D2.2
State-of-the-art of cellular backhauling technologies

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Abstract:
This is Deliverable D2.2 of the SANSA “Shared Access Terrestrial-Satellite Backhaul Network enabled by Smart Antennas” project which documents the outcome of Task 2.2 “State of the art backhauling technology review”. The objective of this deliverable is to review current mobile backhaul technologies, standards, requirements and performances. The material documented in D2.2 will allow the SANSA consortium to define the standards to be used in SANSA as well as the requirements and the targeted performances beyond state of the art.
D2.2: State-of-the-art of cellular backhauling technologies

**Document History**

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<td>RNC</td>
<td>Radio Network Controller</td>
</tr>
<tr>
<td>RoF</td>
<td>Radio over Fibre</td>
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<tr>
<td>ROHC</td>
<td>Robust Header Compression</td>
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<tr>
<td>RTN</td>
<td>Return</td>
</tr>
<tr>
<td>RTP</td>
<td>Real-time Transport Protocol</td>
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<tr>
<td>RTT</td>
<td>Round Trip Time</td>
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<tr>
<td>SA</td>
<td>Security Association</td>
</tr>
<tr>
<td>SACK</td>
<td>Selective Acknowledgement</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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<tr>
<td>SCCN</td>
<td>Small Cell Core Network</td>
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<tr>
<td>SCPC</td>
<td>Single Carrier Per Channel</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single-Carrier Frequency Division Multiple Access</td>
</tr>
<tr>
<td>SCN</td>
<td>Small Cell Network</td>
</tr>
<tr>
<td>SCPC</td>
<td>Single Carrier Per Channel</td>
</tr>
<tr>
<td>SDH</td>
<td>Synchronous Digital Hierarchy</td>
</tr>
<tr>
<td>SeGW</td>
<td>Serving Gateway</td>
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<tr>
<td>SF</td>
<td>Super Frame</td>
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<tr>
<td>SFPB</td>
<td>Single Feed per Beam</td>
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<td>SIPTO</td>
<td>Selected Internet IP Traffic Offload</td>
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<td>SNACK</td>
<td>Selective Negative Acknowledgment</td>
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<tr>
<td>SONET</td>
<td>Synchronous Optical Networking</td>
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<td>SSL</td>
<td>Secure Sockets Layer</td>
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<tr>
<td>SSTHRESH</td>
<td>Slow Start Threshold</td>
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<tr>
<td>SYN</td>
<td>Synchronisation</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
</tr>
<tr>
<td>TDM/TDMA</td>
<td>Time Division Multiplexing / Time Division Multiple Access</td>
</tr>
<tr>
<td>TE</td>
<td>Traffic Engineering</td>
</tr>
<tr>
<td>THP-MMSE</td>
<td>Tomlinson Harashima – MMSEE</td>
</tr>
<tr>
<td>TPC</td>
<td>Turbo Product Code</td>
</tr>
<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
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<tr>
<td>VCM</td>
<td>Variable Coding Modulation</td>
</tr>
<tr>
<td>VL-SNR</td>
<td>Very Low Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>VoIP</td>
<td>Voice over IP</td>
</tr>
<tr>
<td>VSAT</td>
<td>Very Small Aperture Terminal</td>
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<tr>
<td>Wi-Fi</td>
<td>Wireless Fidelity</td>
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Executive Summary

This is Deliverable D2.2 of the SANSA “Shared Access Terrestrial-Satellite Backhaul Network enabled by Smart Antennas” project which documents the outcome of Task 2.2 “State of the art backhauling technology review”. The objective of this deliverable is to review current mobile backhaul technologies, standards, requirements and performances. The material documented in D2.2 will allow the SANSA consortium to define the standards to be used in SANSA as well as the requirements and the targeted performances beyond state of the art.

The objective of this document is to review the current mobile backhaul technologies, standards, requirements and performances. This will allow for a subsequent identification of the standards to be used in SANSA as well as the requirements and the targeted performances beyond the state of the art.

This document provides a review of current mobile backhaul technologies, standards, requirements and performances. Terrestrial cellular backhauling technologies comprise a variety of physical transmission technologies including optical fiber, microwave radio, copper DSL and occasionally satellite. This document paid special focus to microwave and satellite backhauling technologies as are the main interest for the SANSA integrated backhaul system to be designed in the frame of the project.
# 1 Introduction

The objective of this document is to review the current mobile backhaul technologies, standards, requirements and performances. This will allow for a subsequent identification of the standards to be used in SANSA as well as the requirements and the targeted performances beyond the state of the art.

This deliverable is the output of the work done under Task 2.2 of WP2. WP2 aims to define the scenarios and network architectures that will be used in SANSA as well as the Key Performance Indicators (KPIs) for evaluating the proposed SANSA solution. Figure 1-1 illustrates how Task 2.2 fits within WP2 work plan.

This remainder of this deliverable is divided into 6 chapters that are organised as follows:

Chapter 2 analyses the demand for backhaul capacity. It presents the crucial factors that will drive this demand in the next years and provides a mobile traffic analysis including future projections for the traffic. Lastly, it assesses the impact of emerging mobile applications on traffic growth.

Chapter 3 discusses the wired and wireless terrestrial backhauling technologies used nowadays by mobile network operators such as copper cables, fibre, PtP and PtMP microwave links and presents the state of the art equipment used. This chapter also elaborates on the emerging wireless backhauling technologies and trends including LTE relaying, millimeter wave technology, massive MIMO, wireless full-duplex technology, and visible light communication technology. Lastly, it presents the various standards that are relevant to terrestrial backhaul.

Chapter 4 discusses the GEO and MEO satellite systems used nowadays for mobile backhaul services and presents the various satellite backhaul applications as well as their design implications on the backhaul system. It identifies the MNO requirements.
for a satellite backhaul service and presents the state of the art equipment used and performance that can be achieved. It details the traffic optimisation techniques used to improve the performance of the service over the satellite link and discusses the standards for satellite backhaul. Lastly, it elaborates on the future satellite broadband trends that are envisaged to affect satellite backhaul.

Chapter 5 defines CDNs, presents the current CDN architectures and discusses their applications in IPTV and LTE broadcast. Additionally, it presents two possible CDN scenarios for SANSA with terrestrial and satellite integrated backhaul.

Chapter 0 draws conclusions from the analysis of the preceding chapters with a focus on the conclusions that will be used for the scenario and network architecture definition.
2 Demand for backhauling capacity

In this chapter, we discuss important factors that set the demand for higher backhauling capacity within the next few years. In particular, we will provide a brief analysis of mobile traffic and future projections of it; we will identify some key mobile traffic growth drivers; and finally, we will assess (qualitatively) the impact of emerging mobile applications.

2.1 Mobile traffic analysis

In February 2015, Cisco released the Cisco VNI Global Mobile Data Traffic Forecast, 2014 – 2019 [1]. Global highlights from the updated study include the following projections:

Cisco forecasts that the 4.3 billion global mobile users of 2014 will increase to 5.2 billion by 2019. Four billion new mobile-ready devices and connections will be present by 2019, resulting in a total of 11.5 billion. More precisely it is expected that there will be 8.3 billion handheld or personal mobile-ready devices and 3.2 billion M2M connections (e.g., GPS systems in cars, asset tracking systems in shipping and manufacturing sectors, or medical applications making patient records and health status more readily available, etc.).

The average mobile connection speed will increase from 1.7 Mbps in 2014 to 4.0 Mbps by 2019. Global mobile IP traffic will reach an annual run rate of 292 exabytes\(^1\), compared to 30 exabytes in 2014. These predicted 292 exabytes would represent 292 times more than all Internet Protocol (IP) traffic, fixed and mobile, generated in 2000; or 65 trillion images (e.g., multimedia message service or Instagram) – 23 daily images per person on earth for a year; or 6 trillion video clips (e.g., YouTube) – more than two daily video clips per person on earth for a year.

Overall mobile data traffic is expected to grow to 24.3 exabytes per month by 2019, nearly a tenfold increase over 2014. Mobile data traffic will grow at a CAGR of 57% from 2014 to 2019.

\(^{1}\)An exabyte is a unit of information or computer storage equal to one quintillion bytes or one billion gigabytes.
Mobile traffic growth increases as more powerful mobile devices and machine-to-machine (M2M) connections are adopted. In 2014, 88 percent of global mobile data traffic was "smart" traffic, with advanced computing/multi-media capabilities and a minimum of 3G connectivity, but that figure is expected to rise to 97 percent by 2019.

Smart traffic also increases due to the worldwide trend towards smartphones, tablets and machine-to-machine (M2M) applications. From a global mobile network perspective, 3G is expected to surpass 2G as the top cellular technology, based on connection share, by 2017. By 2019, 3G networks will support 44% of global mobile devices and connections; 4G networks will support 26% of connections, though will generate 68% of traffic.

Moreover, according to [80], it is expected that in a dense urban information society the average traffic consumption per mobile user will be 500 GBs/month/subscriber (DL+UL), the average data rate 5 Mbps / 1 Mbps (DL/UP) and the traffic volume per area 700 Gbps/km2 (DL+UL).

2.2 Key Global Mobile Data Traffic Drivers
From 2014 to 2019, Cisco anticipates that global mobile traffic growth will outpace global fixed traffic growth by a factor of three. Trends driving mobile data traffic growth include:
Figure 2-2: Cisco forecasts 24.3 exabytes per month of mobile data traffic by 2019.

- More mobile users: 4.3 billion mobile users of 2014 will increase to 5.2 billion by 2019.
- More mobile connections: 7.4 billion total mobile-ready devices and M2M connections of 2014 will increase to 11.5 billion by 2019.
- Faster mobile speeds: Average global mobile network speed will increase from 1.7 Mbps (2014) to 4.0 Mbps (2019).
- More mobile video: Mobile video is expected to represent 72% percent of global mobile data traffic, compared to 55% percent in 2014.

Figure 2-3: Mobile Momentum Metrics by 2019.
2.3 Mobile Applications
As mentioned above, mobile video is expected to generate much of the mobile traffic growth of the coming years, due to its higher bit rates than all other mobile content. Mobile video will grow at a CAGR of 66% from 2014 to 2019. Of the 24.3 exabytes per month crossing the mobile network by 2019, 17.4 exabytes will be due to video.

Moreover, cloud applications and services (such as Netflix, YouTube, Pandora, Spotify) will account for 90% of total mobile data traffic by 2019, compared to 81% in 2014. Mobile cloud traffic will grow 11-fold from 2014 to 2019, a CAGR of 60%. This is due to the fact that many Internet video applications are actually cloud applications that allow users to overcome the memory capacity and processing power limitations of mobile devices.
Therefore the expanding and increasing course of mobile data services, including mobile data, mobile voice and mobile video, is more than evident. The expected increase in data traffic brings new requirements for the operators to sustain and satisfy the ever growing demand for bandwidth and backhaul capacity.
3 Terrestrial cellular backhauling

The backhaul network lies from the Base Station, (BTS or Node B), to the metro network core as depicted in Figure 3-1. Moreover, Figure 3-1 shows the different technologies and components employed by the mobile backhaul network. As can be seen, cellular backhauling comprises a variety of transmission technologies such as optical fibre, microwave radio, and copper DSL. The type of the backhauling technology depends on the long term traffic projection and the geographical terrain of the area.

In this deliverable, we will focus mainly on microwave radio and in particular, in the Ka-band. This decision is due to the fact that current regulation of Ka-band designates terrestrial services as incumbent users and allows deploying satellite receivers, which cannot claim any protection from terrestrial transmitters. SANSA aims to resolve this by designing shared access that will enable satellite operators to profit from this band and to participate in the mobile network business. Moreover, optimal utilization of this band will be achieved also for terrestrial operators.
In this chapter, firstly, we discuss wireless backhauling technologies describing the current status of wireless technologies including employed topologies, PtP and PtMP microwave links, focusing on technologies operating at 6-30 GHz band. Secondly, we overview other backhauling technologies for backhauling of small cells such as LTE and WiFi and finally, thirdly, we overview emerging trends in terrestrial cellular backhauling.

3.1 Current wireless backhauling technologies between 6 GHz and 30 GHz

While fibre-based backhaul provides virtually unlimited capacity, the lack of ubiquitous fibre availability along with the densification of mobile cell architectures led to the increasing demand for backhaul solutions based on wireless technologies. Increasingly, fibre and wireless backhaul technologies complement each other with fibre being deployed where it is available or required due to high traffic and wireless links distributing the available capacity to many other cell sites, over one or multiple hops.

Wireless transmission solutions offer additional operational benefits, when compared to optical fibre ones, mainly due to their ease of deployment and flexibility in overcoming certain terrestrial obstacles, their rapid deployment time, their lower cost (especially CAPEX) in comparison with optical transmission solutions (under certain conditions), and their adequate throughput for many scenarios and use-cases of interest.

In this section we provide an overview of the current wireless transmission technologies for mobile backhauling focusing mainly on those ones that are of highest importance to SANSA.

3.1.1 Basic Backhauling Topologies

2G/3G generation mobile networks do not have direct interconnections between the base stations, thus logical topology of the backhaul transport network is always a pure star, i.e. traffic goes directly from each base station to its controller. However, the physical topology is very different, as it is based on economic optimization of transport links and nodes as well as on the need to have resilience at least on the upper layers of the network. Physical topology is also very much the result of network history and gradual evolution, as with time more and more base station sites have been gradually added to the network.

The most common topologies for wireless networks are rings, trees, or a combination of both, as described in [4], while the tree topology is a combination of the star and chain topologies, as shown below in Figure 3-2.
Star topologies use a link from a hub to each BTS. This is quite simple, yet not efficient for microwave systems, as it requires longer radio links and Line of Sight (LOS) for each link (which may not be possible). On the other hand, the re-use of frequency by the star topology is rather poor, since all the links towards BTSs originate from the same point, and there is higher probability to confront interference due to the fact that multiple links use the same frequency.

In chain topologies, sequential nodes connected through a single path do not demonstrate the issues observed in e.g. star topologies, however the resulting topology is very sensitive, meaning that a single malfunction in only one link may cause a complete network failure. Therefore, protection of each one of these links is mandatory.

The combination of the chain and the star results in the well-known tree topology, which comprises fewer links whose failure may cause also a network failure. Moreover, adding a link to connect the first and the last node of a chain topology results in the ring topology, which demonstrates double efficiency compared to the chain one, at least in terms of protection and availability.

Figure 3-2: Basic mobile backhauling topologies [4].
Concerning network deployment costs (CAPEX), we observe that in order to connect a specific set of nodes, the ring may require less microwave links. On the other hand, a ring topology usually requires links with higher-capacity, which comes at a higher cost and thus are consuming more spectrum. In the ring topology, a larger number of antennas is required, and therefore the comparison with the ring topology is not straightforward. One more factor that influences cost is the reuse of spectrum. Taking into account that the ring topology has two links max at each node, more efficient reuse of frequency is achieved, thus the ring topology is often deployed using a single pair of frequency channels.

Moreover the ring and the tree topologies are more resilient in the case of equipment failure, but in the case of tree topology no path redundancy is provided. Therefore, the tree may be vulnerable to heavy load conditions, as well as to failures of sites/nodes (e.g. due to a power outage, or weather circumstances).

The ring topology, as expected, also provides high availability, due to the fact that the communication failures only if both paths fail. Thus, in order to achieve the same level of service availability, a network planner can deploy smaller antennas with reduced power at the nodes, so as to reduce expenses.

On the other hand, the number of hops to reach a specific node in a ring topology may be up to $N-1$ hops in an $N$ node ring topology, which may have significant impact on latency and delay variations, both for data transmission and signaling traffic, e.g. synchronization signals. Compared to the ring topology, in the tree one less hops are required on the average to reach a specific node; however specific links may constitute bottlenecks in the tree in terms of bandwidth, as many flows may travel over them; thus having negative implications and performance deterioration for those flows. A
Combination of ring and tree topologies may eliminate the negative effects of the two topologies.

Usually the capacity of a link in a ring topology is larger than the capacity of a link in a tree one, thus statistical multiplexing is more effective and more easily deployable. Though, any capacity upgrade is usually much more expensive in the case of a ring topology compared to the tree one, where only the central branch needs to be upgraded along with any branch upgrade or addition. An alternative for upgrading a ring topology in a more cost-efficient way is to add links inter-connecting intermediate nodes, thus creating smaller rings, and practically turning the topology into a mesh one. Nonetheless, such an upgrade would imply increase of OPEX, as the complexity introduced by the mesh topology would result in increased management overhead.

In Table 3-1, a qualitative comparison between the tree and the ring topology is presented. As expected, also based on the analysis so far, there is no “perfect” topology, or a “correct” topology for any case. On the contrary, each topology has weaknesses and is appropriate for specific circumstances. A network designer should always take into account the specific circumstances, business, application and technical requirements, geographical and demographic characteristics, spectrum and antenna costs, in order to determine an optimal best solution for a specific setup.

**Table 3-1: Qualitative comparison of tree and ring topologies [4].**

<table>
<thead>
<tr>
<th></th>
<th>Tree Topology</th>
<th>Ring Topology</th>
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</thead>
<tbody>
<tr>
<td>CAPEX</td>
<td>✔️</td>
<td>✔️</td>
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<tr>
<td>Resiliency</td>
<td>✔️</td>
<td>✔️</td>
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<tr>
<td>Availability</td>
<td>✔️</td>
<td>✔️</td>
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<tr>
<td>Latency</td>
<td>✔️</td>
<td>✔️</td>
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<tr>
<td>Scalability</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Capacity</td>
<td>✔️</td>
<td>✔️</td>
</tr>
</tbody>
</table>

The average number of hops until a site with optical connection to the core network in rural and urban deployments depends on topology. In particular, the number of hops may vary from 1 to N-1 in the case of ring topology, where N depends on the area that needs to be covered and its special characteristics, while the actual hop may be of 2-15 km in rural areas and 3 km (max) in urban ones.
Moreover, concerning main topology differences between rural and urban deployments, we observe that typically, the 6GHz to 23GHz frequency bands are used by MNOs to deploy microwave in rural areas, which typically need longer hops. This is because these bands support longer “hop” distances, than the higher frequency bands, and this greater “hop” length is important for rural cell sites which tend to be further away from the operators’ fibre network nodes.

However, this sub-band is becoming congested in rural areas because most operators use this band. The 26GHz to 42GHz frequency bands are typically used by MNOs to deploy backhaul for urban cell sites. This is because, urban cell sites are typically within 3 km of the MNO fibre network and microwave systems using 26GHz to 42GHz sub-band can achieve this hop distance. However, these bands are also becoming congested (in urban areas) due to heavy use by operators.

3.1.2 Point-to-Point and Point-to-Multipoint microwave links

Point-to-Point (PtP) and Point-to-Multipoint (PtMP) microwave (MW) links represent currently the dominant wireless transmission technologies used for mobile backhauling.

Both technologies set up bi-directional wireless communication links between a ‘hub’ or ‘central’ station and many ‘terminal’ stations. Typically, the central station has access to high capacity backhaul, for example fibre. Both the central and terminal stations are static, but terminal stations may be added or removed to meet capacity requirements.

The difference between the two technologies is that in PtP topology each link has access to dedicated capacity, while in PtMP multiple terminal stations share the same radio resources with the hub terminal. The PtMP systems are similar to Local Multipoint Distribution Systems (LMDS) which were used to distribute traffic directly from a central antenna to individual antennas for businesses and homes. They operated at 28GHz in USA and at 40 GHz in Europe. In a PtP architecture, the hub and terminal stations use directional antennas to set up individual one-to-one links. This means that LoS is required for PtP topologies. Usually the same radio resources can be reused in all the \( N \) hub-terminal station pairs. Instead, in a PtMP topology, omnidirectional or sectored antennas are typically deployed and the radio resources, such as the carrier, are shared between many terminal stations [86]. PtMP topologies can operate in both LoS and NLoS conditions, making this type of topology particularly attractive for providing backhaul to small cell deployments. In some cases directional antennas are used to setup radio links, but a single radio transceiver is used at the hub station leading to sharing of resources (for example, time or spectrum) between the
terminal stations. In SANSA we treat such topologies as PtMP. Furthermore, multiple PtMP topologies may be overlapping with different carriers used for groups of terminal stations. The two topologies are described in Figure 3-4, below.

![Point-to-Point and Point-to-Multipoint architectures](image)

There are significant differences between the two architectures in terms of utilization of the available spectrum capacity, band suitability, equipment requirements, ease of deployment, and the associated costs. We summarise these differences below.

**Capacity**
PtMP uses the same radio resources to provide backhaul to \( N \) terminal stations. If the total capacity \( \text{('C')} \) is shared equally, each individual terminal station is allocated \( \frac{C}{N} \) backhaul capacity. However, it is possible for the hub to dynamically change the allocation of resources, leading to statistical multiplexing efficiencies where more capacity is allocated to those terminal stations that need it. PtP, on the other hand, allocates the full capacity of the used spectrum for each individual link, meaning that each terminal station is allocated \( C \) backhaul capacity, while the total capacity provided by the hub to all the terminal stations is \( N*C \), subject to cross link interference [86].

**Spectrum bands**
PtP architectures require spatial separation between the individual hub-terminal station links to achieve their full capacity potential. Depending therefore on the density of the terminal stations, higher frequency spectrum bands may be more appropriate due to their ability to produce narrower beams and reduce interference between neighbouring terminal stations. However, these bands require LOS conditions which could limit the usability of PtP backhaul systems in dense urban environments where the terminal stations are installed at the street level (on lamp posts or other street furniture).

Instead, PtMP distinguishes between terminal stations at the MAC layer and therefore does not require separation at the PHY layer (for example by using directional antennas). This renders PtMP advantageous for dense urban small cell deployments,
where spatial separation may not be feasible, subject to adequate spectrum being available at the hub station.

Both PtP and PtMP topologies can be used with the spectrum bands considered in SANSA.

**MAC layer**
A MAC layer is only needed in PtMP topologies since in PtP there are no multiple terminals sharing the connection (and relevant resources). Our analysis of commercial PtMP products available in the market shows that TDMA and OFDMA (including reuse of LTE hardware adapted for higher frequencies [83]) are typically used to allow sharing of the common resources between multiple terminal stations. This is because both TDMA and OFDMA allow flexibility in allocating different amounts of resources to different terminals depending on their respective capacity requirements, generating statistical gains at the backhaul.

**Equipment requirements, ease of deployment, and associated costs**
PtP is more demanding in terms of equipment. This is because separate radio transceivers and baseband units are required at the hub station to provide backhaul to each terminal station. Furthermore, directional antennas are required both at the hub and the terminal stations to reduce cross-link interference. Installing these directional antennas is usually more difficult, time consuming, and expensive. Depending on the spectrum band used and the regional regulations, a separate spectrum license may be required for each individual link which further increases costs and deployment complexity.

PtMP, on the other hand, uses a single radio transceiver and baseband unit for each sector, regardless of the number of terminal stations served. Omnidirectional or sectored antennas are typically used at both the hub and the terminal stations which are easier, faster, and cheaper to deploy. Finally, a single spectrum license is needed for all the links served. However, significantly wider spectrum is required to match the capacity provided by PtP deployments.

Some PtP solutions have been developed which make use of adaptive antenna arrays to offer easy (and potentially cheaper) installation where the hub and terminal station antennas self-align their beams. Such solution is offered by CCSL’s Metnets².

Concluding, if an operator has sufficient spectrum, a PtMP architecture provides more flexibility (i.e., the operator can add a small cell without having to install new equipment at the aggregation point) and cost savings (i.e., less equipment has to be installed and maintained). The downside of the PtMP architecture is that the maximum

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² For more information on CCSL’s product see: http://www.ccsl.com/metnet-system/self-organising-nodes/node-specifications/
capacity density (e.g. Mbps per square mile) is lower than for the PTP architecture, in
which the same spectrum channel can be more extensively reused. Operators with
control over substantial spectrum assets will be able to support PtMP, but the others
will have to rely on PtP, unless they have a low density of small cells and/or their
capacity requirements are constrained [86]. On the other hand, PtP allows higher
resources reuse since the terminal-hub pairs are separated spatially using directional
antennas. PtP, however requires more costly installation (since the beams of the
terminal and hub antennas have to be aligned). For these reasons PtP is the preferred
topology for static cell deployments (i.e. where it is unlikely to deploy more cells in the
same area in the foreseeable future) and for connection between macro cells.

I. Evolution of PTP MW transmission technologies for mobile backhauling

During the days of the 2nd Generation (2G) and 3G mobile communications systems,
Plesiochronous / Synchronous Digital Hierarchy (PDH / SDH) technology was used to
transport Time Division Multiplexing (TDM) and Asynchronous Transfer Mode (ATM)
payloads, respectively. As 3G was evolving to a more packet-based network, hybrid
technologies such as Ethernet over SDH (EoSDH) were introduced. The pre-4G system
Long Term Evolution (LTE), on the other hand, was designed by the beginning as an all-
IP network in order to achieve the envisioned throughput and delay goals. Thus, a
switch towards native Ethernet technology took place in PTP MW mobile backhauling
technology. Packet microwave technology presents a number of advantages against
legacy systems:

- Higher capacity.
- Greater flexibility (e.g. support of multiple services).
- Greater Quality of Service (QoS) support (e.g. adaptation to channel quality).
- Improved Operation, Administration and Maintenance (OAM) support.

II. Factors affecting throughput

Two of the main factors that affect the throughput of microwave links are the
spectrum band and spectrum bandwidth.

A. Spectrum band

Traditionally, microwave bands have been licenced in the 6GHz to 42GHz bands in
Europe. In addition, systems are now slowly being deployed in the millimetre wave
(mmWave) band (also called “E-Band”) [6], i.e. between 60GHz and 100GHz, as
illustrated in Figure 3-5.

Let us state the three key principles associated with the operation of microwave links:
Due to propagation characteristics (higher absorption and lower diffraction around obstacles), the higher the frequency band, the shorter the reach of the system.

The higher the frequency band, the larger the typical spectrum bandwidth available and thus the higher the throughput of the microwave system, when all other things being equal.

PTP MW links, which typically operate at frequencies above 6GHz, require Line of Sight (LOS) propagation conditions.

The LOS requirement might be a significant issue for small-cell sites because microwave equipment is typically just above street level and there may be many obstacles in the urban environment, resulting in near LOS (nLOS) or non-LOS (NLOS) transmission conditions.

In the following, we describe the use of traditional microwave bands. The use of millimeter wave technology (E-Band) as well as the use of alternatives for small-call wireless backhauling is discussed in subsequent sections.

Traditional microwave bands can be decomposed into two sub-bands:

- 6GHz to 23GHz sub-band
- 26GHz to 42GHz sub-band

Typically, 6GHz to 23GHz sub-band spectrum is used by MNOs for backhauling in rural areas, which typically need longer hops e.g., between 2-15 km. This this because this sub-band supports longer “hop” distances than the higher frequency sub-bands, and this greater “hop” length is important for rural cell sites which tend to be further away from each other.
from the operator’s optical network nodes. However, this sub-band is becoming congested in rural areas because most operators use this band [6]. 26GHz to 42GHz sub-band spectrum is typically used by MNOs to deploy backhaul for urban cell sites. This is because, urban cell sites are typically within 3 km of the MNO fibre network and microwave systems using 26GHz to 42GHz sub-band can achieve this hop distance. However, this sub-band is also becoming congested (in urban areas) due to heavy use by operators.

B. Spectrum bandwidth

The throughput that can be delivered by a microwave point to point link is proportional to the spectrum bandwidth. For example, a microwave system using 28MHz of bandwidth will deliver twice the throughput of a microwave system using 14MHz, all other factors being equal.

Standard spectrum bandwidths are 7MHz, 14MHz, 28MHz and 56MHz for “traditional” microwave bands (see Figure 3-5). It should be noted that “traditional” microwave bands are becoming heavily congested and obtaining 56MHz spectrum bandwidth is becoming increasingly difficult.

C. Improving throughput

LTE puts a high burden to the capacity of the mobile backhaul. Several techniques are in use today to improve the throughput of microwave backhaul [83], [84]:

- Higher-order modulation: In general, the higher the modulation order, the higher the throughput and the lower the availability and reach of the link. The selection of a modulation scheme depends on the frequency band and frequency spectrum as well as on the transmission conditions – Line-of-Sight (LOS), near LOS (nLOS), or non-LOS (NLOS).

- Adaptive Modulation and Coding (AMC): This technique enables the microwave system to adapt to channel quality (e.g. severity of fading) such that it achieves at any given time the maximum possible throughput under the current transmission conditions.

- Compression techniques: Multi-layer packet header compression enables today an increase in throughput around 15-20%. An improvement of about 2-3% per year is expected in the future, due to the advances in compression.

- Interference mitigation techniques: Interference limits the achieved throughput. For that purpose, interference mitigation techniques such as Automatic Transmit Power Control (ATPC) and interference suppression are commonly used.
- Frequency diversity: This mechanism doubles over-the-air (OTA) capacity by using two different transmission channels at two different carrier frequencies. High carrier frequency separation is promoted over the use of contiguous carrier frequencies since it provides resilience against fading (i.e. it is highly likely that at least one of the two channels will be always available).

- Cross Polarisation Interference Cancellation (XPIC): XPIC is a technique that enables the transmission of two microwave signals in the same spectrum by using orthogonal polarisation for each of the signals (one signal is sent using polarisation on the X axis and the other signal is sent using polarisation on the orthogonal Y axis) to ensure they do not interfere with each other. This results in a doubling of capacity for the microwave link without using additional spectrum. However, we have to mention that microwave links using XPIC technology can use a single antenna but have to use two different radios, nearly doubling the cost of the solution.

- Multiple Input Multiple Output (MIMO) [83]: MIMO at microwave frequencies is an emerging technology that offers an effective way to further increase spectrum efficiency and so the available transport capacity. Unlike “conventional” MIMO systems, which are based on reflections in the environment, the channels are “engineered” in PTP MW MIMO systems for optimum performance. This is achieved by installing the antennas with a spatial separation that is hop distance and frequency-dependent. In principle, capacity increases linearly with the number of antennas (at the expense of additional hardware cost, of course). Since the antennas must be spatially separated, there is a practical limitation on the number of transmit and receive antennas that can be used, depending on tower height and surroundings. 2x2 MIMO systems are the most common today. The antennas could either be single polarized (two carrier system) or dual polarized (four carrier system). Microwave MIMO is at the early stages of development, e.g. its regulatory status still needs to be clarified in most countries, and its propagation and planning models still need to be established. The antenna separation can also be challenging especially for lower frequencies and longer hop lengths.

- Radio link bonding: This technique refers to the aggregation of multiple radio carriers into a virtual one in order to enhance the peak capacity as well as increase the effective throughput through statistical multiplexing gain.

MAC Protocols of current deployments: Use of a MAC protocol is only required in PtMP topologies where multiple terminal stations share the same resources. Our review of commercial solutions available (see Section 3.1.4) suggests that TDMA and OFDMA are typically used due to the ability of such MAC protocols to dynamically
distribute the share of the resources to different terminal stations (backhaul links) depending on their traffic load.

3.1.3 QoS over LTE networks

In this section, we will focus on traffic classification techniques applied on eNodeB, as they are of high interest to SANSA that aims to design resource network management algorithms that will allow efficient and flexible allocation of resources among different types of traffic with heterogeneous QoS requirements.

Traffic classification at the eNodeB level and accompanying intelligent routing decisions between terrestrial and satellite backhaul links would allow to use the supplementary satellite backhaul provided by SANSA, while minimizing any effect on the perceived user experience. However, in contemporary IP-based cellular networks (such as LTE), complexity is added by the various levels of encapsulation present, as described below.

One of the key design goals of the LTE technology was to support purely IP (including Voice over IP). As a consequence, QoS was implemented in the context of the ‘inner-tunnel’, which interoperates with the packet core and radio network, and the ‘outer-tunnel’, which uses traditional IP traffic engineering techniques. The various tunneling and encapsulation protocols that are required are shown in Figure 3-6.

![Figure 3-6: LTE transport encapsulation [72.]]
It is common practice for telecom operators to employ MPLS or other tunneling protocols to support QoS. Moreover, a best practice is to engineer the network such that there is only one point of congestion, i.e., the eNodeB.

Moreover, in IP-based networks, differentiated service is performed on a per-hop basis by means of DiffServ (RFC 2474, RFC 2475, RFC 3260) and MPLS (RFC 3270). The basic classes defined by DiffServ are ‘default’, ‘expedited forwarding’, and ‘assured forwarding’. Out of these classes, expedited forwarding is used to provide ‘strict’ priority to delay-sensitive applications such as video and voice, while ‘assured forwarding’ is employed to support business differentiation, e.g., to provide weighted-fair priority to traffic flows of business customers against traffic flows originated by home-users.

An open issue with DiffServ is its interworking with virtual links and tunnels. In a 3GPP environment, the outer marking would be used by backhaul networks, whereas inner marks would be ignored. Examples of interchange between the two types of marking are proprietary per vendor, which implies that the various equipment types vary in the number of queues supported, as well as in the queuing behavior, despite the number of levels supported in signaling.

### 3.1.4 State of the art equipment for terrestrial backhaul

For the purposes of SANSA, we overviewed a number of state-of-the-art equipment for wireless (microwave) terrestrial backhaul with a focus on Ka band, which are currently provided by large vendors such as Huawei, Ericsson, Alcatel Lucent, NEC, Ruckus, Intracom Telecom, CBNL, and CCSL. Table 3-2 and Table 3-3 summarize the outcome of the overview providing information (where available) focusing on characteristics such as radio technology, frequency, channel space, RF direction, switch capacity, etc. for macro cells and small cells market, respectively.

The solution by Huawei presented in Table 3-2 is the one employed also in the 95% of the cases in the production network of OTE/Cosmote. The ODU’s of the PtP links employed go up from QPSK to 1024 QAM, while it is planned to go up to 2048 QAM in the near future depending on the link budget. EIRP is between 50-60 dBm, while the traffic capacity that can be transported is up to 400 Mbps. Moreover, linear horizontal polarization is employed.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Huawei</th>
<th>Ericsson</th>
<th>NEC</th>
<th>Alcatel Lucent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product name</td>
<td>RTN</td>
<td>MINI-LINK</td>
<td>iPASOLINK</td>
<td>9500 MPR</td>
</tr>
</tbody>
</table>

Table 3-2: Overview of commercial products for wireless terrestrial backhauling for macro cell.
### Market (access)

<table>
<thead>
<tr>
<th></th>
<th>Macro cell</th>
<th>Macro-cell</th>
<th>Macro-cell</th>
<th>Macro-cell / Metro-cell</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radio technology</strong></td>
<td>TDM</td>
<td>TDM</td>
<td>TDM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4x4VC-4, 32x32VC-4, 32x32VC-4, 128x128VC-4</td>
<td>TDM</td>
<td>TDM</td>
<td></td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>6/7/8/10/10.5/11/15/18/23/26/28/32/38/42 GHz</td>
<td>5, 6, 7, 8, 10, 11, 13, 15, 18, 23, 26, 28, 32, 38 &amp; 42 GHz</td>
<td>6, 7, 8, 10, 11, 13, 15, 18, 23, 26, 28, 32, 38, 42, and 52 GHz</td>
<td>6, 7, 8, 10, 11, 13, 15, 18, 23, 26, 28, 32, 38, 42, and 52 GHz</td>
</tr>
<tr>
<td><strong>Channel space</strong></td>
<td>3.5/7/14/28/40/50/56 MHz</td>
<td>7-56 MHz</td>
<td>7/14/28/40/56 MHz</td>
<td>7/14/28/40/56 MHz</td>
</tr>
<tr>
<td><strong>Radio access method</strong></td>
<td>TDD, 1024-QAM</td>
<td>TDD, 1024 QAM</td>
<td>TDD</td>
<td>TDD</td>
</tr>
<tr>
<td><strong>RF direction</strong></td>
<td>1U/2RF, 2U/6RF, 2U/6RF, 5U/14RF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Antenna polarization</strong></td>
<td>Single horizontal polarization</td>
<td>Single and dual polarized</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Switch capacity</strong></td>
<td>8, 10, 10, 22 Gbps</td>
<td>570 Mbps over 56 MHz using 1024 QAM (ETSI). 510 Mbps over 50 MHz using 1024 QAM (ANSI). 1.1 Gbps using XPIC</td>
<td>L2 switch capability along with a built-in 16 channel E1 interface</td>
<td>25 Gb/s per MG-ISM</td>
</tr>
<tr>
<td><strong>Link aggregation</strong></td>
<td>2 links, 2-4 links</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Synchronization</strong></td>
<td>Synchronous Ethernet, IEEE1588v2</td>
<td>Sync E, 1588v2, NTP transparent, STM-1, E1 and 2MHz</td>
<td>Ethernet synchronization, IEEE1588</td>
<td>SyncE, IEEE 1588v2, Packet-microwave synchronization, STM-1 (SDH)/OC-3 (SONET)</td>
</tr>
<tr>
<td><strong>Scheme</strong></td>
<td>PtP</td>
<td>PtP</td>
<td>PtP</td>
<td>PtP</td>
</tr>
</tbody>
</table>
Table 3-3: Overview of commercial products for wireless terrestrial backhauling for small cell.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Ericsson</th>
<th>CCSL</th>
<th>Ruckus</th>
<th>Intracom</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product name</strong></td>
<td></td>
<td>CCS Metnet</td>
<td>ZoneFlex 7731</td>
<td>WiBAS</td>
</tr>
<tr>
<td><strong>Market (access)</strong></td>
<td>Small cell</td>
<td>Small cell</td>
<td>Small cell</td>
<td>Small cell</td>
</tr>
<tr>
<td><strong>Radio technology</strong></td>
<td>Spatial TDMA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>28 GHz</td>
<td>26GHz, 28GHz</td>
<td>10.5 GHz, 26 GHz, 28 GHz, 32 GHz, 42 GHz</td>
<td></td>
</tr>
<tr>
<td><strong>Channel space</strong></td>
<td>56MHz</td>
<td>112MHz, 100MHz (USA) Single frequency channel used across all nodes</td>
<td>14 / 28 / 56 MHz</td>
<td></td>
</tr>
<tr>
<td><strong>Radio access method</strong></td>
<td>FDD/single carrier 512QAM</td>
<td>TDD Future support: FDD, Dual-TDD</td>
<td>1024-QAM</td>
<td></td>
</tr>
<tr>
<td><strong>Antenna details</strong></td>
<td>270° horizontal x 20° vertical</td>
<td>Internal 17dBi directional antenna</td>
<td>Sectoral 90° / 20 or 17 dBi, Parabolic 300 or 600 mm / 45.8 dBi</td>
<td></td>
</tr>
<tr>
<td><strong>Switch capacity</strong></td>
<td>400 Mbps (max)</td>
<td>480Mbps – single node 960Mbps – dual node 112MHz channel</td>
<td>Up to 190 Mbps at 1.5 km</td>
<td>540 Mbit/s</td>
</tr>
<tr>
<td><strong>Network timing</strong></td>
<td>GPS, 1588v2</td>
<td></td>
<td>ITU-T G.8362 (Synchronous Ethernet), IEEE 1588v2 TC</td>
<td></td>
</tr>
<tr>
<td><strong>Scheme</strong></td>
<td>PtMP</td>
<td>Self-organising MPtMP</td>
<td>PtMP</td>
<td>PtP / PtMP</td>
</tr>
</tbody>
</table>
3.1.5 Standards for terrestrial backhauling technologies at 6-30 GHz

IEEE 802.16 is a series of wireless broadband standards written by the Institute of Electrical and Electronics Engineers (IEEE) to describe the air interface. The IEEE Standards Board established a working group in 1999 to develop standards for broadband for wireless metropolitan area networks (MANs). Although the 802.16 family of standards is officially called WirelessMAN in IEEE, it has been commercialized under the name "WiMAX" (from "Worldwide Interoperability for Microwave Access") by the WiMAX Forum industry alliance.

The current standard is IEEE Std 802.16-2012, which is an amendment of the IEEE Std 802.16-2009, while five more amendments are currently active which specify modifications or specializations of the IEEE Std IEEE 802.16-2012.

The standard specifies the air interface, including the medium access control layer (MAC) and physical layer (PHY), of combined fixed and mobile point-to-multipoint (PMP) broadband wireless access (BWA) systems providing multiple services. The MAC is structured to support the WirelessMAN-SC, WirelessMAN-OFDM, and WirelessMAN-OFDMA PHY specifications, each suited to a particular operational environment.

The 10–66 GHz bands provide a physical environment where, due to the short wavelength, line-of-sight (LOS) is required and multipath is negligible. In the 10–66 GHz band, channel bandwidths of 25 MHz or 28 MHz are typical. With raw data rates in excess of 120 Mb/s, this environment is well suited for PMP access serving applications from small office/home office (SOHO) through medium to large office applications. Frequencies below 11 GHz provide a physical environment where, due to the longer wavelength, LOS is not necessary and multipath may be significant.

Regarding the frequency allocation and for the propagation characteristics, Rec. ITU-R F.746.5 and Rec. ITU-R P.530-9 are used respectively, while for the backhauling systems the following ETSI standards are used:

- **ETSI EN 302 217-1 V1.3.1 (2010-01):** Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 1: Overview and system-independent common characteristics.
- **ETSI EN 302 217-2-1 V1.3.1 (2010-01):** Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 2-1: System-dependent requirements for digital systems operating in frequency bands where frequency co-ordination is applied.
- **ETSI EN 302 217-2-2 V1.3.1 (2009-04):** Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 2-2: Digital
systems operating in frequency bands where frequency co-ordination is applied; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive.

- ETSI EN 302 217-3 V1.2.1 (2008-02): Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 3: Harmonized EN covering essential requirements of article 3.2 of R&TTE Directive for equipment operating in frequency bands where simplified or no frequency co-ordination procedures are applied.

- ETSI EN 302 217-4-1 V1.2.1 (2007-06): Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 4-1: System-dependent requirements for antennas.

Further details on standards can be also found in the SANSA Deliverable D2.1 “Review of Regulatory Environment” (Chapter 5).

3.2 Other current backhauling technologies

3.2.1 LTE and Wi-Fi for wireless backhauling of small-cell sites

Mobile operators have access to sub-6GHz spectrum which they could use for small cells backhaul. Sub 6GHz spectrum bands take advantage of multipath propagation and do not require direct line of sight. For instance, the 2.6GHz LTE spectrum can be used to provide PtP and PtMP backhaul, employing up to 40MHz of spectrum. However, use of LTE bands is not a future-proof solution since it will not be long (due to the rapid adoption of LTE) before the complete LTE spectrum will need to be used at the Radio Access Network.

An alternative option could rely on the use of unlicensed spectrum, such as the 5GHz ISM band, traditionally used for WiFi. However, unlicensed bands are typically prone to interference due to the lack of coordination between the various users of these bands. For example, both the 2.4GHz and 5GHz ISM bands are becoming increasingly congested due to the take up of WiFi-based connectivity.

For these reasons, we anticipate that future small cell deployments will rely on microwave links using spectrum at bands above 20GHz for their backhaul requirements.

3.2.2 Fixed cellular backhauling

Fixed cellular backhauling includes both copper cables and optical fibres. In both cases, TDM techniques are prevalent techniques which allow multiplexing multiple voice channels from base stations and transporting them to the BSC in different time slots. In this regard, there are two standard hierarchies which are similar in their operation but
primarily differ in the delivered bit rates: the T-carriers (T1,T2,...,T4) and E-carriers (E1,...,E5). For instance, T1 links operate on 1.544 Mbit/s while E1 connections operate on 2.048 Mbit/s. The T-carriers are primarily used in North America and Japan while E-carriers are used in Europe and the rest of the world.

In many cases leased T1/E1 copper lines from multiple sites are merged at a multiplexer which multiplexes lower rate T1/E1 connections into higher rate optical fiber connections such as STM-1 (155.52 Mbit/s), STM-4 (622 Mbit/s) and STM-16 (2.4 Gbit/s) [5]. The STM standards are used as Synchronous Optical Networking (SONET) in North America and as Synchronous Digital Hierarchy (SDH) in Europe and the rest of the world.

SDH/SONET over optical fibers are also implemented in ring topologies [5], although their use is decreasing. The add/drop multiplexer is an important element of an optical fiber network which combines or multiplexes several lower-bandwidth data streams into a single beam of light. In addition, it can add one or more lower-bandwidth signals to an existing high bandwidth data stream, while at the same time, extract or drop other low bandwidth signals by removing them from the stream and redirecting them to other network paths.

More on fixed cellular backhauling can be found in [3] and [4].

3.2.3 Standards for other terrestrial backhauling technologies

3GPP TSG Radio Access Network (TSG RAN) is responsible for the definition of the functions, requirements and interfaces of the UTRA/E-UTRA network in its two modes, FDD & TDD. More precisely: radio performance, physical layer, layer 2 and layer 3 RR specification in UTRAN/E-UTRAN; specification of the access network interfaces (Iu, lub, lur, S1 and X2); definition of the O&M requirements in UTRAN/E-UTRAN and conformance testing for User Equipment and Base Stations.

The TSG Radio Access Network (TSG RAN) is responsible for the UTRAN and evolved UTRAN, including their internal structures and functions, of systems for evolved 3G and beyond. Specifically it has a responsibility for radio aspects of Terminal Equipment and evolved Terminal Equipment and evolved UTRAN functions (FDD & TDD), requirements and interfaces.

In particular, RAN WG1 (Radio layer 1) is responsible for the specification of the physical layer of the radio Interface for UE, UTRAN, Evolved UTRAN, and beyond; covering both FDD and TDD modes of the radio interface. The working documents of RAN WG1 can be found in [81].
Moreover, the Study Groups of ITU’s Telecommunication Standardization Sector (ITU-T) assemble experts from around the world to develop international standards known as ITU-T Recommendations which act as defining elements in the global infrastructure of information and communication technologies (ICTs). There are over 4000 Recommendations in force on topics from service definition to network architecture and security, from broadband DSL to Gbit/s optical transmission systems to next-generation networks (NGN) and IP-related issues, all together fundamental components of today's information and communication technologies (ICTs).

The Recommendation G.989.1 describes the general requirements of NG-PON2 systems supporting a 40-Gbit/s capable aggregate downstream capacity for residential, business, mobile backhaul, and other applications. The Recommendation G.989.1 includes the principal deployment configurations, migration scenarios from legacy PON systems, and system requirements. This Recommendation also includes the service and operational requirements to provide for a robust and flexible optical access network supporting all access applications.

The international standards (ITU-T Recommendations) produced by Study Group 15 detail technical specifications giving shape to global communication infrastructure. The group’s standards define technologies and architectures of optical transport networks enabling long-haul global information exchange; fibre- or copper-based access networks through which subscribers connect; and home networks connecting in-premises devices and interfacing with the outside world.

Finally, Metro Ethernet Forum (MEF) – CE 2.0 for Mobile Backhaul, as the defining body for Carrier Ethernet, is a global industry alliance comprising more than 220 organizations including telecommunications service providers, cable MSOs, network equipment/software manufacturers, semiconductors vendors and testing organizations. The MEF’s mission is to accelerate the worldwide adoption of Carrier-class Ethernet networks and services.

In the economically pressured world of mobile networks, efficient growth of the backhaul infrastructure is critical to financially viable mobile operator and access provider networks. The adoption of Ethernet for Mobile Backhaul has been accepted by the vast majority. CE 2.0 for Mobile Backhaul brings answers to the challenges associated with managing rapid backhaul data growth while scaling costs to new revenues.
CE 2.0 works inter alia on the implementation of CE 2.0 MEF Mobile Backhaul Implementation Agreement (Phase 2), the efficient deployment of 4G/LTE plus legacy migration use cases, Small and Macro Cell implementation, and fixed and mobile convergence.

3.3 Emerging wireless technologies for mobile backhauling
In this section, we provide an overview of emerging wireless technologies for mobile backhauling.

3.3.1 LTE relaying for mobile backhauling
LTE base stations can act as relay nodes (RNs) to provide backhauling functionality. This setup is particularly useful in rural areas where wired backhauling solutions have often prohibitively high cost, while at the same time there exists typically vacant spectrum.

A benefit of backhauling using LTE RNs is that LTE spectrum is more tolerant to weather-dependent signal attenuation due to the higher wavelength that is used in this case in comparison with the range of wavelength values that is found in microwave point-to-point transmissions. Moreover, this method provides cost savings related with the fact that no microwave transmission equipment (e.g., RF modules) is needed.

Of course, proper network planning and design (e.g., locations and transmission power of RNs) is required for this backhauling technique to be effective.

![LTE relay nodes used to implement wireless backhaul](image)

*Figure 3-7: LTE relay nodes used to implement wireless backhaul [6].*

3.3.2 Millimetre wave technology for mobile backhauling
The apparent spectrum scarcity and the need to access additional spectrum in order to meet the increased capacity demands of emerging mobile communication systems have shifted the focus of the community to the millimetre-wave region of the wireless
spectrum (i.e., the unlicensed 60 GHz band and the licensed 70/80 GHz band) where there is abundant available spectrum.

The utilization of the millimetre-wave spectrum has the potential not only to address the spectrum crunch issue but also to provide multi-gigabit capacity.

Moreover, due to the propagation characteristics of the electromagnetic waves in millimeter-wave bands, it is possible to use highly directive “pencil beams”, thus completely eliminating interference and enhancing spectrum re-use. Furthermore, due to the high attenuation and signal quality degradation caused in such high frequencies by phenomena such as rain fading, the range of mm-wave systems is relatively short (a few kilometers).

It becomes apparent that the deployment of mm-wave systems requires minimal frequency coordination. Nevertheless, currently the cost of mm-wave licenses and equipment is prohibitive for commercial use.

However, the so-called E-Band of the mm-wave spectrum is already fully-licensed in some countries (e.g., Spain, France, Germany etc.) as well as lightly licensed in some other countries (e.g., UK), but still there are also countries where this band is not available yet. In some of the aforementioned countries where the E-Band has been licensed, the deployment of the first E-Band systems has started.

Typically, the E-Band frequency allocation consists of a single pair of non-channelized 5 GHz bands (i.e., 71-76 GHz and 81-86 GHz) as shown in Figure 3-8.

![Figure 3-8: ITU allocation of 71-76 and 81-86 GHz E-band frequencies [6].](image)

Let us describe the light licensing principle. Several national regulators have recognized the benefits of mm-wave communications, including the ease of registration, coordination and licensing which stems from the abundance of available spectrum, the short-range of mm-wave links, and the interference-mitigation property of “pencil-beam” transmissions. In addition, they have realized that licensing fees based on the volume of data transfer or on bandwidth usage would discourage the adoption of these ultra-broadband systems. Therefore, they decided to keep license fees low.
A representative example of light licensing adoption is the UK. The UK Office of Communications (Ofcom) is responsible for the registration of the licensees (an application to Ofcom has to be sent prior by the corresponding licensee) and the licensing of individual mm-wave point-to-point links (each licensee can obtain license for an arbitrary number of links). Interference analysis responsibility rest on the licensees, which have to conduct Ofcom’s link database prior to link registration (the concept of “first come, first served” applies). This self-coordinated process reduces significantly administration costs, thus enabling Ofcom to deliver licenses with a relative low cost – about £50 per year.

In countries which follow a fully-licensed approach, on the other hand, the licensee has to apply for individual links to the corresponding authority, which coordinates spectrum allocation and determines the conditions of band utilization, such as maximum transmission power.

### 3.3.3 Massive MIMO for mobile backhauling

Massive MIMO is an emerging technology for the radio access of cellular mobile communications systems. In massive MIMO, the base station (BS) is equipped with an excessive number of antennas. The additional degrees of freedom (DoF) enable the formation of very narrow beams, such that the mobile users are orthogonalized in the spatial domain. Thus, a large number of users can be served simultaneously without interfering with each other.

It is expected that massive MIMO will be combined with small-cells (SCs) and mm-wave technologies. In that context, massive MIMO can be used also as a wireless mobile backhauling solution. More specifically, assume a macro-cell BS (MBS) equipped with a large antenna array, and a number of small-cell BSs (SBS) located within the service area of the macro-cell. The wireless backhaul traffic of the small cells can be transmitted in that case to the MBS by mm-wave communication links, and then the aggregated backhaul traffic at the MBS may be forwarded to the core network (CN) by any means (e.g. fiber to the cell (FTTC) links). This concept is illustrated in Figure 3-9.
3.3.4 Wireless full-duplex technology and self-backhauling

Wireless full-duplex (FD) is an emerging paradigm that allows a radio to simultaneously transmit and receive signals using a single frequency channel. By using a single channel for sending signals in the uplink (UL) and downlink (DL) at the same time, we double the spectral efficiency of the system.

Wireless FD requires the use of efficient Self-Interference Cancellation (SIC) techniques. Self-interference refers to the energy that leaks into a radio’s receiver while transmitting. Due to its local generation, self-interference is 100+ dB stronger than the desired receive signal.

So far, it was impossible to provide so high isolation between the transmitting and receiving interface of a radio. Therefore, the only way to avoid self-interference was to operate in half-duplex (HD) mode, that is, either to transmit and receive at different frequency channels or at different times. The former technique is known as Frequency Division Duplex (FDD), while the latter is referred to as Time Division Duplex (TDD). Recent advances, though, in SIC resulted in the development of hybrid analog-digital SIC systems which are able to provide TX-RX isolation of about 120 dB, making wireless FD possible.
Wireless FD can be used for backhauling through PTP MW links as a means to double wireless capacity and reduces spectrum requirements. It can also be used as a self-backhauling solution for small-cells. We refer to self-backhauling as the ability of a wireless transceiver to use concurrently the same frequency band for both wireless access and wireless backhauling. Thus, an FD-enabled small-cell (SC) could reuse its LTE access spectrum to backhaul itself while maintaining end-end throughput.

3.3.5 Visible light communications technology for mobile backhauling
Visible light communication (VLC) can be used as an alternative to Wi-Fi for hot spot connectivity as well as to indoor small-cell radio access. Such an optical access point (AP) is referred to as atto-cell [7]. The benefits of VLC APs are listed below:

1. Abundance of available spectrum to achieve ~Gbps data rates.
2. No interference with RF infrastructure.
3. Use of low-cost LED light bulbs.

The technology that will be used for the backhauling of Li-Fi networks will be probably the same as the one used for the backhauling of Wi-Fi and fem-to-cell networks, i.e., cable or digital subscriber line (DSL) broadband Internet connections.
3.3.6 Standards for emerging terrestrial backhauling technologies

3.3.6.1 ETSI ISG mWT
ETSI produces globally-applicable standards for Information and Communications Technologies (ICT), including fixed, mobile, radio, converged, aeronautical, broadcast and internet technologies and is officially recognized by the European Union as a European Standards Organization. ETSI has recently announced that the newly formed Industry Specification Group on millimetre Wave Transmission (ISG mWT) [6] held its first meeting at ETSI on 14-15 January 2015 and immediately commenced work developing a set of five specifications.

According to the newly elected chairman of ETSI’s ISG mWT, the ISG mWT was conceived as an industry wide platform to prepare for large scale usage of millimetre wave spectrum in current and future transmission networks by improving the conditions to make millimetre wave spectrum a suitable and convenient choice for all stakeholders. The ISG aims to be a worldwide initiative with global reach and to address the whole industry: national regulators, standards organizations, telecom operators, product vendors and key component vendors.

Millimetre wave spectrum, in the 30GHz to 300GHz range, offers more available spectrum than in lower bands with larger channel bandwidths granting a fibre like capacity. The spectrum can be made available readily and can be reused easily, and lower licensing costs lead to lower total cost of ownership and lower cost per bit of radio systems.
4 Satellite backhaul technologies

The use of satellite backhaul has sometimes been considered an expensive solution by mobile network operators (MNOs) thus preventing its use in a large scale. However with the advance of the mobile networks and the cost/bit reductions of current state of the art satellite technology as well as the need to serve the ever increasing traffic demands and expand to unserved and underserved areas, satellite has become a very promising solution for mobile backhaul.

Satellite backhaul is an ideal choice for MNOs to expand their service in rural areas where the existing infrastructure is limited or non-existent. The cost of installing terrestrial backhaul infrastructure in such rural areas both in the developed and developing countries is prohibitive most of the times. In the case of the developing countries the ARPU is very low to justify the expansion of the network, whereas in the developed countries the population density is low. The use of satellite for backhaul reduces the infrastructure cost while at the same time provides access to new users for the MNO.

Another case where satellite backhaul can be beneficial is for serving remote areas. Remote areas are usually geographically challenging which means that fixed links are frequently non-existent and wireless links might need numerous hops to provide backhaul capability increasing the cost. Satellite links which only require LOS with the satellite can overcome this problem and relay the mobile traffic to the core network.

Even though satellite is naturally a well-suited solution for rural and remote areas, it still can bring benefits to urban areas in cases where a very quick solution is required as a backhaul link can be installed within a day if necessary. Additionally, when the terrestrial backhaul links are congested due to high traffic demand or fail, satellite links can serve as bandwidth extension or as backup solution for service continuity.

4.1 Satellite backhaul systems

When referring to satellite backhaul we will assume that the satellite used is a High Throughput Satellite (HTS) using Ka band frequencies which is operating as a bent pipe without any on board processing capability.

HTSs provide multiple times the throughput of a traditional FSS satellite assuming the same amount of spectrum by employing spot beam technology. This technology allows the use of narrow beams covering smaller geographical areas and enabling high frequency reuse. A representation of the footprint of a HTS is presented in Figure 4-1 where the different beam colours represent different pairs of frequencies and...
polarisations. Each spot beam is usually served from a specific teleport which is connected to the internet through a fiber network.

Figure 4-1: Frequency reuse in Ka band with spot beams.

Satellites are classified into four categories based on their distance from Earth; High Earth Orbit (HEO), Geosynchronous Orbit (GSO), Medium Earth Orbit (MEO) and Low Earth Orbit (LEO). In the context of SANSA we will be focusing on GEO and MEO satellites as these types are used nowadays for mobile backhaul in Ka band.

4.1.1 Backhaul architecture with GEO satellite

Geostationary satellites (GEO), a subcategory of GSO satellites, are located above the Earth’s equator at about 36,000 km. GEO satellites have an orbit period of 24 hours meaning that their location in respect to Earth is fixed so there is no need for satellite tracking at the user site.
Figure 4-2 presents the high level backhaul architecture when using a GEO satellite. At the mobile site a VSAT needs to be installed that will enable the communication with the satellite. The traffic from the BTS/Node B/eNodeB will go through a local RAN optimiser which will perform the necessary functions to optimise the signal for the transmission over the satellite. The use of the RAN optimiser is optional and its use depends on the optimisations that the satellite router performs. Then the traffic will go through the satellite router to be modulated according to the air interface used and transmitted via the remote antenna to the satellite. On the teleport site, after the traffic is received by the gateway antenna and demodulated from the satellite hub it goes through the central RAN optimiser and is then routed to the mobile core network through the satellite backbone fibre network.

4.1.2 Backhaul architecture with MEO satellites
The distance of MEO satellites from the Earth ranges from 2,000 km to 36,000 km which leads to an orbital period from 2 hours to almost 24 hours. In order to be able to provide coverage of a geographical region throughout the day a constellation of MEO satellites needs to be in orbit so that at any given time at least one satellite is visible from that particular location.

Figure 4-3 presents the high level backhaul architecture when using a MEO satellite constellation. The architecture is the same with the one used for GEO with the exception of the remote and gateway antennas.
Both at the user site and the teleport two antennas with tracking capability are needed; one that is communicating with the satellite that is currently serving the area and a second that is tracking the sky to connect with the next satellite that will be serving the area. The handover from one satellite to the next is done at the mobile site and the teleport during the interval when both satellites are visible from both sites simultaneously.

### 4.1.3 Backhaul Applications

As a backhaul solution satellites can interoperate with all the mobile standards supporting the following applications:

- 2G access backhauling connecting the BTS and the BSC (Abis interface);
- 3G access backhauling connecting the Node B and the RNC (IUB interface) or the 3G small cell and the home gateway (IUH interface);
- LTE access backhauling connecting the eNodeB and the S-GW (S1-U interface);
- BSC to core network backhauling;
- RNC to core network backhauling;
- MSC to core network backhauling.

While Figure 4-2 and Figure 4-3 focused on the high level system design for delivering satellite backhaul to rural areas through GEO and MEO satellites, in this section we present other applications of satellite backhaul as well as any additional network design requirements that have to be fulfilled for their operation. These applications are depicted in Figure 4-4.
4.1.3.1 Mobile sites

Mobile sites such as ships and aircrafts are characteristic scenarios of satellite backhaul since most of the time they cannot be reached by terrestrial links. Because these sites are mobile there is need for using a tracking antenna to maintain precise pointing with the satellite. Once the traffic is received by the VSAT it is distributed within the ship/aircraft through a local network.

In case of events when a high volume of traffic is expected mobile operators can use mobile sites that they can quickly deploy at the site of interest. These usually consist of a van that is equipped with a VSAT and a Wi-Fi antenna that beams over the area to be covered.

4.1.3.2 Backup solution

Satellites can be used to connect the BSC, RNC and MSC with the core network either in case of backup solution or for fast deployments that will later be substituted with permanent links. Because the BSC/RNC/MSC carry high amount of traffic they need to have access to dedicated bandwidth which can drive the cost up if allocated permanently. Therefore, a monitoring and control system with an out of band antenna is installed at the site. This monitoring system is used to detect the failure of the link to the core and coordinate the allocation of the appropriate satellite capacity from the pool of the MNO’s available bandwidth on the satellite.
4.1.3.3 Rural small cells
The Small Cell Forum has looked into network architectures to facilitate the service provision in rural and remote small cells [7]; one of the proposed end-to-end network architectures is presented in Figure 4-5. This particular topology refers to a village or a small town where multiple small cells can be deployed. The traffic from these cells can be aggregated at a concentrator in the local Small Cell Network (SCN) and after optimisation from the backhaul adaptor it will be backhauled to the Small Cell Core Network (SCCN) via satellite. The satellite in this case will provide the link between the local concentrator and the serving gateway (SeGW) at the SCCN.

![Backhaul architecture for rural small cell](image)

4.1.4 Satellite backhaul access techniques
There are two main access techniques that can be used for satellite backhaul; time division multiplexing/time division multiple access (TDM/TDMA) and single carrier per channel (SCPC). With SCPC the user is assigned dedicated frequencies to use both in the forward (gateway to remotes) and return link (remotes to gateway). A solution employing TDM/TDMA will statistically multiplex the signals in the forward link to serve multiple users using a shared frequency pool and in the same way it will allocate on demand timeslots to remotes in the return link. In practice the access technique usually applied is the use of TDM in the forward link and SCPC or TDMA in the return link. The two access schemes are depicted in Figure 4-6.
The main advantage of the TDM/TDMA scheme [8] is that the sites can dynamically share the spectrum which is assigned to them based on their real-time demands. This is an ideal solution for connecting multiple sites through satellite backhaul taking advantage of the different traffic patterns of these sites throughout the day. By allowing spectrum sharing the total bandwidth usage by the MNO is minimised and therefore the cost is reduced. For “bursty” data TDM/TDMA can provide 30-40% of bandwidth savings as shown in Figure 4-7. Figure 4-8 illustrates the bandwidth savings achieved by comparing the number of channels required to support n BTSs with terrestrial/SCPC and TDMA satellite. The mobile operator can also easily scale up the network of sites served by the satellite as long as they are within the coverage area of the same beam. On the other hand spectrum sharing among numerous sites introduces a higher complexity at the satellite hub side which becomes more difficult to set up and manage. Additionally due to TDM/TDMA being based on a contended access to the medium, it cannot guarantee that a site will be served in case of high traffic which might be problematic for some applications.
With SCPC, frequencies are assigned to specific sites irrespective of their traffic volume and as a consequence the bandwidth allocated to each site should ensure availability with peak traffic which leads to higher cost for the MNO. However, SCPC is preferred over TDM/TDMA solutions in cases where a site is serving high traffic which is relatively constant over time or when it needs guaranteed service. As the use of the frequency is exclusive the site experiences lower jitter which can be very important in voice backhauling or time-sensitive applications.

**Figure 4-7: Bandwidth savings with TDM/TDMA versus SCPC.**

**Figure 4-8: Number of channels to support n BTSs with TDMA satellite vs SCPC terrestrial.**
4.2 Satellite backhauling requirements from MNO

The satellite backhaul requirements set by the MNO are dependent on the type of application that the backhaul is intended to serve. These requirements can be broadly categorised into network, equipment and performance requirements.

4.2.1 Network requirements

The satellite backhaul service needs to be dimensioned properly to be able to handle the MNO’s traffic. Careful traffic profiling and identification of the number and location of the remote sites to be served are essential for deciding the bandwidth, access method and other characteristics of the service.

4.2.2 Equipment requirements

These requirements relate to the selection of the appropriate equipment that is going to be used. Limitations such as power consumption, physical space, security conditions at the site, interoperability, interfaces with the MNO’s network as well as budgetary implications are taken into consideration for the equipment selection. Other considerations around the site to be served might be applicable such as whether it is mobile or whether the satellite router will be installed indoors/outdoors.

4.2.3 Performance requirements

The main performance indicators that are assessed are Bit Error Rate (BER), frame delay, frame jitter and end-to-end service availability.

4.2.4 Regulatory requirements

According to national laws but also European Union decisions, there is need for lawful interception (LI) of the telecommunication traffic and related information. ETSI has published a technical specification document that describes the requirements that different Law Enforcement Agencies (LEAs) might impose on network operators, access providers and service providers for the implementation of LI [9].

The architecture in Figure 4-9 shows the implementation of LI in a network where the different interception measures (content of communication, location information, service and communication associated information) are passed on to the LEA through the handover interface. The intercepted content which is referred to as “result of interception” is delivered to the law enforcement monitoring facility.
There are cases of services provided in a country (here “home country”) while the switching point of the network operator, service or access provider is in foreign territory as depicted in Figure 4-10. This scenario is applicable to satellite operators who have a wide coverage area but operate gateways in specific locations within it. Depending on the regulations of the home country and the requirements of its LEA there might be implications in the provision of service, which dictates the importance of LI requirements for the home country MNO when using a satellite backhaul solution.

4.3 State of the art equipment for satellite backhaul

Based on the architectures presented in Figure 4-2 and Figure 4-3 the equipment that is needed for satellite backhaul is standard and includes the VSAT, the RAN optimiser and the satellite router. The optimisation functions of the RAN optimiser can be performed either by the satellite router or by dedicated hardware.
The VSAT configuration can be split in the outdoor and indoor unit (ODU and IDU respectively). The ODU comprises of the antenna, the block upconverter (BUC), the low-noise block downconverter (LNB), the orthomode transducer (OMT) whereas the IDU is the satellite router.

The Ka band antenna used for backhaul is a parabolic dish with its diameter ranging from 74 – 240 cm depending on the application and the requirements.

Table 4-1 and Table 4-2 show the forward and return satellite link details that are offered by the state-of-the-art IDU available.

Table 4-1: State-of-the-art satellite forward link details [10]-[17].

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Model (remote)</th>
<th>Forward link - Gateway to Remote</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard/Access scheme</td>
<td>Carrier symbol rate</td>
</tr>
<tr>
<td>Comtech (GEO/MEO)</td>
<td>CDM-840</td>
<td>DVB-S2 with ACM</td>
</tr>
<tr>
<td>Hughes (GEO)</td>
<td>HX280</td>
<td>DVB-S2 with ACM</td>
</tr>
<tr>
<td>Gilat (GEO)</td>
<td>SkyEdge II - c Capricorn</td>
<td>DVB-S2 with ACM</td>
</tr>
<tr>
<td>Gilat (MEO)</td>
<td>meoEdge</td>
<td>DVB-S2 with ACM</td>
</tr>
<tr>
<td>iDirect (GEO)</td>
<td>X7</td>
<td>DVB-S2 with ACM</td>
</tr>
<tr>
<td>Newtec (GEO)</td>
<td>MDM3300</td>
<td>DVB-S2 with ACM</td>
</tr>
<tr>
<td>NovelSat (GEO)</td>
<td>NS3000</td>
<td>DVB-S2 with ACM or NS3™</td>
</tr>
</tbody>
</table>
**Table 4.2: State-of-the-art satellite return link details [10]-[17].**

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Model (remote)</th>
<th>Return link – Remote to Gateway</th>
<th>Standard/Access scheme</th>
<th>Inbound symbol rate</th>
<th>Modulation</th>
<th>Coding</th>
<th>FEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comtech (GEO/MEO)</td>
<td>CDM-840</td>
<td>dSCPC (Dynamic SCPC)</td>
<td>16 Ksps-4.5 Msp</td>
<td>BPSK, QPSK,</td>
<td>VersaFEC® (family of short-block LDPC codes)</td>
<td>BPSK 0.488, QPSK 0.533, 0.631, 0.706, 0.803, 8QAM 0.642, 0.711, 0.780, 16QAM 0.731, 0.780, 0.829, 0.853</td>
<td></td>
</tr>
<tr>
<td>Hughes (GEO)</td>
<td>HX280</td>
<td>FDMA/TDMA</td>
<td>256-6,144 Ksp</td>
<td>QPSK</td>
<td>TurboCode, LDPC (Star TDMA channels only)</td>
<td>TurboCode 1/2, 2/3, 4/5, LDPC 1/2, 2/3, 4/5, 9/10</td>
<td></td>
</tr>
<tr>
<td>Gilat (GEO)</td>
<td>SkyEdge II-c Capricorn</td>
<td>MF-TDMA, Dynamic channels</td>
<td>128 Ksps-4 Msp</td>
<td>QPSK, 8PSK</td>
<td>TPC</td>
<td>1/2, 2/3, 3/4, 4/5, 6/7</td>
<td></td>
</tr>
<tr>
<td>Gilat (MEO)</td>
<td>meoEdge</td>
<td>MF-TDMA, Dynamic channels</td>
<td>128 Ksps-2.56 Msp</td>
<td>QPSK, 8PSK</td>
<td>TPC</td>
<td>1/2, 2/3, 3/4, 4/5, 6/7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SCPC</td>
<td>300 Kps – 10 Msp</td>
<td>QPSK, 8PSK, 16APSK</td>
<td>LDPC, BCH</td>
<td>1/4, 1/3, 2/5, 1/2, 3/5, 2/3, 3/4, 4/5, 5/6, 8/9, 9/10</td>
<td></td>
</tr>
<tr>
<td>iDirect (GEO)</td>
<td>X7</td>
<td>A-TDMA</td>
<td>128 Ksps-7.5 Msp</td>
<td>BPSK, QPSK, 8PSK</td>
<td>2D 16-State</td>
<td>1/2-6/7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SCPC</td>
<td>128 Ksps-11.75 Msp</td>
<td>BPSK, QPSK, 8PSK</td>
<td>2D 16-State</td>
<td>1/2-6/7</td>
<td></td>
</tr>
<tr>
<td>Newtec (GEO)</td>
<td>MDM3300</td>
<td>MF-TDMA</td>
<td>Symbol rate is dependent on the spacing and the MODCOD.</td>
<td>4CPM with 6 MODCODs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HRC™/Mx-DMA™ or SCPC</td>
<td>30 Ksps-5 Msp</td>
<td>QPSK up to 32APSK with 40 MODCODs</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3 The dynamic channels technology reconfigures the return carrier plan based on demand and channel conditions.
4 Adaptive TDMA (A-TDMA) enables the support of return carriers with different symbol rates and MODCODs which adjust to the uplink conditions.
In the forward link almost all satellite routers support DVB-S2 with Adaptive Coding and Modulation (ACM) the coding and modulation applied changes dynamically based on the channel conditions to improve the performance.

Although DVB-RCS/RCS2 is the standard that defines the complete air interface for the return link most vendors use their proprietary interfaces instead as per the Satellite backhauling performance

Typical performance measures for satellite backhaul are latency, jitter, BER, availability and throughput. Although these depend heavily on the specific hardware used and the optimisations applied, we summarise in Table 4-3 indicative values.

Table 4-3: Typical satellite backhaul performance parameters.

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over-the-air delay</td>
<td>260 ms (GEO)</td>
</tr>
<tr>
<td></td>
<td>100 ms (MEO)</td>
</tr>
<tr>
<td>Jitter</td>
<td>10 ms for SCPC</td>
</tr>
<tr>
<td></td>
<td>30 ms for TDMA</td>
</tr>
<tr>
<td>Throughput</td>
<td>FWD 128kbps – 360Mbps (TDM)</td>
</tr>
<tr>
<td></td>
<td>RTN 128kbps – 14Mbps (TDMA)</td>
</tr>
<tr>
<td></td>
<td>RTN 128kbps – 360Mbps (SCPC)</td>
</tr>
<tr>
<td>BER</td>
<td>&lt;=10^{-6}</td>
</tr>
<tr>
<td>Availability</td>
<td>99.5 – 99.9%</td>
</tr>
</tbody>
</table>

5 High Resolution Coding (HRC) is a patented waveform which optimises low to medium rate traffic and avoids latency over the satellite by using short block codes.

6 Cross-Dimensional Multiple Access (Mx-DMA) is an access technology applied to the return link which enables allocation of dedicated bandwidth based on real time demand and channel conditions.
4.4 Traffic optimization techniques for satellite backhaul

Traffic optimisation techniques can be employed to reduce the amount of traffic that needs to be backhauled via the satellite to the core or improve the quality of the service provided. Both cases are important as they offer savings in the amount bandwidth that has to be used by the MNO and improve the quality of service that the MNO’s customers experience.

4.4.1 TCP optimisation

TCP is a well-established protocol for reliable delivery of data over IP. In the sections that follow we will present a brief overview of TCP and explain the impact it has on the performance of a satellite system, as well as the optimisations that are applied for transmission over the satellite link.

4.4.1.1 TCP overview and limitations over the satellite link

The operation of TCP is based on the transmitter sending a pre-defined number of segments known as window size to the receiver and waiting for all the corresponding acknowledgements of receipt (ACKs) before sending the next group of segments. In case an ACK is not received within the expected timeframe the transmitter re-sends the segment corresponding to the missing ACK assuming it has been lost.

TCP configures its operation based on the level of congestion in the network by employing four congestion control algorithms; Slow Start, Congestion Avoidance, Fast Retransmit and Fast Recovery [18], [19]. The two main variables that are used in these algorithms are the congestion window (CWND) and the slow start threshold (SSTHRESH). CWND represents the number of segments that can be sent by the transmitter without waiting to receive ACKs and SSTHRESH is used to decide which algorithm will be applied to increase CWND. SSTHRESH is initially set to the receiver’s advertised window size when the TCP session is established.

- **Slow start**: This mechanism is used when establishing a new session or after the unsuccessful delivery of an ACK. The transmitter starts sending data segments using the minimum CWND size which increases by 1 with every ACK received. The slow start process finishes when CWND is equal to or greater than the SSTHRESH or when a loss occurs. In case of a lost ACK, TCP assumes that there is network congestion and applies the slow start process setting the SSTHRESH to half the current CWND value and resetting the CWND value to the minimum.

- **Congestion avoidance**: This is an alternative mechanism for increasing the CWND which is activated when CWND has reached the value of SSTHRESH. In this case the CWND value increases only if all ACKs for the transmitted segments
within the current CWND have been received, which leads to a linear CWND growth rate.

- **Fast retransmit:** This mechanism is used to reduce the time the transmitter needs to wait before resending a lost segment. Instead of waiting for the retransmission timeout before resending, the transmitter can send the lost segment after the receipt of three duplicate ACKs.

- **Fast recovery:** This mechanism is employed for the transmission of new segments until non-duplicate ACKs are received. With the receipt of a non-duplicate ACK the CWND is set equal to SSTHRES so that the Congestion avoidance algorithm is initiated.

The main factor that affects TCP performance over the satellite is the propagation delay that the signal experiences [19]. For GEO satellites the delay can reach 260 ms which leads to a round trip time (RTT) of about 520 ms (only considering satellite over-the-air path). In comparison, terrestrial RTT range from 35 to 100 ms. The high RTT experienced with a satellite system is interpreted as congestion by TCP and it imposes on the growth rate of CWND leading to operation in the slow start state for longer time. As a result the throughput that can be achieved is limited and the available resources are underutilized.

Another factor that adds to the high RTT and influences the TCP performance is the asymmetry between uplink and downlink traffic that naturally exists in the satellite system [20]. Usually the forward path has higher rates compared to the return link, so the ACKs from the remote terminal have to reach the transmitter through a lower rate link than the one used to transmit the TCP segments. This might cause congestion on the return link that will in turn have an impact on the forward link through the TCP congestion control mechanisms.

### 4.4.1.2 TCP optimisation techniques

In order to improve TCP performance in satellite systems, there are a number of possible enhancements that can be implemented which will be presented in this section. VSAT vendors usually implement a combination of the following optimisation techniques either integrating them in the satellite IDU or using third party hardware.

**TCP Performance Enhancing Proxy (PEP)**

Performance Enhancing Proxies (PEPs) are generally used to improve IP performance by mitigating the impact of inherent link characteristics. In the case of satellite links, TCP PEPs operate at the transport layer and enhance the operation of TCP in order to mitigate the effects of link delay [23].
TCP PEPs employ different mechanisms but the one most commonly used in satellite systems is referred to as TCP interception or spoofing, which virtually breaks the end-to-end TCP connection between the transmitter and the receiver as presented in Figure 4-11 [21]. However, this process is transparent to the end points of the link (TCP client and server).

The gateway satellite router receives the TCP segments coming from the transmitter, looks at their headers and sends back spoofed ACKs enabling new segments to be sent out. When the real ACKs from the receiver arrive the gateway satellite router suppresses them to prevent them from reaching the transmitter. This technique reduces the time it takes for the ACKs to reach the transmitter as they don’t have to experience the delay over satellite link and enables the CWND to increase faster during the slow start phase improving essentially the throughput of the system.

Although Figure 4-11 presents the process for the forward link, the same technique is applied in the return link, so both the gateway and the remote satellite router can support the TCP interception functionality.

Figure 4-11: TCP interception on the forward link.
Selective Acknowledgement (SACK) and Selective Negative Acknowledgment (SNAck)

TCP employs a cumulative acknowledge scheme according to which all the received segments that are not on the left edge of the received window are not acknowledged. As a result, the transmitter has to either wait for a multiple RTTs to find out which segments were dropped or proactively resend segments that might have already been received successfully.

In [26] the SACK scheme is proposed as a solution for the implications of the cumulative acknowledgement scheme. This option enables the receiver to communicate the successful delivery of every segment after it has been received. Thus the transmitter knows within an RTT whether the segment was lost and can resend it.

Moving beyond SACK, a TCP extension discussed in [22] introduced an error recovery mechanism called SNACK. When SNACK is implemented the receiver communicates to the transmitter only the segments that were lost and the sequence number of the segment before the first missing segment. As a result the transmitter knows accurately which segments are missing and can re-transmit them quicker.

Window scaling

TCP performance depends on the bandwidth-delay product which represents the maximum amount of traffic that the system can facilitate at any given time and it dictates the size of the buffer required at the transmitter and the receiver. For links with high delay such as satellite links, the bandwidth-delay product is so high that the window size field in the TCP header cannot hold this value. Without any modification in the maximum window size, TCP does not take advantage of the full capacity of the link. To overcome this problem, the window scaling option was introduced in [24], [25] that expands the TCP window field to 32 bits and defines a scaling factor to carry that information in the 16-bit window field header. The scaling factor is agreed between the transmitter and the receiver during the setup of the TCP session using the SYN segments.

Payload and header compression

One of the most common techniques implemented to minimise the amount of data transmitted over the satellite link is header and payload compression. Further advantages linked to compression are improved link efficiency and utilisation.

Payload compression is generally distinguished between lossless and lossy compression. Lossless compression algorithms identify the redundant data within the payload and replace them with a pointer that is removed at the receiver side. This
process allows the full reconstruction of the original payload in contrast to lossy compression where the redundant data are discarded. Lossy compression can achieve higher compression rates and is typically applied on images [27]. The IP Payload Compression Protocol (IPComp) presented in [28] is one of the protocols that provides lossless compression.

The Robust Header Compression (ROHC) is a standardised method by IETF for compressing IP, UDP and TCP headers of IP packets [29]. Header compression can be applied to packet headers that belong to same flow as there is significant data redundancy among them. The relative compression gain will vary depending on the size of the payload used in the various applications. For example the combined overhead for Voice over IP (VoIP) using Real-time Transport Protocol (RTP) is 40 or 60 bytes when using IPv4 or IPv6 respectively. ROHC can compress this overhead into 1 or 3 bytes [30] which yields a substantial reduction in the traffic and an important improvement in efficiency.

### 4.4.2 IPsec processing

IPsec is a protocol suite for securing end-to-end IP communication standardised by the IETF [31]. IPsec includes protocols for authenticating and encrypting the IP packets exchanged during a session. IPsec includes two security protocols, the Authentication Header (AH) and the Encapsulating Security Payload (ESP) as well as cryptographic key management protocols that enable the operation of the security protocols. AH is used for authentication and ESP for integrity and encryption. Security associations (SAs) are used to establish one-way security functions between the transmitter and the receiver through the use of appropriate algorithms and keys.

The IPsec security protocols can operate in two modes:

- **Transport mode**: Only the payload of the IP packet is authenticated/encrypted leaving the IP header intact. This mode is used when two hosts communicate without a security gateway.
- **Tunnel mode**: The IP packet is authenticated/encrypted and encapsulated in a new IP packet with a different header. When a security gateway intervenes in the communication of the transmitter and the receiver then it is mandatory to use the tunnel mode.

The packet structure for transport and tunnel mode before and after ESP is applied are presented in Figure 4-12. From the packet structure it is obvious that independent of the mode used the TCP header is encrypted. Therefore TCP PEPs are not able to apply any optimisation as they need access to information in the TCP header for their operation such as the TCP source and destination ports and sequence numbers [33].
addition to this, encryption renders data compression impossible as it hides the data redundancy that would be removed.

![IPv4 and IPv6 packets](image)

Figure 4.12: IPv4 and IPv6 packets (a) before and after ESP in (b) transport (middle) and (c) tunnel mode [32].

In order for the TCP PEP to have visibility of the TCP headers the IPsec tunnel needs to break before the PEP functions are applied and is reinstated before the traffic reaches the mobile operator’s core according to Figure 4.13. The IPsec tunnel needs to be terminated only for the user plane packets; the control plane remains in the original IPsec tunnel [7].

![IPsec processing methodology](image)

Figure 4.13: IPsec processing methodology [7].

Although this solution enables TCP optimisation and improves performance, it cancels the end-to-end security provided by breaking the IPsec tunnel [33]. Security methods can be employed over the satellite link such as use of link layer encryption or even new IPsec tunnel between the satellite remote and the gateway. Breaking the initial IPsec
tunnel means that until the encryption for the satellite link is applied the user data might be susceptible to interception.

Research currently focuses on ways of enabling the TCP PEP operation without terminating the IPsec tunnel; one is the transport friendly ESP [34] that permits the inspection of some header fields by authenticating without encrypting them and another is the multi-layer IPsec protocol [35] where the TCP PEP node can decrypt the TCP header, apply the optimisation and encrypt again as presented in Figure 4-14.

![Multi-layer IPsec model for TCP](image)

**Figure 4-14: Multi-layer IPsec model for TCP [35].**

### 4.4.3 HTTP PEP

The Hypertext Transfer Protocol (HTTP) is an application protocol that enables the exchange of content between a server and a client. The HTTP request of a web page on behalf of a client is split up in multiple requests to the server for downloading every content item within the web page. The first request will be for the basic HTML page that contains multiple references to other resources and it will be downloaded to the client using a TCP connection. Following this, new TCP connections will have to be established for requesting and downloading all the embedded objects within the web page [36].

Optimising HTTP operation for high latency links improves the user experience even if TCP acceleration is applied on the same link. HTTP PEPs use a mix of three methods to achieve HTTP acceleration; using cache proxies, prefetching of HTTP content and establishing HTTP persistent connections.

Cache proxies [37] are servers that aim to reduce the latency in delivering content to the client as well as the traffic going through the network. This is achieved by reducing the amount of HTTP requests to the server by keeping local copies of accessed
content. Requests from the client are first received by the cache proxy that looks whether the requested object is saved locally. If a local copy of the object is available and fresh it is sent to the client, otherwise the request is forwarded to the original server. When content is sent from servers to the client local copies are stored in the cache proxy for future use. The cache proxy monitors the client requests and proactively gets content that is likely to be requested next through the HTTP prefetching function [38].

Persistent HTTP [36] establishes a single TCP connection to send multiple requests and receive the respective responses instead of using separate connections for the request/response. The advantage of the persistent connection is the reduced latency as there is less time spent on setting up and tearing down TCP connections and the pipelining of requests and responses becomes possible. The latest versions HTTP 1.1 and HTTP 2.0 use persistent connections as a default.

4.4.4 Selected Internet IP Traffic Offload (SIPTO)
The high amount of traffic generated by mobile devices is posing a problem on the backhaul network but also in the core network as the bandwidth needed to serve the traffic is increasing. Mobile operators are considering ways to limit the amount of bandwidth needed in the core by reducing the traffic that goes through their core networks. Selected Internet IP Traffic Offload (SIPTO), which is being standardised by 3GPP [39], is such a solution that enables mobile traffic offloading in IP networks.

![SIPTO solution for a UMTS macro cell based on local PDN GW selection](image)

SIPTO can be applied both at macrocells and femtocells and enables the operator to define the routing applied so that only selected IP traffic by-passes the core. Alternatively SIPTO can be used to select the optimal path within the MNO’s core.

Figure 4-15 presents the normative SIPTO architecture in a macro cell when the breakout happens “at or above the RAN”. This approach takes into consideration the current location of the user to set up the PDN connection by selecting the geographically or topologically closest Packet Data Network Gateway (PGW). This local
PGW, which is denoted as L-PGW in Figure 4-15, has external IP connectivity that enables the data offloading process. This solution can be implemented in a satellite backhaul scenario with the offloading happening after the satellite gateway.

The main benefits in implementing SIPTO are [40]:

- Reduction of the amount of traffic that goes through the core which leads to improve quality for the users;
- The decision for offload with SIPTO is made on an IP traffic type level so that the same user device can have part of its traffic offloaded while the rest is routed through the core;
- The offloading process is implemented transparently to the user;
- SIPTO supports mobility and service continuity for users moving between eNodeBs and between femtocells.

4.4.5 BTS local switching capability

One of the optimisations applied for the backhauling of GSM voice is the provision of local switching at the BTS through an Abis optimiser [41]. Figure 4-16 presents the network topology and shows how the local switching works.

Assuming there are two mobile users that are served by the same BTS with access to satellite backhaul, the Abis optimiser will switch the GSM voice locally and will only let the associated signaling be backhauled to the mobile core network. The Abis optimiser on the other end will transmit silent frames along with the signaling. This solution reduces the traffic volume that needs to be backhauled as well as the end-to-end transit delay.
4.5 Standards for satellite broadband

4.5.1 DVB Project
The Digital Video Broadcasting (DVB) Project is a consortium of more than 200 companies that develops specifications for digital television systems that are standardised by international bodies like ETSI or CENELEC [42].

4.5.1.1 DVB-S standards
Digital Video Broadcasting – Satellite (DVB-S) is the original DVB standard designed for the forward satellite link to deliver satellite television. Its first release was in 1995 and it specifies the modulation, channel coding and framing structure of the links [43]. DVB-S was designed for delivery of satellite digital multi programme Television (TV) and High Definition Television (HDTV) services for primary and secondary distribution in Fixed Satellite Service (FSS) and Broadcast Satellite Service (BSS) bands [44]. While DVB-S defines the physical layer of the links, the standardised MPEG transport stream (MPEG-TS) is assumed to be the delivered over those links.

DVB-S2, the successor of DVB-S, was developed in 2003 to improve the performance of the standard taking advantage of the advances in transmission technology. DVB-S2 achieves a 30% performance gain over DVB-S for the same transponder bandwidth and transmitted power [45] with its main features being [46]:

- Use of higher modulation schemes;
- Improved coding techniques and multiple code rates;
- Adaptive Coding and Modulation that enables the system to adapt to the link conditions;
- Generic Stream (GS) is the native stream format that can support IP-based data efficiently.

DVB-S2X is currently an optional extension of DVB-S2 and a draft ETSI standard introduced by the DVB Project in 2014. The new features introduced are [47], [48]:

- Additional MODCODs and higher modulation schemes that provide sufficient granularity for achieving up to 51% efficiency gain;
- Smaller roll-off and advanced filtering technologies that enable bandwidth savings from closer carrier spacing;
- Very Low Signal-to-Noise Ratio (VL-SNR) MODCODs implemented with spread spectrum technology to be used with heavy fading link conditions;
- Support of wideband transponders;
- Additional physical layer scrambling sequences to tackle co-channel interference.

A comparison between the main features of DVB-S2 and DVB-S2X is presented in Table 4-4. The core application areas targeted by these two standards are [46], [48]:

- Broadcasting services for transmission of multi-programme television and High Definition Television (HDTV) and other Direct-To-Home (DTH) applications;
- The forward link of broadband interactive services;
- Digital Satellite News Gathering (DSNG) services;
- Professional services such as point-to-point video distribution and IP trunking;
- VL-SNR services which are taken into consideration with DVB-S2X like airborne, maritime and civil aviation internet access.

<table>
<thead>
<tr>
<th>Feature</th>
<th>DVB-S2</th>
<th>DVB-S2X</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODCODs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QPSK</td>
<td>1/4, 1/3, 2/5, 1/2, 3/5, 2/3, 3/4, 4/5, 5/6, 8/9, 9/10</td>
<td>1/4, 1/3, 2/5, 1/2, 3/5, 2/3, 3/4, 4/5, 5/6, 8/9, 9/10, 13/45, 9/20, 11/20</td>
</tr>
<tr>
<td>8PSK</td>
<td>3/5, 2/3, 3/4, 5/6, 8/9, 9/10</td>
<td>3/5, 2/3, 3/4, 5/6, 8/9, 9/10, 13/45, 9/20, 11/20</td>
</tr>
<tr>
<td>16APSK</td>
<td>2/3, 3/4, 4/5, 5/6, 8/9, 9/10</td>
<td>2/3, 3/4, 4/5, 5/6, 8/9, 9/10, 13/45, 9/20, 11/20, 26/45, 32/45</td>
</tr>
<tr>
<td>32APSK</td>
<td>3/4, 4/5, 5/6, 8/9, 9/10</td>
<td>3/4, 4/5, 5/6, 8/9, 9/10, 13/45, 9/20, 11/20, 26/45, 32/45</td>
</tr>
<tr>
<td>64APSK</td>
<td>11/15, 7/9, 4/5, 5/6</td>
<td>NA</td>
</tr>
<tr>
<td>128APSK</td>
<td>3/4, 7/9</td>
<td>NA</td>
</tr>
<tr>
<td>256APSK</td>
<td>32/45, 3/4</td>
<td>NA</td>
</tr>
<tr>
<td>FEC</td>
<td>LDPC in combination with BCH FEC as outer code</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-4: Main features of DVB-S2 [46] and DVB-S2X [48].
<table>
<thead>
<tr>
<th>Feature</th>
<th>DVB-S2</th>
<th>DVB-S2X</th>
</tr>
</thead>
<tbody>
<tr>
<td>FECFRAME (normal)</td>
<td>68,400 bits</td>
<td></td>
</tr>
<tr>
<td>FECFRAME (short)</td>
<td>16,200 bits</td>
<td></td>
</tr>
<tr>
<td>Roll-off</td>
<td>0.35/0.25/0.20</td>
<td>0.15/0.10/0.05</td>
</tr>
<tr>
<td>CCM</td>
<td>Normative(^7)</td>
<td>Not applicable</td>
</tr>
<tr>
<td>VCM</td>
<td>Optional(^8)</td>
<td>Normative</td>
</tr>
<tr>
<td>ACM</td>
<td>Normative for Interactive services, Optional for DSNG and Professional services and Not applicable for Broadcast services</td>
<td>Normative for Interactive and VL-SNR services, Optional for DSNG and Professional services and Not applicable for Broadcast services.</td>
</tr>
</tbody>
</table>

### 4.5.1.2 DVB-RCS standards

While DVB-S designed for the forward satellite link, DVB- Return Channel Satellite (DVB-RCS) was designed to provide return channel connectivity for satellite terminals. The latest revision of DVB-RCS [49] ensures integration with DVB-S and DVB-S2, application to both regenerative and transparent satellites as well as support of mobile terminals.

DVB-RCS specifies the complete air interface for the communication of the VSAT with the satellite gateway. The access scheme used is MF-TDMA that enables multiple users to share the bandwidth on the return channel.

The 2\(^{nd}\) generation DVB-RCS2 that was completed in 2011 achieves 30% improvement in bandwidth efficiency over DVB-RCS [50]. The new features of DVB-RCS2 include [51]:

- The modulation schemes that can be used are CPM, QPSK, 8PSK and 16QAM in contrast to DVB-RCS where only QPSK was used.
- Two types of FEC are used; convolutional coding with CPM and a 16-state turbo code with QPSK/8PSK/16QAM. DVB-RCS was using either Turbo coding or outer Reed-Solomon coding with inner convolutional coding.
- It supports ACM functionality where the modulation and coding can be selected independently in every timeslot.
- The waveforms used can have configurable characteristics for different applications.
- It supports random access user traffic.

\(^7\) Normative are the functionalities that should be implemented both in the receiver and the transmitter for compliance with the standard.

\(^8\) Optional are the functionalities that are optional to implement, however if implemented they should comply with the specifications in the standard.
4.5.2 CCSDS
The Consultative Committee for Space Data Systems (CCSDS) was founded in 1982 and is comprised from 11 governmental space agencies, 28 observer agencies and over 140 industrial associates. CCSDS was formed to provide a forum for discussing common problems in the design and operation of space data systems and develop recommendations and standards to promote interoperability among its members [52].

CCSDS’s work is divided into six thematic areas; Space Internetworking Services, System Engineering, Mission Ops and Information Management Services, Cross Support Services, Spacecraft Onboard Interface Services and Space Link Services. Their publications are categorised into Recommended Standards (Blue Books), Recommended Practices (Magenta Books), Informational Reports (Green Books), Experimental specifications (Orange Books), Record documents (Yellow Books) and Historical documents (Silver Books). The Space Communication Protocol Specification – Transport Protocol (SCPS – TP) [22] belongs to the Blue Books and it defines the transport protocol recommended for implementation by CCSDS for all space missions.

4.6 Future trends on satellite broadband affecting backhaul

4.6.1 Next Generation High Throughput Satellite Systems
Recent studies [53] have estimated that 2-3 Tbps of satellite capacity will be required to serve the addressable market for satellite broadband in Europe by 2020. Next generation HTS will need to be able to offer both higher overall throughput and higher end-user data rates, flexibility to adapt to traffic demand across the coverage area, and at the same time decrease the cost per transmitted bit. In order to be able to serve this increasing demand, the satellite community is spending considerable research effort in the design of next generation Broadband satellite communication systems able to deliver up to a Terabit per second of aggregated capacity and an order of magnitude cost/bit reduction. The increased satellite throughput calls for a multibeam design with extensive frequency reuse across the user beams. In order to maximize the transmission capacity, the whole civil band allocated to FSS in Ka-band according to the radiofrequency regulation authorities in Europe is used for the user links. The occupied spectrum will include shared civil bands [17.7-19.7] GHz on the downlink and [27.5-29.5] GHz on the uplink, and exclusive civil bands [17.3-17.7] GHz and [19.7-20.2] GHz on the downlink and [29.5-30] GHz on the uplink. This implies the need for feeder links to rely on other frequency bands. Given the very large aggregated bandwidth required, an attractive solution is to move the feeder link transmission to higher frequency bands, such as the Q/V-bands (around 40-50 GHz), where 5 GHz are available for both up- and downlink satellite communications. Another solution is to move the feeder link
to optical frequencies. These have already been a hot topic for research in several applications in leading countries such as France, Germany, Japan and USA. In Europe, systems using 0.8μm and 1.06μm technologies have been successively put into orbit for data relay application and LEO-LEO links. Recently the European DRS program has been specified by ESA for LEO-GEO links at 1.06μm. The 1.55μm technology widely deployed in terrestrial networks could be used also for free space links, subject to its qualification for space applications. Optical links allow the entire spectrum of 225 GHz (uplink) and 75 GHz (downlink) to be transmitted over one site.

The EC FP7 research project Broadband Access via integrated Terrestrial and Satellite systems (BATS) [54] has done extensive work on the design of next generation HTS with both Q/V-band and optical configurations. Independently from the feeder link configuration, the mission defined for the BATS project comprises two GEO satellites covering the EU27 countries and Turkey, both co-located at the orbital slot in 13°E and based on the Alphabus Extended platform. The user coverage includes $302 \times 0.21°$ beams, with an East / West coverage sharing between the two satellites, as illustrated on Figure 4-19. Each satellite involves 2 Ka-band antennas with 4.8m reflectors and multiple feed per beam technology. Each of these antennas is used in both reception
(Rx) and transmission (Tx). The air interfaces will be based on the DVB-S2X standard on the F/L and DVB-RCS2 on the R/L as defined in Section 4.5.1.

**Figure 4-19: User Beam layout covering EU27 and Turkey for both Q/V-band and Optical configurations.**

### 4.6.1.1 HTS design with Q/V-band feeder link configuration

In this configuration the bands of interests are for the feeder uplink the [42.5 – 43.5] GHz, [47.2 – 50.2] GHz and [50.4 – 51.4] GHz bands, allocated in V-band to FSS by the ITU. For the feeder downlink, the considered Q-band spectrum is the [37.5 – 42.5] GHz band. The satellite feeder antenna in Q/V band is based on a single reflector with 2m diameter, fed by a Single Feed per Beam (SFPB) focal array, each feed being in charge of one gateway site, in transmission and reception.

The frequency plan considered for the system allows a gateway to convey the traffic of 6 user beams in Q/V band, with the following bandwidth allocation strategy: in the FWD link, 1.5 GHz is allocated to 66% of the beams with the highest expected need for capacity by 2020, whereas the remaining 33% is allocated with 1GHz; in the RTN link, 500 MHz is allocated to user beams. The channel allocation to the user beams relies on a conventional four-colour reuse scheme. Based on the frequency plan defined, the satellite system will be fed by approximately 50 active gateways on ground. Gateway sites need to be selected so to maximise the distance between stations while minimising the terrestrial link costs, using where possible existing teleports. The ground segment configuration has been studied in detail in [55]and [56].
Figure 4-20: Frequency plan for Q/V-band feeder link system

In [56] initial assessment of the performances of this system is provided. On the F/L, considering 420 Mb/s carriers, the maximum throughput is 735 Gbps provided by both satellites across the 302 beams in nominal conditions. The average spectral efficiency is 1.87 bit/s/Hz. The average user beam capacity is 2.5 Gbps in the beams with 1.45 GHz allocated to the forward link, and 1.67 Gbps in the beams with 1 GHz on the forward link. On the R/L, considering 20.7 Mb/s carriers, the maximum satellite capacity provided by the two spacecraft is 260 Gbps. The average spectral efficiency is 1.72 bit/s/Hz, and the average beam capacity is 850 Mbps on the return link. This system configuration will allow satellite operators to provide much more capacity for satellite cellular backhaul applications compared to current state of the art HTS systems.

4.6.1.2 HTS design with Optical feeder link configuration

The innovative optical feeder link architecture proposed for the BATS project (ground-GEO) is based on the Dense Wavelength Division Multiplexing (DWDM) technology to multiplex channels and high power Erbium Doped Fibre Amplifier (EDFA) booster amplifiers. The optical feeder link must be transparent with respect to the user terminal air interface in order to minimize the on-board hardware. This is possible using either digital or analogue modulation of the optical carrier. Both options have been assessed for the BATS mission. The digital option increases the required optical bandwidth due to the quantization of the DVB-S2 and DVB-RCS2 user signals; however it benefits from error correcting codes and framing schemes which are efficient against atmospheric impairments. The digital option needs a high-speed processor on board.
for the digital-to-analogue and analogue-to-digital conversions. The analogue option implemented with Radio over Fibre (RoF) is more bandwidth efficient and it does not require a high-speed processor. However, with the analogue modulation, the atmospheric turbulence impairments can only be mitigated with complex optics on the ground terminal. Both analog and digital options are feasible in the 2025 timeframe but the digital option is considered more mature, in particular with respect to the implementation of the fade mitigating techniques.

An optical feeder link will obviously be of higher capacity than a Q/V band feeder link. As a consequence, the number of simultaneously active gateways is expected to be limited to one or two per satellite, which is a very significant reduction compared to the Q/V option. On the other hand, it is much more sensitive to the atmospheric events (link blockage by the clouds) and site diversity will be required to maintain the 99.9% availability level. An optimisation process has been performed to locate the Optical Gateways (OGs) by minimising the weather correlation between the OGs over 2 years of cloud mask data files [57]. Results show that 8 to 14 OGs are sufficient to reach 99.9% to 99.7% availability under the assumption that OGs can be anywhere in Europe + Turkey and OGs are constrained to be in a radius of less than 50 km around PoPs selected from the global high data rate carrier network (terrestrial and submarine), By including PoPs in Africa and Middle East, the number of required OGs reduces to 3 to 5 OGs.

An end-to-end performances assessment has been carried out and results show that, considering both satellites combined, a total capacity going above 1Tbps is achieved with the proposed design. On the F/L, considering 420Mbaud carriers, a maximum throughput of circa 800Gbps is obtained with both satellites in nominal conditions (Clear Sky). The average user beam capacity is 2.65 Gbps. On the R/L link, up to 249Gbps are reached with an average user beam capacity of 825Mbps.

As for the Q/V-band system, such HTS system would allow order of magnitude increase in the throughput able to be offered over satellite.

**4.6.1.3 Increasing the frequency Re-use factor**

Looking further in time, towards the 2025 timeframe, the BATS project envisages HTS able to operate with more aggressive frequency re-use schemes (2-colours) thanks to advancements on interference cancellation techniques.

This frequency reuse scheme clearly involves very high intra-system interference levels, which call for interference management solutions to allow the capacity improvement.
The following have been identified as suitable techniques to address the frequency reuse interference issue on the forward link:

- **Precoding**: Generally speaking, precoding is used to pre-distort the signal with the goal of minimizing the distortions of every user received signal resulting from non-orthogonality between different antennas beams. The linear precoding technique MMSE (Minimum Mean Square Error) and the non-linear THP-MMSE (Tomlinson Harashima –MMSEE) have been identified as the most performing precoding techniques leading to promising results, above all in the high SNR regime (above 10dB). It should be noted that THP-MMSE is more adequate to counteract the transmission power constraints inherent to precoding techniques especially with aggressive frequency re-use patterns. Note that precoding in the system presented in Section 4.6.1.1 will require cooperation among all 50 gateways so as to allow the joint processing of the signals interfering in the same bands, which could be a technically challenging task to manage.

- **Dynamic fractional frequency reuse**: Rather than implying the processing of all signals in the system, this technique consists in smartly scheduling the resource allocation, using the user locations and the antenna patterns to minimize the frequency reuse interference and maximize the overall capacity. Typically, this technique allows combining several frequency reuse factors in the coverage. The resulting capacity then depends on the respective bandwidth of the channels dedicated to these reuse schemes, and on the interference levels in the related zones.

The application of such techniques and frequency re-use factor would increase even more the aggregated throughput of next generation satellite systems. Details on the work around interference cancellation techniques can be found in [58] and [59].

### 4.6.2 Advanced waveforms

Current research activities are evaluating the application of Fast Fourier Transforms (FFT) based waveforms, such as orthogonal frequency division multiple access (OFDMA), single-carrier frequency division multiple access (SC-FDMA) and filter bank multi-carrier (FBMC), in geostationary orbit satellite communications. The use of these
waveforms can potentially improve the overall spectral and power efficiencies of the system at a manageable computational complexity.

The confined spectrum of the FFT-based waveforms enables the reduction of the guard band between the physical carriers in a satellite system. Two contiguous aggregated carriers based on OFDMA or SC-FDMA can be employed with as little as 5% guard band [60]. OFDMA even provides higher reduction of the spectral sidelobes. In terms of power efficiency, in [61] SC-FDMA demonstrates an improvement of the power efficiency of more than 1 dB as compared to state-of-the-art TDMA with 20% roll-off, and it is able to outperform TDMA with 5% roll-off by 0.5 dB for 16-QAM.

It is important to note though that these waveforms add more complexity to the transmitter and receiver chains, imposing significant challenges on time, frequency and phase synchronization.

These waveforms are extensively used in terrestrial systems, and OFDM in particular is one of the candidates for 5th generation (5G) mobile networks. The application of such waveforms also for satellite communications can open doors for tighter integration of terrestrial and satellite networks. Details on this work can be found in [61], [62], and [63].

4.6.3 Ultra Wide Band Communication

In the ESA project TARGETS [64], by using the finer granularity of DVB-S2x MODCODs and the Super-Frame (SF) structure of DVB-S2x Annex E [65], the feasibility of transmitting 1 Gbit/s on a single carrier over current state of the art wideband satellite transponders is being investigated.

As illustrated in Figure 4-22, the SF concept follows a simple rule to provide a common container that allows hosting different format-specific contents. In essence, each SF consists of exactly 612,540 physical layer symbols. In particular, SF format 4 provides support for wide-band carrier transmission. In the frame of this activity wide-band modulator and modulator have been developed in order to validate the system for the next generation of high speed IP-based broadcasting and broadband access in future Ka-band or Q/V-band HTS systems.
Figure 4-22: Common structure of the super-frame of DVB-S2X Annex E

With the equipment developed in the frame of this ESA activity up to 1 Gbps on a single carrier and full satellite transponder could be offered over in orbit Ka-band satellites. Further details of this project can be found in [66].
5 Optimizing Content Delivery

5.1 Content Delivery Networks (CDN)
The coextending evolution of mobile technologies and devices has made it possible for people to consume video using handheld equipment without compromising their experience. Despite the diversity of available content and an obvious shift by subscribers towards on-demand viewing, watching certain events and programs live continues to appeal to large audiences. This use case covers regional and local interest events, such as concerts, sports fixtures or breaking news. Such as the Super Bowl, FIFA World Cup matches, as well as elections and royal weddings. Given suitable content security and digital-rights handling, this use case can be enhanced to allow users to store and replay the event on-demand from their device for a certain period of time.

A content delivery network (CDN) is a large distributed system of servers deployed in multiple data centres across the Internet. The goal of a CDN is to serve content to end-users with high availability and high performance whilst reducing core Internet traffic. CDNs serve a large fraction of the Internet content today, including web objects (text, graphics and scripts), downloadable objects (media files, software and documents), applications (e-commerce, portals), live streaming media, on-demand streaming media, and social networks.

Most CDNs are operated as an application service provider (ASP) on the Internet (also known as on-demand software or software as a service). An increasing number of Internet network owners have built their own CDNs to improve on-net content delivery, reduce demand on their own telecommunications infrastructure, and to generate revenues from content customers. This might include offering access to media streaming to internet service subscribers.

Some larger software companies such as Microsoft build their own CDNs in tandem to their own products. Examples include Windows’ Azure CDN, Google’s PageSpeed and Amazon’s CloudFront.

Content Delivery Networks (CDNs) are envisaged to ensure the delivery of different types of content, including media (audio/video), files and software, in IP networks. The demand for CDNs has significantly increased in the recent years [73]. This development has been predominantly motivated by the explosive popularity and growth of video-based IP traffic as well as the need for service providers to ensure high-quality services for their customers. This trend is depicted in Figure 5-1 and Figure 5-2 [73].
Figure 5-1: CDNs growth over the last decade by region [73].

As reported in recent studies [74], video is bound to dominate the traffic growth in fixed and mobile networks in the upcoming years. On one hand, the trend is supported by the increasing availability of video capable devices and networks as well as the change in the habits people have in accessing and using video services; that is, with any device and in any location. On the other hand, video is increasingly integrated as a part of other internet services (e.g. news, social media) while the popularity of streaming video continues its increase and is dominated by over-the-top (OTT) services (e.g. YouTube, Netflix).

The foreseen dominance of video over IP traffic is expected to play a detrimental role in the CDN market. The increase of demand for video caching will explode due to both the expected increase in number of subscribers as well to the increase of the average required quality of content. More users will require Ultra-HD video content, in real time. As a result, the global CDN revenues are already accelerating as predicted in [73]. The predictions illustrated in Figure 5-2 indicate that the market for commercial CDN services is expected to be worth US$ 4.63 billion in 2017. This is threefold compared to the revenues in 2012.
To cover for such an explosion in the demand in a timely and efficient manner, the interest of moving to multi-CDN approaches, is emanated. The goal is to increase the content availability to the end user in the most efficient manner. This can be achieved by using the most relevant CDN for each geographical area to serve the related users.

5.1.1 CDN architectures

In a CDN world, content (potentially multiple copies) exists on multiple servers close to the edge of the service provider cloud. When a user makes a request to a CDN hostname, DNS will resolve to an optimized server (based on location, availability, cost, and other metrics) and that CDN content server will handle the request.

CDNs provide services that improve network performance by maximizing bandwidth, improving accessibility and maintaining correctness through content replication. They offer fast and reliable applications and services by distributing content to cache or edge servers located close to users. A CDN has some combination of content-delivery, request-routing, distribution and accounting infrastructure. The content-delivery infrastructure consists of a set of edge servers (also called surrogates) that deliver copies of content to end-users. The request-routing infrastructure is responsible to directing client request to appropriate edge servers. It also interacts with the distribution infrastructure to keep an up-to-date view of the content stored in the CDN caches. The distribution infrastructure moves content from the origin server to the CDN edge servers and ensures consistency of content in the caches. The accounting
infrastructure maintains logs of client accesses and records the usage of the CDN servers. This information is used for traffic reporting and usage-based billing. In practice, CDNs typically host static content including images, video, media clips, advertisements, and other embedded objects for dynamic web content. Typical customers of a CDN are media and Internet advertisement companies, data centers, Internet Service Providers (ISPs), online music retailers, mobile operators, consumer electronics manufacturers, and other carrier companies. Each of these customers wants to publish and deliver their content to the end-users on the Internet in a reliable and timely manner. A CDN focuses on building its network infrastructure to provide the following services and functionalities: storage and management of content; distribution of content among surrogates; cache management; delivery of static, dynamic and streaming content; backup and disaster recovery solutions; and monitoring, performance measurement and reporting.

The operation of a CDN can be considered in four main functions:

- Publishing and storage;
- Caching;
- Delivery;
- Management and control

The main CDN components are shown below in Figure 5-3.

The main node functions are:

- **Delivery Nodes** – their primary purpose is the delivery of data to consumers. It contains caches each running one or more delivery applications; these tend to be deployed as close to the edge (near the consumers) as possible;
- **Storage Nodes** – their primary purpose is providing data to the delivery nodes, these can be deployed in a hierarchical model to allow tiered caching and protection to any origin servers. These nodes can also be used where pre-publishing of content is required rather than content being acquired on demand from origin servers;
- **Origin Nodes** – these are the master sources for content and can be deployed within the operator’s network (on-net) or more commonly within a content owner’s infrastructure. A number of origins will be provided for scale and resilience;
- **Control Node** – primary purpose is to host the management, routing and monitoring components of a CDN. This will be typically the integration point into any OSS/BSS systems and Network Operations Centres.
Content acquisition can either be:

- Pre-Ingested (uploaded);
- Acquired on demand (possibly based on volume of demand);
- Live (streamed content).

Delivery is the process where a consumer request is received, authenticated and routed to a relevant delivery device for fulfilment of the request.

All delivery interactions within a classical CDN follow a regular 3 stage process:

- The Publisher server (DNS server or web server) issues a redirect to the CDN Request Router. This stage is critical to understanding CDNs. CDNs only deliver the content a Publisher has authorised for distribution;
- A CDN Request Router issues a redirect to a CDN Surrogate (i.e. delivery cache with replicated content);
- The CDN Surrogate serves the content (actual delivery).

The architecture of content delivery networks can be presented according to a layered approach. In Figure 5-4, we present the layered architecture of CDNs, which consists of
the following layers: Basic Fabric, Communication & Connectivity, CDN and End-user. The layers are defined in the following as a bottom up approach.

- **Basic Fabric** is the lowest layer of a CDN. It provides the infrastructural resources for its formation. This layer consists of the distributed computational resources such as SMP, clusters, file servers, index servers, and basic network infrastructure connected by high-bandwidth network. Each of these resources runs system software such as operating system, distributed file management system, and content indexing and management systems.

- **Communication & Connectivity** layer provides the core internet protocols (e.g. TCP/UDP, FTP) as well as CDN specific internet protocols (e.g. Internet Cache Protocol (ICP), Hypertext Caching Protocol (HTCP), and Cache Array Routing Protocols (CARP), and authentication protocols such as PKI (Public Key Infrastructures), or SSL (Secure Sockets Layer) for communication, caching and delivery of content and/or services in an authenticated manner. Application specific overlay structures provide efficient search and retrieval capabilities for replicated content by maintaining distributed indexes.

- **CDN** layer consists of the core functionalities of CDN. It can be divided into three sub-layers: CDN services, CDN types and content types. A CDN provides core services such as surrogate selection, request-routing, caching and geographic load balancing, and user specific services for SLA management, resource sharing and CDN brokering. A CDN can operate within an enterprise domain, it can be for academic and/or public purpose or it can simply be used as edge servers of content and services. A CDN can also be dedicated to file sharing based on a peer-to-peer (P2P) architecture. A CDN provides all types of MIME content (e.g. text, audio, video etc) to its users.

- **End-users** are at the top of the CDN layered architecture. In this layer, we have the Web users who connect to the CDN by specifying the URL of content provider’s Web site, in their Web browsers.

### 5.1.2 IPTV: Live TV and VoD

IPTV has been deployed by multiple network operators for distribution of both live TV as well as video-on-demand (VoD), i.e. on-demand delivery of video content. Unlike (residential) broadband Internet service which is provided on a best-effort basis, ensured high quality-of-service (QoS) is critical for an IPTV service. Therefore, the especially high sensitivity of the IPTV application to impairments creates very big network management challenges.
Figure 5-4: Layered architecture of a CDN.

Figure 5-5 illustrates the network infrastructure involved in IPTV service delivery to end customers including the transport network, the content delivery network, and the access network [67]. The transport network infrastructure consists of high-bandwidth MPLS/IP core and distribution. A series of specific hardware elements need to be planned, deployed and managed specifically for this service – set top boxes and Video Switching Offices, for example. As Quality of Service demands are not possible to fulfil with a best effort infrastructure, a new virtual network needs to be defined and managed through specific VLAN tags deployed in the DSLAM.

The video head-end consists of real-time encoders/decoders for local and national broadcast video channels, VoD libraries for on-demand video services, and video switching equipment for video transport. The VoD servers implement the storage and real-time streaming functionality for on-demand services. The conditional access system (CAS) provides encryption and decryption services, as well as key generation and distribution functionality, for both broadcast and on-demand services.
The middleware ties a number of logical components together into a more comprehensive IPTV/video software system. The middleware implements the user interface for both broadcast and on-demand services. Note that there are several different middleware implementations depending upon existing/proposed OSS architecture. Billing of content services can be either pre-paid or post-paid. The end user access is xDSL, or FTTx for wireline providers and QAM/coaxial for cable operators.

The set-top box (STB) is the hardware and common software infrastructure component that is used by the on-demand and broadcast clients as well as by the video decryption function and the video decoder. The hardware may also include a hardware-based decoder and decryption subsystem. The STB software typically includes an embedded operating system, and may also include application infrastructure components such as a Web browser.

5.1.3 Context Aware CDNs over satellite
Advanced content caching and delivery methods are a high priority in the upcoming generations of wireless communication standards. An extensive review of recent advances can be found in [75].

Figure 5-5: Network infrastructure involved in IPTV service delivery to end customers [67].
Conventional CDNs lack the required cost-efficient scalability, to cope with the increasing demands of video traffic. Video traffic trends have shown that a small fraction of video content is popular and requested with high frequency by different end users, and thus multicasting is a desired feature for content distribution. The satellite is considered as an ideal multicast source for delay-tolerant, bandwidth-intensive CDN traffic. Therefore, in [76] satellite-based overlays for existing terrestrial CDNs where proposed, that exploit the satellites broad coverage to feed cashes with the requested context. A recent review on context aware caching for CDNs can be found in [79].

Already deployed terrestrial CDN architectures aim at minimizing the delay of the content delivery to the end user. Fundamental parameters such as the number of the edge caches and the store space available at them, affect the performance of a CDN, at the expense of increasing the capital investment. Reducing the size and the number of the caches however has a detrimental effect in the added delay and the quality of service for the end users. Therefore the caching optimization by taking into account various criteria (traffic, caching cost, system spectral efficiency etc.) is of high value.

5.1.4 LTE broadcast
Mobile Broadband users are demanding spontaneous access to video content, a higher-quality experience and more convergent mobile services than ever before. Owing to the popularity and adoption of Smartphone’s and tablets, as discussed in previous subsections, mobile subscriptions for high data consumption devices are expected to reach 6.5 billion by 2018, while mobile data traffic is expected to grow 15 fold by the end of 2017, driven mainly by video [1].

LTE Broadcast enables operators to efficiently launch media services over LTE to meet this demand, whereas it also enables multiple users to receive the same content simultaneously. LTE broadcast can deliver the same content to multiple users with the capability to support a virtually unlimited number of users in parallel, thereby maintaining efficient use of spectrum and network investments.

Offered solutions employ a new overlaying architecture with several new network elements offered as a simple to deploy end-to-end software license. Such solutions usually include a unique end-to-end implementation of three new standards:

- **eMBMS (Evolved Multimedia Broadcast Multicast Service)** [68]– a 3GPP standard, it enables mobile networks to offer broadcast/multicast services.
- **HEVC (High Efficiency Video Coding/H.265)** [69]– the new video compression standard promises to halve the bandwidth required to transport video content
compare to today’s leading implementation of MPEG-4 AVC.

- MPEG DASH (Dynamic Adaptive Streaming over HTTP) [70] – simplifies and standardizes the adaptive delivery of video to consumer devices, ensuring a better quality of service, greater efficiency and introducing opportunities for monetization.

LTE Broadcast enables Mobile Network Operators to charge premium rates for premium content. They can guarantee quality because they have ability to deliver at all times, no matter how popular any certain live event or media offering may become. This certainty allows the MNO’s and its media partners to offer new services boldly over the mobile networks, using innovative business models, without the fear of congestion or failure to deliver to the consumers.

Figure 5-6 depicts an LTE broadcast architecture.

![LTE Broadcast Architecture](image)

Figure 5-6: Architecture for LTE broadcast [71].

### 5.2 CDN Scenarios for SANSA terrestrial/satellite integrated backhaul

The following scenarios, inspired by a previous ESA study on service delivery over integrated terrestrial/satellite networks [77], are identified in accordance to the scenarios of SANSA.
5.2.1 Scenario 1: Satellite Backhauling towards the edge CDN servers
In remote locations that do not pose a viable business case for the deployment of high throughput terrestrial backhaul networks (e.g. fiber), the satellite can play a key role. A simplified architecture of this deployment scenario is given in Figure 5-7.

![Architecture overview of deployment scenario 1.](image)

5.2.2 Scenario 2: Hybrid Satellite-Terrestrial Backhauling towards the edge CDN servers
The deployment of flexible architectures is an essential parameter of future wireless networks. Focusing on areas where the terrestrial infrastructure is unreliable, the satellite can serve as a complementary component of the system that will boost the capacity of the network while ensuring the uninterruptable delivery of services. Such challenges are often faced in developing regions as well as rural areas where the upgrade of existing terrestrial infrastructures is not cost efficient. It should be noted that such hybrid satellite/terrestrial networks dedicated to the improvement of multimedia content delivery have also been considered in [78].
Figure 5-8. Architecture overview of deployment scenario 2.
6 Conclusions

This document provides a review of current mobile backhaul technologies, standards, requirements and performances. Terrestrial cellular backhauling technologies comprise a variety of physical transmission technologies including optical fiber, microwave radio, copper DSL and occasionally satellite. This document paid special focus to microwave and satellite backhauling technologies as are the main interest for the SANSA integrated backhaul system to be designed in the frame of the project.

Chapter 2 provided an overview of the mobile traffic trends from the present up to 2019, concluding that average mobile connection speeds per user will increase from 1.7 Mbps to 5 Mbps in the downlink and 1 Mbps in the uplink and a consumption of 500 GBs/month/subscriber. This information is relevant for sizing the capacity requirements for backhaul links in the 2019-2020 timeframe. In this chapter, we also presented trends on the mobile applications use, highlighting the increase of video streaming consumption on mobile handhelds. Satellite systems with their almost ubiquitous coverage and multicast capabilities are a good fit for distributing content to CDN caches located at the mobile network base stations. Such solution would optimize the content distribution and reduce the latency for the end-user to get the content from servers in the Internet.

In Chapter 3, we presented, first in Section 3.1, the basic backhauling topologies and provided a qualitative assessment with respect to cost and efficiency. Based on this analysis, we have seen that there is no “perfect” topology, or a “correct” topology for any case. On the contrary, each topology has weaknesses and it is appropriate for specific circumstances. The most common topologies for wireless backhaul networks are rings, trees or a combination of both. In urban scenarios, the trend would be to have a macrocell providing an overlay to several microcells. The backhaul from microcell to macro-cell would tend to have a star topology, with the macrocell acting as central hub and backhauling to the core over a fiber network. In any case, a network designer should always take into account the specific circumstances, business, application and technical requirements, geographical and demographic characteristics, spectrum and antenna costs, in order to determine an optimal best solution for a specific setup. For instance, a ring topology requires lower number of links than a tree one, but higher capacity available per links, which usually implies higher costs and higher spectrum consumption.

Second, we presented the PtP and PtMP link topologies. PtP links require a dedicated transceiver at the hub station for each terminal station and directional antennas both at the hub and the terminal stations. These requirements increase the cost of
ownership and deployment. However, PtP links allow for spectrum reuse between the different hub-terminal pairs. On the other hand, PtMP topologies offer easier installation and are considered to be more cost efficient. However, the available resources (e.g. spectrum, time, or power) are shared between all the terminal stations and would thus fit better to operators who have access to large amounts of spectrum. The most common techniques for shared access to the medium are TDMA and OFDMA, as they allow more flexibility in allocating different amount of resource to the different nodes depending on their load.

Currently PtP links are widely used to provide macro-cell backhaul, while PtMP is receiving a lot of attention in relation to small-cells’ backhaul in urban scenarios. In the SANSA scope, the proposal is to consider the Smart Antennas as providing different PtP links at different times depending on the network topology, as the different links (i.e., pointing to different relay stations) will be re-using resources at different times rather than sharing them.

In terms of spectrum and focusing on the Ka-band, the 6 GHz and 23 GHz bands are normally used for microwaves links in rural areas (i.e., 18 GHz sub-band of Ka-band). Urban areas deployments tend to use bands between 26 GHz and 42 GHz (i.e., 28 GHz sub-band of Ka-band). Distance between backhaul nodes ("hops") are between 2 – 15 km in rural areas and below 3 km in urban areas. Standard channel bandwidths for the microwave links in Ka-band are 7 MHz, 14 MHz, 28 MHz and 56 MHz, with the later getting less common due to congestion in the band.

Third, in Chapter 3 we briefly discussed traffic classification at the eNodeB as a means to provide differentiated service and QoS over LTE. On a first approach to this issue, which needs to be addressed by the SANSA design in order to off-load the right type of traffic over the satellite backhaul link and not to degrade end-user's quality of experience, it seems possible to use at least DiffServ differentiation always depending on the level of encryption provided by the operator over the backhaul interfaces.

Fourth, we provided an overview of existing commercial solutions both for macro and small cells with respect to various technical characteristics, and fifth, we provided a brief overview of standardization activities related to microwave radio at the 6-30 GHz band. As we have seen both from the analysis of commercial product and standardization activities, no standard exists for wireless terrestrial backhauling, thus telecom operators employ proprietary solutions on a large extent.

In Section 3.2, we overview other terrestrial backhauling technologies that either operate at lower frequency bands or are based on fixed solutions (i.e. copper and fibre), and we briefly visited related standardization activities. Section 3.3 provides an
extended overview of emerging trends in wireless terrestrial cellular backhauling including LTE relaying, millimeter wave technologies, massive MIMO, and visible light communications.

Chapter 4 focused to satellite backhaul technologies in particular. In Section 4.1 we presented the satellite backhaul architecture when using GEO and MEO satellites, the various applications of satellite backhaul and their impact on the architecture as well as the access techniques commonly used. For the SANSA scenarios the main focus is to consider the use of Ka-band GEO satellites without any on board processing capability, which provide less complexity, cost and energy consumption compared to MEO systems. Depending on the SANSA scenario use cases we could possibly consider both the TDM/TDMA and SCPC access schemes where appropriate.

Section 4.2 discussed the MNO requirements for satellite backhaul that are dependent on the application but can be broadly categorized into network, equipment, performance and regulatory requirements. Section 4.3 includes the state of the art hardware for satellite backhaul focusing on the remote satellite router; almost all remote satellite routers receive DVB-S2 signals from the satellite gateway to the VSAT but utilize proprietary air interfaces for the RTN link. In the context of SANSA the FWD channel air interface with the satellite will use DVB-S2 based on its widespread adoption but considering its evolution, DVB-S2X which provides additional modcods, smaller roll-off factors and higher modulation schemes. For the RTN channel we will adopt DVB-RCS2 to maintain compatibility with ETSI standards. The standards that are used for satellite broadband are presented in detail in Section 4.5. From the typical performance parameters presented in Table 4-3 of Section 0 we can conclude that the throughput that can be achieved currently with State of the Art technologies is 128kbps – 360Mbps in the FWD link and 128kbps – 14Mbps in the RTN link using TDM/TDMA, while with the use of SCPC in the RTN link 360Mbps can be also reached.

Section 4.4 analyses the techniques that are implemented to optimise traffic over the satellite link. The main on is the implementation of a TCP PEP that mitigates the negative effects of TCP when used in high delay links, while HTTP PEP that optimises the use of HTTP over satellite links and IPsec processing techniques are also considered. For the operation of the satellite backhaul in the scenarios we assume that TCP and HTTP PEP are implemented in combination with a solution for IPsec, in case it is implemented by the MNO. For SANSA, it is considered of high interest the use of SIPTO as a mechanism for traffic offloading between satellite and terrestrial links at the eNodeB, but the feasibility of this operation needs to be investigated in detail in the frame of WP4.
Section 4.6 elaborates on the future satellite broadband trends that are expected to influence satellite backhaul. The first trend mentioned is the next generation HTSs that will use Q/V band or optical feeder links and more aggressive frequency reuse schemes in order to provide higher satellite capacity. The use of advanced waveforms to improve the spectral and power efficiency and ultra wide band communication with the use of the DVB-S2X super-frame are also mentioned. These next generation systems should be considered as well as part of the SANSA scenarios to ensure our solutions are future proofed.

Chapter 5 presents the current CDN architectures. In addition, two possible CDN scenarios for the SANSA integrated backhaul are discussed. In the first one satellite backhaul is used to populate the edge CDN servers, whereas in the second uses a hybrid backhauling approach to the edge CDN servers. Both of these scenarios will be further analyzed in Task 2.3 where the SANSA scenarios will be selected.
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