
\sum_{j \in O_n^+} a_j^c + \sum_{k \in \hat{L}_t^+} \alpha_{j,k}^c & \leq t_n & \forall (j, k) \in \hat{L} & (3-6) \\
\sum_{k \in O_n^-} a_k^c + \sum_{j \in \hat{L}_t^-} \beta_{j,k}^c & \leq r_n
\end{align*}
\]

\[
a_j^c + a_k^c \leq \alpha_{j,k}^c + \beta_{j,k}^c + 1 & \forall (j, k) \in \hat{L} & (3-7)
\]

\[
\begin{align*}
\alpha_{j,k}^c & \leq a_j^c & \forall (j, k) \in \hat{L} & (3-8) \\
\beta_{j,k}^c & \leq a_k^c & \forall (j, k) \in \hat{L}
\end{align*}
\]

\[
\alpha_{j,k}^c + \beta_{j,k}^c \leq 1 & \forall (j, k) \in \hat{L} & (3-9)
\]

Constraint (3-6) ensures that the available effective DOFs are used either in the transmitting or receiving nodes to have secondary conflict free links. Constraint (3-7) prevents the interfering links from being active if no nullifying or suppressing DOF is associated to either the transmitter or the
receiver respectively. Additionally, constraint (3-8) guarantees that no DOF is associated to the non-active links in the scheduling configuration c. Constraint (3-9) prevents the use of the DOFs by both the transmitter and the receiver and ensures that only one DOF is used for one transmission. The same set of constraints is used in case the multiple link transmission is not allowed. The only change is that constraint (3-6) becomes

\[
\begin{align*}
1 + \sum_{k \in \hat{L}_t} \alpha_{j,k}^c & \leq t_n \\
1 + \sum_{j \in \hat{L}_t} \beta_{j,k}^c & \leq r_n
\end{align*}
\]  
\tag{3-10}

The stream control and scheduling problem proposed in [19], which is based on a similar formulation can be adopted to find the links that are free from the secondary conflict.

The second formulation is based on solving the problem of finding the transmit and receive beamforming weights. Assuming that all the nodes have the same number of antennas M and assuming that the transmit power at the transmitter on link t(l) is $P_l$, then the SINR $\Gamma_l$ at the receiver on the link l when the power noise is normalized to unity is

\[
\Gamma_l = \frac{G_{r(l) t(l)} P_l}{1 + \sum_{l' \neq l, l \in \hat{L}} G_{r(l) t(l')} P_{l'}}
\]  
\tag{3-11}

where $G_{r(l) t(l)}$ denotes the channel gain between $t(l)$ and $r(l)$. If we define $w_l, g_l \in \mathbb{C}^M$ to be the unit-norm receive and transmit beamformer weights and $H_{r(l) t(l)}$ to be the channel matrix between $t(l)$ and $r(l)$, then $G_{r(l) t(l)}$ is given by

\[
G_{r(l) t(l)} = |w_l^H H_{r(l) t(l)} g_l|^2
\]  
\tag{3-12}

The optimal receive beamformer that maximize the SINR with fixed transmit power and beamforming weights is equivalent to the one that minimizes the Minimum Mean Square Error (MMSE). However, considering the coupling between the different links, finding the optimal transmit beamformer is not trivial [26],[37]. One possible approach to check the secondary conflict is the one proposed in [37]. With a given set of initial links, the algorithm checks if a feasible solution is available. If the algorithm diverges, the link with lowest SINR is dropped and the algorithm is reapplied. This process is repeated until the algorithm converges.

### 3.3.3 Maximum Hop Count Consideration

Excluding extra-long routes can help in reducing the delay in the network. By assuming that $R_{th}$ is the threshold such that the maximum hop count between a given backhauling node and the core network is smaller than the multiplication of this threshold by $Z_{\text{min}}$. $Z_{\text{min}}$ denotes the shortest distance in terms of hop count between the backhauling node and the core network. The route...
exclusion is performed on the different scheduling configurations. This constraint is optional and depends on the specific requirements of the system and is more applicable for larger network than we consider in the simulation section afterwards.

3.4 Mathematical Formulation of the Joint Flow Control and Link Scheduling Problem

As described before, we are interested in the problem of upstreaming the aggregated traffic from the different users in a given geographical area to the core network. A similar approach can be followed for the downstream as well. The target is 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. Before formulating the main mathematical problem, the adopted flow model and MAC layer capacity constraint are explained in the following subsections.

3.4.1 Multi-commodity Flow Model and Flow Conservation Constraints

We are assuming that the aggregate traffic demand per cell is constant over the scheduling execution time where \( T = \{ T_1, \ldots, T_N \} \) denotes the traffic demand vector with \( T_n \) representing the traffic demand at the backhauling node \( n \). The Multi-Commodity Flow (MCF) model is assumed here, considering that the queuing effect is negligible at each backhauling node. The generated traffic at each backhauling node is considered as a single commodity \( s_n \), where \( T = \sum_{n\in\mathcal{N}} s_n \). Note that Node 0 which represents the core network has no generated traffic as it is the destination for the traffic generated at the different backhauling nodes. Let \( f_{l}^{d} \) to represent the amount of flow assigned to the \( l \)th link and corresponding to the commodity \( d \). The flow conservation law should be satisfied to ensure that the sum of ingoing and outgoing flows belong to the commodity \( d \) at each relaying backhauling node is equal; which can be expressed mathematically as

\[
\sum_{l \in O_n} f_{l}^{d} = \sum_{l \in O_n} f_{l}^{d}, \quad \forall n \in \mathcal{N} \setminus \{0, d\}, d \in \mathcal{N} \setminus \{0\} \tag{3-13}
\]

Note that Nodes 0 and \( d \) are excluded in the previous equation as they are representing the source and destination nodes. For each source backhauling node, the sum of the traffic should be equal to the amount of the traffic generated in the node as given in the following equation

\[
\sum_{l \in O_n} f_{l}^{d} - \sum_{l \in D_n} f_{l}^{d} = s_d, \quad \forall d \in \mathcal{N} \setminus \{0\} \tag{3-14}
\]

3.4.2 Link Capacity Constraints

The sum of flows belonging to different commodities which are passing through a given link should not exceed the capacity of that link. Let \( \lambda_c \) to denote the fraction of time in which the scheduling
configuration \( c \) is active and \( \bar{C} \) to represent the number of all possible scheduling configurations, hence the effective MAC layer capacity is expressed as

\[
\sum_{d \in \mathcal{N}} f_l^d \leq \sum_{c \in \bar{C}} \lambda_c a_c^c x_l, \forall l \in \mathcal{L}
\] (3-15)

where \( x_l \) is the physical layer capacity which depends on the physical layer resource like power, bandwidth, interference, etc.

### 3.4.3 Optimization Problem Formulation

The joint flow control and link scheduling problem can be mathematically formulated as follows:

\[
\min U(s, \lambda, f)
\]

subject to

\[
C1: \sum_{l \in \mathcal{O}_n^+} f_l^d = \sum_{l \in \mathcal{O}_n^-} f_l^d, \ \forall n \in \mathcal{N} \setminus \{0, d\}, d \in \mathcal{N} \setminus \{0\}
\]

\[
C2: \sum_{l \in \mathcal{O}_n^+} f_l^d - \sum_{l \in \mathcal{O}_n^-} f_l^d = s_d, \ \forall d \in \mathcal{N} \setminus \{0\}
\] (3-16)

\[
C3: \sum_{d \in \mathcal{N}} f_l^d \leq \sum_{c \in \bar{C}} \lambda_c a_c^c x_l, \forall l \in \mathcal{L}
\]

\[
C4: f_l^d \geq 0
\]

\[
C5: \lambda_c \geq 0
\]

where \( C1 \) and \( C2 \) satisfies the flow conservation law while \( C3 \) represents the MAC layer capacity constraints. Constraints \( C4 \) and \( C5 \) ensures positive values of the amount of flow and the scheduling configuration time ratios. It is assumed that the traffic is admissible, i.e. \( \sum_{c=1}^{C} \lambda_c \). In case of not having an admissible traffic, admission control criterion should be applied in order to deliver the traffic.

\( U(s, \lambda, f) \) represents the utility function which was selected in a way that captures the objective of both minimizing the scheduling time to deliver a fixed amount of traffic and at the same time to account the cost of using the satellite links when compared with the terrestrial links. Accordingly, the utility function is formulated as
where $\Delta$ is a positive constant that is multiplied with the sum of flows on the satellite links. $\mathcal{S}$ is the set that contains all the satellite links. Once an amount of flow is allocated to any satellite link, the utility function increases. However, the effect of this increment on the utility function is calibrated by selecting the value of $\Delta$. By considering this utility function, the satellite links are used in case the amount of traffic is not schedulable by the terrestrial nodes or in case of link failure that prevents a node from reaching the core network. With this approach, we are taking advantage of the inclusion of higher capacity satellite links with continues availability and with no interference with the terrestrial links, and avoiding the disadvantages of utilizing the satellite links when the terrestrial network is capable of scheduling the traffic.

### 3.5 Solution of the Joint Flow Control and Scheduling problem

To obtain the optimal solution for problem (3-16), all the scheduling configurations should be generated so that the problem is solved over all of them. Generating all the possible configurations is not practical as the number of configurations grows exponentially with the size of the network. Alternatively, column generation technique can be used to solve the problem over a subset of the possible scheduling configurations $[38],[39]$. This approach is widely applied in large sized linear programming setups. In general terms, the column generation method has two main parts, the master problem and the pricing one. The master problem consists of solving the original problem with a restricted scheduling configurations while the pricing problem incorporates the dual variables found by the master problem to find the new scheduling configuration (column) to be added to the initial restricted scheduling configurations. The process continues until no new/better scheduling configuration is added. Let $\tilde{C}_T \subset \tilde{C}$ represents a subset of the scheduling configurations, hence the master problem can be re-formulated mathematically as follows
\[
\min \sum_{c=1}^{C_T} \lambda_c + \Delta \sum_{l \in S} \sum_{d \in N} f_l^d
\]

subject to

\begin{align}
C1: & \sum_{l \in O_n^+} f_l^d = \sum_{l \in O_n^-} f_l^d, \; \forall n \in \mathcal{N} \setminus \{0, d\}, \; d \in \mathcal{N} \setminus \{0\} \\
C2: & \sum_{l \in O_n^+} f_l^d - \sum_{l \in O_n^-} f_l^d = s_d, \; \forall d \in \mathcal{N} \setminus \{0\} \\
C3: & \sum_{d \in \mathcal{N}} f_l^d \leq \sum_{c \in \mathcal{C_T}} \lambda_c \alpha_l^c x_l, \forall l \in \mathcal{L} \\
C4: & f_l^d \geq 0 \\
C5: & \lambda_c \geq 0
\end{align}

To solve problem (3-18) by applying the dual composition technique, the dual problem associated with the primal problem (3-18) can be written as

\[
\max g(\mu_l) \\
\text{subject to} \; \mu_l \geq 0, \forall l \in \mathcal{L}
\]

where \(\mu_l\) are the dual variables associated with the MAC layer capacity constraint and \(g(\mu_l)\) is the dual function defined as follows

\[
g(\mu_l) = \min \mathcal{F}(\lambda_c, f, \mu_l)
\]

subject to

\begin{align}
\sum_{l \in O_n^+} f_l^d = \sum_{l \in O_n^-} f_l^d, \; \forall n \in \mathcal{N} \setminus \{0, d\}, \; d \in \mathcal{N} \setminus \{0\} \\
\sum_{l \in O_n^+} f_l^d - \sum_{l \in O_n^-} f_l^d = s_d, \; \forall d \in \mathcal{N} \setminus \{0\} \\
f_l^d \geq 0 \\
\lambda_c \geq 0
\end{align}
where $F(\lambda_c, f, \mu_l)$ is the Lagrangian function given by

$$F(\lambda_c, f, \mu_l) = \sum_{c=1}^{C_T} \lambda_c + \Delta \sum_{l \in L} \sum_{d \in N \setminus \{0\}} f_l^d + \sum_{l \in L} \mu_l \left( \sum_{d \in N \setminus \{0\}} f_l^d - \sum_{c \in C} \lambda_c a_l^c x_l \right)$$ (3-21)

The Lagrangian function can be re-arranged as

$$F(\lambda_c, f, \mu_l) = \sum_{c=1}^{C_T} \lambda_c - \sum_{l \in L} \mu_l \sum_{c \in C_T} \lambda_c a_l^c x_l + \Delta \sum_{l \in L} \sum_{d \in N \setminus \{0\}} f_l^d + \sum_{l \in L} \mu_l \sum_{d \in N \setminus \{0\}} f_l^d$$ (3-22)

The first two terms contain the link scheduling variable $\lambda_c$ while the last two terms contain the flow control variable $f_l^d$. Accordingly, the dual function can be separated into two independent sub-problems. The link scheduling sub-problem can be formulated as

$$\min \quad \sum_{c=1}^{C_T} \lambda_c - \sum_{l \in L} \mu_l \sum_{c \in C_T} \lambda_c a_l^c x_l$$

subject to

$$\lambda_c \geq 0, \forall \ c \in C_T$$ (3-23)

and the flow control sub-problem can be formulated as

$$\min \quad \Delta \sum_{l \in L} \sum_{d \in N \setminus \{0\}} f_l^d + \sum_{l \in L} \mu_l \sum_{d \in N \setminus \{0\}} f_l^d$$

subject to

$$\sum_{l \in L} f_l^d = \sum_{l \in L} f_l^d, \forall n \in N \setminus \{0, d\}, d \in N \setminus \{0\}$$ (3-24)

$$\sum_{l \in L} f_l^d - \sum_{l \in L} f_l^d = s_d, \forall d \in N \setminus \{0\}$$

$$f_l^d \geq 0$$
The subgradient method \[40\] is used to solve the dual problem with guaranteed convergence. After finding the optimal solution, i.e. \(f_l^{d*}\) and \(\lambda_{c}^{*}\) of the dual function at a given dual point \(\mu_i\), the dual variables at the \((i + 1)^{th}\) iteration are updated as follows

\[
\mu_i^{(i+1)} = \mu_i^{(i)} - \delta^{(i)} \left( \sum_{d \in \mathcal{N}, d \neq 0} f_l^{d} - \sum_{c \in \mathcal{C}} \lambda_c a_{l}^{c} x_l \right) \quad (3-25)
\]

where \(\delta^{(i)}\) is the step size that can be updated according to the nonsummable diminishing step size policy \[40\].

Once the master problem is solved, the pricing problem is solved by ensuring that the reduced cost of any new scheduling configuration satisfies

\[
\min_{c \in \mathcal{C} \setminus \mathcal{C}_T} 1 - \sum_{i \in \mathcal{C}} a_{l}^{i} \mu_i < 0 \quad (3-26)
\]

If the resulting reduced cost is not negative or the obtained configuration set is already available in \(\mathcal{C}_T\), the obtained solution of the master problem is the optimal solution of the main problem. If the cost is negative, the obtained scheduling configuration is added to \(\mathcal{C}_T\) and the master problem is solved again.

Note that the previous problem formulation is considering an STDMA network. However, if Frequency Division Multiple Access (FDMA) is applied and if the link transmission frequencies are pre-assigned and fixed with the initial network deployment, the problem is converted into flow control without scheduling. Nevertheless, the formulation is still valid and amount of flow per link is evaluated under a single scheduling configuration. On the other hand, if adaptive frequency allocation is possible for the backhauling nodes, the same approach can be followed in general. However, different mathematical formulation for the different constraints should be used depending on the frequency reuse ability of the system.

To summarize the solution procedures, firstly a subset of the scheduling configurations is selected. Afterwards, the master problem is solved considering the restricted scheduling configuration set to find the dual variables related to the MAC layer capacity constraints. These dual variables are used to find a possible new scheduling configuration via solving the pricing problem. Depending on the reduced cost value and the existence of the obtained scheduling configuration in the subset used by the master problem, the algorithm decides whether the solution is found or a new iteration is required after adding the obtained scheduled configuration to the initial restricted subset.
3.6 Simulation Results

To show the performance of the proposed scheme, the topology depicted in Figure 3-2 is considered with 11 nodes and 34 directional links. The numbers above the links refer to the link’s number. The mobile core network is referenced as Node 0. Nodes 4 and 10 are assumed to be hybrid satellite-terrestrial nodes and connected to satellite (Node 11) while the rest of the nodes are assumed to be terrestrial only. The satellite node is forwarding the incoming traffic and has no generated traffic. We assumed that the system has sufficient resources and DoFs to use these links and maintain the minimum required SINR on the links. However, this is a general case and other techniques provided in section 3.3.2 can be used to avoid the transmission on the interfering links. The scheme provided in this simulation is general and can be applied to any considered set of the scheduling configurations. All the nodes traffic demands as well as the channel capacities are normalized to 1 Mbps. We consider that the two satellite links have capacities of 160 bps which is the double of the capacities of the terrestrial links. The algorithm performance is not dependent on specific selection of these parameters. We always consider the uplink streaming; however, the downlink streaming is similar and can be adopted accordingly. The starting set of scheduling configurations $\hat{C}_T$ represents a simple TDMA scheme, i.e. only one link is active in every scheduling configuration.

Figure 3-2 The simulated wireless backhauling network.
3.6.1 Convergence of the Columns Generation Method

First, we compare the performance of the proposed scheme at different iterations and check the convergence of the column generation method to the optimal solution. The optimal solution is evaluated considering all the maximal transmission sets. The scheduling cost against the iteration number is plotted in Figure 3-3 with $\Delta = 1$ and different traffic demands. All the terrestrial nodes are assumed to have the same amount of generated traffic. It is revealed that the column generation technique is capable of achieving the optimal solution with a few iterations. The dotted horizontal lines represent the optimal value for each traffic demand. It can be seen from the figure, that more scheduling cost is required when the traffic demand per node increases. This is due to the need of scheduling higher traffic and the use of the different scheduling configurations for an extended period of time.

![Figure 3-3 Convergence of the column generation algorithm.](image)

3.6.2 Understanding the Effect of $\Delta$

The utility function in equation (3-17) has two main parts. The first part represents the scheduling cost, which is the summation of the fraction of time over which a given scheduling configuration is
used. The second part consists of the multiplication of constant $\Delta$ by the traffic flow on the satellite links. Selecting high value of $\Delta$ enforces the system to avoid transmitting on satellite links unless the traffic is not schedulable by the terrestrial network. This case is considered as the most logical case to avoid the high cost of the satellite links and only enable its usage when necessary. Another case is considering a zero or close to zero $\Delta$. In this case, the system assumes that the satellite links are always available even for a small amount of traffic. The third case considers selecting a value for $\Delta$ that makes the system behave in an intermediate state between blocking the use of satellite if the terrestrial links are sufficient and enable the free use of the satellite links. As already mentioned, the case of high value of $\Delta$ is preferable from our point of view and is used for the rest of simulations.

Figure 3- 4, Figure 3- 5, and Figure 3- 6 depict the scheduling cost of the network with high $\Delta$ ($\Delta = 1$), medium $\Delta$ ($\Delta = 0.016$) and low $\Delta$ ($\Delta = \varepsilon \approx 0$) respectively. The proposed utility function is compared for three cases; network with the cases of having always available satellite links and with no available satellite links. We referred to these cases by “SAT ON” and “SAT OFF”, respectively.

![Graph](image)

*Figure 3- 4 Scheduling time vs. traffic demand per node with high $\Delta = 1$.***
Figure 3-5 Scheduling time vs. traffic demand per node with medium $\Delta = 0.016$.

Figure 3-6 Scheduling time vs. traffic demand per node with low $\Delta \approx 0$. 
For all simulated values of $\Delta$, the scheduling time increases with the increment of the traffic per node and always the “SAT ON” scheme has the lowest scheduling cost. As expected, when the traffic is schedulable by the terrestrial nodes, the proposed utility function network acts as either “SAT OFF” or “SAT ON” depending on what the value of $\Delta$ is. Once the traffic is not schedulable by the terrestrial nodes, i.e. the scheduling cost is more than one, the satellite links are used with the terrestrial ones to schedule the traffic. The value of the scheduling cost is always one because the algorithm, by applying the proposed utility function, tries to reduce as much as possible the amount of traffic transmitted by the satellite links. Hence, it is not searching only for the scheduling configurations that enable reduced scheduling time but also that allow minimal traffic to flow over the satellite links.

### 3.6.3 Link Failure Simulation

In this part, we simulate the link failure. We select $\Delta = 1$ and the amount of traffic demand per node to be $s_d = 10$. Firstly, we assume that links between the Nodes 1,2 and the core network are failed. Accordingly, the nodes have to reach to the core network through the satellite. Figure 3-7 and Figure 3-8 depict the flow assignment per link before and after the link failure respectively. The thickness of the lines represents the amount of flow on that link. The red-colored lines represent the generated traffic per nodes while the green one represents the traffic received by the core network. Dashed line represents available links with zero traffic.

Additionally, link failure between the Nodes 9 and 10 is simulated. Figure 3-9 depicts the flow assignment per link after the link failure. The before link failure traffic assignment is already plotted in Figure 3-7. With this failure, link 10 should reach the core through the satellite. Additionally, with this link failure, Node 10 represents a remote cell use-case such as a separated rural node with only satellite backhauling. It is worth noting that only the traffic of Node 10 is transmitted via satellite while the flow assignment of the other nodes remains the same.
Figure 3: Flow assignment before links failure between nodes 1,2 and the core and before congestion, 
\[ \sum_c \lambda_c = 0.8750. \]
Figure 3- 8 Flow assignment after links failure between nodes 1,2 and the core, $\sum c \lambda_c = 0.4250$. 
Figure 3-9 Flow assignment after links failure between nodes 9 and 10, $\sum \lambda_c = 0.8222$. 
3.6.4 Link Congestion Simulation

In this part, we simulate the link congestion. We select $\Delta = 1$ and the amount of traffic demand per node to be $s_d = 10$ prior to congestion. It is assumed that the traffic generated at Node 4 is increased due to an event with $s_4 = 100$. 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. Figure 3-10 depicts the flow assignment per link after the congestion. The prior to congestion traffic assignment is already plotted in Figure 3-7.
Figure 3-10 Flow assignment after link congestion, $\sum_c \lambda_c = 1$. 
4 Conclusions

This deliverable is part of the work carried out in task T3.4 and consists with D3.1 the output of the work performed in this task. The deliverable is composed of two main parts. The first part considers the problem of satellite link access via random access techniques. By taking advantage of the ability of the interference cancellation techniques to distinguish between two signals that arrive at a receiver with random polarization angle, a scheme based on Direct Sequence Spread Spectrum (DSSS) together with Slotted Aloha is proposed. The proposed scheme is illustrated and compared with the currently used Collision Resolution Diversity Slotted Aloha (CR-DSA) technique. It is shown that the proposed scheme achieves lower packet loss ratio especially in low traffic regimes which reflects the superiority of the proposed scheme in the backhaul access request setup. As the backhaul setup delay scales linearly with number of retransmission before an access request is successfully received, the proposed scheme reveals more effectiveness in that sense as its expected number of retransmissions is lower. Additionally, the effect of increasing the number of orthogonal codes on the packet loss ratio as well as expected number of retransmissions is analyzed. The proposed scheme can increase the maximum achievable throughput as it allows more than one packet to be received over the same time and code resource.

The second part of the deliverable addresses the problem of allowing concurrent transmissions over the network links via space time division multiple access scheme. The problem of cross-layer design of the flow control and link scheduling policies in hybrid terrestrial-satellite wireless backhaul network is treated with the objective of minimizing the time required to deliver the traffic. The problem is solved by taking into account the use of the satellite links only in cases of traffic offloading, link failure and remote access. However, the system is still able to use the satellite links continuously if desired. The active links are selected based on the network requirements and limitations. As considering all the links activation possibilities is not practical, column generation technique is used to obtain the optimal solution with lower complexity and guaranteed convergence. The benefits of using the satellite links in cases of link failure and traffic congestion are revealed via simulations. As the work in this deliverable considers the different problems from a MAC layer perspective, the work will be continued in the radio resource management task in order to consider efficient utilization of the network resources and take advantages of the proposed MAC schemes.
References


[29] P. Thulasiraman, and X. Shen, "Decoupled optimization of interference aware routing and scheduling for throughput maximization in wireless relay mesh


