Integrated Backhaul Management for Ultra-Dense Network Deployment

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Abstract

Mobile data traffic is expected to increase substantially in the coming years, with data rates 1000 times higher by 2020, having media and content as the main drivers together with a plethora of new end-user services that will challenge existing networks. Concepts and visions associated with the ICT evolution like the network society, 50 billion connected devices, Industrial Internet, Tactile Internet, etc., exemplifies the range of new services that the networks will have to handle. These new services impose extreme requirement to the network like high capacity, low latency, reliability, security, seamless connectivity, etc. In order to face these challenges, the whole end-to-end network has to evolve and adapt, pushing for advances in different areas, such as transport, cloud, core, and radio access networks. This work investigates the impact of envisioned 2020 society scenarios on transport links for mobile backhaul, emphasizing the need for an integrated and flexible/adaptive network as the way to meet the 2020 networks demands.

The evolution of heterogeneous networks and ultra-dense network deployments shall also comprise the introduction of adaptive network features, such as dynamic network resource allocation, automatic integration of access nodes, etc. In order to achieve such self-management features in mobile networks, new mechanisms have to be investigated for an integrated backhaul management. First, this thesis performs a feasibility study on the mobile backhaul dimensioning for 2020 5G wireless ultra-dense networks scenarios, aiming to analyze the gap in capacity demand between 4G and 5G networks. Secondly, the concept of an integrated backhaul management is analyzed as a combination of node attachment procedures, in the context of moving networks. In addition, the dynamic network resource allocation concept, based on DWDM-centric transport architecture, was explored for 5G scenarios assuming traffic variation both in time and between different geographical areas. Finally, a short view on techno-economics and network deployments in the 2020 time frame is provided.

Keywords: Heterogeneous networks, mobile backhaul, network dimensioning, ultra-dense networks, moving networks, dynamic network resource allocation, fronthaul/backhaul architectures.
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<td>4G</td>
<td>4&lt;sup&gt;th&lt;/sup&gt; Generation mobile networks or 4&lt;sup&gt;th&lt;/sup&gt; Generation wireless systems</td>
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<tr>
<td>5G</td>
<td>5&lt;sup&gt;th&lt;/sup&gt; Generation mobile networks or 5&lt;sup&gt;th&lt;/sup&gt; Generation wireless systems</td>
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<tr>
<td>AP</td>
<td>Access Point</td>
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<td>BBU</td>
<td>Baseband Unit</td>
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<td>BSC</td>
<td>Base Station Controller</td>
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<td>CAPEX</td>
<td>Capital Expenditure</td>
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<tr>
<td>C-RAN</td>
<td>Centralized Radio Access Network or Cloud Radio Access Network</td>
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<td>CO</td>
<td>Central Office</td>
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<td>CPRI</td>
<td>Common Public Radio Interface</td>
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<td>DL</td>
<td>Down Link</td>
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<tr>
<td>DWDM</td>
<td>Dense Wavelength Division Multiplexing</td>
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<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
</tr>
<tr>
<td>EPC</td>
<td>Evolved Packet Core</td>
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<tr>
<td>E – UTRA</td>
<td>Evolved UMTS Terrestrial Radio Access</td>
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<td>GSM</td>
<td>Global System for Mobile Communications</td>
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<td>HDLC</td>
<td>High-Level Data Link Control</td>
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<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
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<tr>
<td>IP</td>
<td>Internet Protocol</td>
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<tr>
<td>IPSec</td>
<td>Internet Protocol Security</td>
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<tr>
<td>IQ</td>
<td>In-phase and Quadrature-phase</td>
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<tr>
<td>KPI</td>
<td>Key Performance Indicators</td>
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<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
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<td>LTE – A</td>
<td>Long Term Evolution – Advanced</td>
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<td>MATLAB</td>
<td>Matrix Laboratory</td>
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<td>MBH</td>
<td>Mobile Backhaul</td>
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<td>METIS</td>
<td>Mobile and wireless communication Enablers for the Twenty-twenty Information Society</td>
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<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
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<td>MPLS</td>
<td>Multiprotocol Label Switching</td>
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<td>MUX</td>
<td>Multiplexer</td>
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<td>NFV</td>
<td>Network Functions Virtualization</td>
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<td>NGMN</td>
<td>New Generation Mobile Networks</td>
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<tr>
<td>OA</td>
<td>Optical Amplifier</td>
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<tr>
<td>OADM</td>
<td>Optical Add Drop Multiplexer</td>
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<tr>
<td>OBSAI</td>
<td>Open Base Station Architecture Initiative</td>
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<tr>
<td>OPEX</td>
<td>Operational Expenditure</td>
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<tr>
<td>OTN</td>
<td>Optical Transport Network</td>
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<tr>
<td>OXC</td>
<td>Optical Cross Connect</td>
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<tr>
<td>QoE</td>
<td>Quality of Experience</td>
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<td>QoS</td>
<td>Quality of Service</td>
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<td>RAN</td>
<td>Radio Access Network</td>
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<td>RAT</td>
<td>Radio Access Technology</td>
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<td>RBS</td>
<td>Radio Base Station</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<td>RNC</td>
<td>Radio Network Controller</td>
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<tr>
<td>RRH</td>
<td>Remote Radio Head</td>
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<td>SDH</td>
<td>Synchronous Digital Hierarchy</td>
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<tr>
<td>SDN</td>
<td>Software Defined Networking</td>
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<td>SON</td>
<td>Self-Organizing Networks</td>
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<tr>
<td>SONET</td>
<td>Synchronous Optical Network</td>
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<td>UDN</td>
<td>Ultra Dense Network</td>
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<tr>
<td>UL</td>
<td>Up Link</td>
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<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication Systems</td>
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<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
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<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
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<td>WSS</td>
<td>Wavelength Selective Switch</td>
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1 Introduction

According to the current forecast studies, the rapid increase in the number of mobile broadband users will lead to a ten times more growth in mobile data traffic between 2013 and 2019 and most of this traffic will be generated from mobile smartphones rather than from PCs, tablets and routers [1]. This increase in data traffic will result in a multifold raise of the data traffic demands and services. As a result, most of the services would be clustered in a cloud. Figure 1 represents ten times increase in mobile data traffic between 2013 and 2019 as well as an estimation of increase in smart phone subscriptions from 1.9 billion (2013) up to 5.6 billion (2019)[1]. Figure 2 represents a thirteen times increase in mobile video traffic between 2013 and 2019 including both live and streaming videos and it also represents that more than 65% of the world population would be covered by LTE by 2019. To address the capacity and coverage demands, heterogeneous networks will play an important role to create an optimal end user experience. With the evolution of heterogeneous networks, balancing user expectations and network value investments, puts extensive requirements on new mobile backhaul technologies.

To support a good end user experience, three possible ways to boost the performance of an existing network are [3]:

1. **Improve existing macro cells.** In order to improve the existing macro cell layer, options like more spectrum deployment, increasing baseband processing capacities, using higher order modulation techniques and deploying multi-carrier advanced antenna solutions could be employed. This accounts to
the capacity enhancement and significant improve in data rates which eventually reduces the need for deploying new macro cells.

2. **Densify the macro network.** This approach involves planned deployment of sites and sector additions on sharing basis or on key locations, which would eventually result in improved coverage and increased capacity. However, this approach comes into play if there is no further scope of improving the macro layer.

3. **Add small cells.** This approach involves correlative deployment of micro, pico and femto cells (also known as small cells) along with the macro cells, thereby forming a layer of heterogeneous networks. By doing so, high capacities and extended coverage can be provided in order to meet end user requirements in dense traffic location and public hotspots. The biggest challenge is however, the extent of the quality of integration and coordination achieved within the heterogeneous networks to provide seamless and unambiguous QoS/QoE.

With the large scale and mass deployment of small cells, to complement improved and densified macrocell layers, highly flexible and scalable mobile backhauling solutions must be considered in order to provide superior end user experience [2]. Until now there have been several investigations on improving the radio access network for meeting high traffic demands from the end user perspective, assuming an ideal backhaul. However, this report focusses on investigating the backhaul issues assuming that the radio access network is ideal. This thesis work also assumes the current challenges related to heterogeneous network architectures, in the context of 2020 fifth generation mobile networks (5G).

1.1 **Background**

With extensive demands from the end-user perspective in 2020 5G networks, the radio access technologies (RAT) have to be evolved from the current Long Term Evolution (LTE) standards to a new 5G RAT, having much higher bandwidths and improved spectral efficiency. However, in parallel, it is also important to address the backhaul challenges which the transport network would face in transporting these bits in the backhaul network all the way to the core. The mobile backhaul as, explained in chapter 2, is basically the network links which connect the radio base station (RBS) sites to the transport network. With increased densification as explained above and introduction of small cells for offloading the capacity requirements of existing macro cells, leads to the existence of ultra-dense networks (UDNs), with very low inter site distances as compared with today. Moreover, each of the above mentioned approaches depend on specific requirements like backhaul availabilities, capacity requirements, spectrum access options and techno-economic aspects; therefore it is important to take into consideration these factors while employing any of the above mentioned approaches.

In order to calculate the backhaul link capacities, mobile backhaul dimensioning techniques are employed as will be discussed later in this report. However, these techniques are used for today’s LTE networks and hence it becomes important to evaluate these techniques for 2020 5G UDN networks and investigate the gap. With 2020 5G networks having extensive demands like higher throughputs, very low delay and latency requirements, seamless connectivity etc. it is necessary to address the challenge faced by the backhaul networks in order to meet the end user QoS/QoE requirements. In addition, the evolution of heterogeneous networks acts as a firm driver towards auto-integration of access nodes and mobile terminals into the existing network infrastructure while introducing dynamicity in the resource allocation.
for these nodes and terminals to actually get access to the network infrastructure [9]. Hence efficient self-
management in mobile networks could be achieved by designing new flexible backhaul solutions and
mechanisms for an integrated backhaul management.

The evolution of mobile network architectures could motivate the need for new transport network
fronthaul/backhaul architectures for the 2020 5G UDN deployments due to a huge difference in the
amount of traffic in the transport network. Hence, investigations of new transport network architectural
features, becomes a key while designing the 5G networks. In addition, due to a significant increase in data
demands, the mobile operators are motivated to migrate towards cost effective packet based backhaul
technologies rather than the traditional circuit switched ones [4] [5]. Therefore, from the operator’s point
of view, it becomes necessarily important to understand the techno-economic impact on new UDN
deployments and which technologies would be suitable for the same.

1.2 Related Work

In the context of mobile backhauling, some work has been done and ongoing. For instance, there has been
a discussion on the concept of millimeter wave radio access technology for meeting the higher capacity
demands in the backhaul and fronthaul links for 5G networks [36]. This study also includes a discussion
on the need for such technologies to support the centralized radio access networks along with dynamic
resource management. In addition, the need for flexible backhaul solutions, transport network
architectures and advanced data traffic management in the context of substantially heterogeneous 5G
networks is discussed in the 5G radio network architecture white paper [37]. There have also been some
discussions about proposing dense wavelength division multiplexing (DWDM) centric transport networks
so as to meet higher capacity demands and at the same time in a cost and energy efficient way. In addition
to this concept, to gain more control and introduce dynamicity in DWDM centric transport network, the
use of software defined networking have been proposed [30]. Finally, investigations are ongoing to
provide input to the Mobile and wireless communication Enablers for the Twenty-twenty Information
Society (METIS) test cases in term of backhaul options and transport network architectures.

1.3 Problem Definition

As the data rate requirements for the 2020 5G networks are about 1000 times the current user demands,
this thesis deals with finding out the backhaul requirements of 2020 5G deployment scenarios using, e.g.,
5G METIS test cases as reference [8]. First, the main approach is to derive the last mile fixed link (fixed
backhaul) requirements for different 5G test cases, in particular to investigate the impact of the future 5G
UDN networks to the access/aggregation transport networks.

With the evolution of heterogeneous networks and UDN deployments, there is a need for the introduction
of new adaptive network features. This thesis aims to identify specific 5G 2020 deployments cases
motivating the advantages of an integrated backhaul management, a fundamental enabler for adaptive
networks deployments. Therefore, this thesis investigates the gains of applying dynamic network resource
allocation (DWDM-centric transport architecture) techniques to avoid overprovisioning during network
deployment planning. Also, automatic integration of access nodes is investigated in the context of moving
networks. In addition, this thesis also addresses some techno-economic aspects related to new and
existing fronthaul/backhaul architectures and deployment strategies.
**GAP:** Although backhaul dimensioning techniques and network management models exist for LTE mobile wireless system [7], new aspects of the 2020 5G ultra-dense network deployment scenarios are yet to be considered in order to build future backhaul networks. This is because, demands on expected 5G networks are to be higher (e.g. up to 1000 times higher data rates) and new algorithms would be required to introduce self-management characteristics in these networks, in order to avoid, e.g., more expensive and overprovisioned access/aggregation networks.

This project work foresees to answer;

1. What is the impact of 5G 2020 network deployment in the access backhaul links, assuming in particular the capacity requirements introduced by UDN and corresponding 1000x more traffic values?
2. In 2020, will traffic increase and RAN scenarios be so different that new techniques for access network planning will be needed?
3. In terms of capacity requirements, will 2020 UDN deployments demand flexible and adaptive networks? What can be the foreseen gains?
4. What is the impact of the introduction of moving networks in the fixed access backhaul links? Is there motivation to introduce automatic node integration and self-managing backhaul networks schemes? (Instead of approaching the problem as pure radio access matter)
5. Assuming the increase in traffic in the access networks by 2020, what are the foreseen pros/cons of packet and optical based backhaul?

**1.4 Goals**

The goals of this thesis project could be summarized as follows.

1. To perform mobile backhaul dimensioning and calculate the backhaul link capacities for 2020 5G UDNs.
2. To analyze the gap between the backhaul link capacities for today’s networks and for 2020 5G UDNs.
3. To analyze the gap between the mobile backhaul dimensioning methodologies for today’s networks and what could be for 2020 5G UDNs
4. To investigate a nomadic node attachment algorithm in the context of moving networks.
5. To analyze the gap between the architectural impact on the cost and efficient network resources usage both for today’s networks and 2020 5G UDNs.
6. To investigate advantages of the use of dynamic spectrum allocation techniques to handle traffic variations both in time and between geographical areas.
7. To highlight techno – economic aspects of deploying 2020 5G UDNs systems.

**1.5 Methodology**

The project will employ quantitative research methodology [6] as the backhaul dimensioning and analysis of integrated backhaul management features mainly include large numerical data like number of end users, percentage availabilities, capacity requirements, mobile data volumes etc. Furthermore, as the numerical analysis would consist of assumptions and results from calculations on MATLAB, the quantitative research methodology is the most appropriate for this project. In addition, since the backhaul
mobile dimensions would be calculated with different radio specifications for different use cases, the experimental research method [6] would be the best possible approach for this quantitative analysis, since the mobile backhaul dimensioning methodology deals with different parameters with different dependencies. Furthermore, since large quantitative data volume are used in different stages of this project in order to test the feasibility of network architectures and backhaul dimensions, deductive approach was considered to deduce conclusions based on assumptions and known theories [6]. Data collection is done via experiments and reasonable assumptions whereas data analysis is done through computational mathematics method as simulations and functions with mathematical formulations along with algorithms are analyzed in this project [6]. Finally, the outcome of this thesis could be repeated and validated by the replicability approach if the same assumptions, methodologies and use cases are taken into consideration.

1.6 Thesis Outline

Chapter 2 illustrates the literature background study which was carried out prior to the actual thesis implementation work. It explains key concepts regarding the fronthaul/backhaul architectures, architecture trends, DWDM centric transport networks, self-organizing networks and enabling technologies like SDN and NFV.

Chapter 3 explains the mobile backhaul dimensioning methodology used to dimension today’s LTE networks. It also illustrates the exercises carried out to calculate the mobile backhaul dimensions using todays methodologies for 2020 5G UDN use cases with current RAT. In addition, it also illustrates mobile backhaul dimensioning using reasonably assumed 5G RAT.

Chapter 4 illustrates the gap analysis carried out while comparing the mobile backhaul capacity requirements for today’s network and 2020 5G UDNs and explains the impact of increased capacity demands on the existing mobile backhaul links.

Chapter 5 deals with investigation of the nomadic node attachment procedure in the context of moving networks along with dynamic resource allocation using different 5G UDN use cases. It also investigates the centralized architecture for networks with today’s RAT and with 5G RAT for a 2020 5G UDN use case.

Chapter 6 illustrates brief techno-economic views on fronthaul/backhaul architectures which are explained from the deployment perspective.

Chapter 7 presents the conclusions, answers to the research questions and explains the scope for future work.
2 Network Architecture Trends and Enabling Technologies

Increase in traffic demands in the access also impacts the transport network with a proportional increase. With new evolving technologies, network architectures have also been evolved in parallel so as to meet the new extensive service demands and meet ender user expectations. In addition, these evolving new architecture solutions also create new business opportunities for the operators by reducing their total cost of ownership (TCO). In addition, evolving optical packet aggregation is seen as a cost efficient network architecture solution when data rates are too high. This is why DWDM centric transport networks are gaining much importance to transport high data volumes. This chapter briefly highlights some architecture solutions being evolved and which are relevant in the context of this report. Furthermore, there have been advancements in a way of handling the network architecture features like SDN and NFV which are also discussed briefly in this chapter.

2.1 Fronthaul/backhaul technology evolution

The mobile backhaul is a commonly used term which corresponds to the network links between the radio base station sites, in the radio access network, and the switch sites at the edge of a transport network [10]. As illustrated in Figure 3, the network links refer to copper wires, optical fiber links or microwave links. In general, optical fiber links are deployed in dense urban areas where the traffic requirements are very high whereas as wireless microwave radio links are deployed where wired solutions are not feasible.

Figure 3: Different Backhaul Network Technologies
Recently a swift transition has been made from traditional low capacity circuit switched connection oriented architectures to higher capacity packet oriented architectures based on IP/MPLS based core networks like the Carrier Ethernet [11]. The transition is however due to the higher data requirements and to achieve seamless connectivity with thousands of small cells. One of the major drivers of this migration is supposed to be the evolution of multi standard radios which are capable of providing all three radio access technologies like GSM, WCDMA and LTE [12]. However, in order to meet the traffic demands in 2020 5G scenarios, these packet based technologies have to be designed in advanced architectures like the C-RAN so as to provide the preferred QoS to the end users in a more cost efficient manner.

The mobile fronthaul corresponds to the transmission link required to connect digital base band unit (BBU) and the remote radio head (RRH) [15][19]. The need of the fronthaul networks arise when BBU has to be moved from the cell sites into a remote central office (CO). Therefore, as illustrated in Figure 4, the transmission connection between the BBU and RRH could be either done by using the common public radio interface (CPRI) protocol standard [13] or by the open base station architecture initiative (OBSAI) standard [14], dedicating one fiber per RRH. Analog RF signals received by the antennas are first demodulated and then sampled in the time domain for the upstream case and vice versa for the downstream [15].

![Figure 4: Mobile Fronthaul Architecture](image)

2.1.1 Centralized Radio Access Networks (C-RAN)

C-RAN, also known as Centralized RAN or Cloud RAN was an initiative taken by the China Mobile. The C-RAN architecture was introduced in order to fulfill the high user expectations in the future mobile network infrastructures. As can be seen in Figure 5, the C-RAN architecture comprises of three building blocks, namely the RRH, antenna system and transmission links connecting to the BBU cloud [16] [34].

Traditionally, the mobile network infrastructure was based on an all in one base station architecture, in which all telecom equipment like the base station unit, radio unit, digital unit, power unit, alarm unit and
battery backup were installed and placed in one shelter on a particular site. This site also had a tower holding the antennas and e.g. microwave links for backhaul purposes. However, with the evolution of WCDMA, this architecture was modified where the radio part was separated from the BBU and is called as RRH. The RRH is mounted on the top of the towers hence separating the radio unit from the BBU which allows faster BBU processing and significantly reduces the RF signal path loss from the BBU to RRH.

The evolution of C-RAN is in accordance to the WCDMA architecture, where the BBU unit is separated far away from the RRH. The use of fiber optic cables makes the transmission and operation much faster and spans few kilometers. Apart from these, there are other advantages of the C-RAN architectures which include lower CAPEX due to reduced macro footprint (rent for RBS sites) enhanced energy efficiency, improved capacity, adaptability to non-uniform traffic variations and smart internet traffic offloading functionalities [17].

### 2.1.2 BBU Hostelling

BBU hostelling or BBU centralization refers to the concept of piling up the BBUs belonging to various RRHs into one pool or central office [18]. By doing so, the BBU shall no longer be collocated at the cell sites along with the RRH. The main difference between the C-RAN and BBU hostelling concepts lies in the fact that the baseband processing functionality can be virtualized in C-RAN. However, in BBU hostelling, the BBUS in the BBU pool as shown in can only be centralized but still a one to one mapping
Integrated Backhaul Management for UDN deployments

(One BBU for one RRH) exists in the BBU pool. According to the topology in Figure 5, a single BBU unit can support multiple cell sites. Hence, it is clear that the concept of BBU Hostelling is a part of the C-RAN architecture as mentioned earlier. As mentioned earlier the RRH in C-RAN architecture, use the CPRI protocol over optical fiber links (DWDM) and hence the digital RF over fiber transmission takes place to reach the remotely located BBU, which results in a high speed fronthaul and enables to span much larger transmission distances and results in a much more centralized base station architecture.

With BBU Hostelling there are many advantages like centralized and efficient management from CO, like reduced CAPEX as the cost of installation is effectively reduced when compared to installing each BBU for every cell site separately and finally reduced OPEX as the entire network can be monitored from a single CO than from each and every cell site. In addition, another important advantage with this architecture is the reduced latency for high data centric services as the BBU is now located in the CO because of which the number of interfaces and the length of the interfaces connecting the BBU-CO and the core network are drastically reduced. In short, this fronthaul architecture incorporates almost all the added advantages of a typical C-RAN architecture as discussed previously.

**Common Public Radio Interface (CPRI):** It is defined as a standard interface which is used to connect the RRHs to the base band units located in a remote position. The CPRI protocol is illustrated in Figure 6.

The IQ data represents the sampled in-phase and quadrature-phase user plane modulation data, where the required bitrate for IQ data per cell site is determined by:

- Number of sectors
- Number of antennas per sector (MIMO)
- Number of carriers per antenna
- Sample rate
- Number of bits per sample

![CPRI Protocol overview](image)

*Figure 6: CPRI Protocol overview [13]*
In general most of the macro cells have three sectors per site and the small cells have once sector per site. In addition, E-UTRA (LTE) can support 30.72 MHz sample rate for 20 MHz channel bandwidth [13]. Finally with 16 bits per sample for each of I and Q, bit rate per antenna for single 20 MHz carrier = 30.72 * 16 * 2 = 983.04 Mbps (for IQ data only). In this report the CPRI link capacity dimensioning would assume only the IQ data [19]. Further explanation of the CPRI protocol is beyond the scope of this report, but more information could be found at CPRI Specification V6.0 [13].

2.2 **DWDM Centric Transport**

Dense wavelength division multiplexing (DWDM) based optical transport network has evolved due to recent advancements in the optical transport networks (OTN) and wavelength division multiplexing (WDM) technologies [21]. The two layer architecture model of IP over WDM in the core networks have proven to be the most coefficient model as compared to the other models which include four as well as three layers as shown in Figure 7. Due to the expected data tsunami and demand for new services, core networks that can offer very high capacities and guaranteed QoS have to be built. Recent advancements in DWDM centric transport technologies are seen to fulfill the same.

![Evolution towards Two Layer Network Architecture](image)

**Figure 7: IP over DWDM evolution**

DWDM corresponds to the underlying carrier for the OTN. The optical signals from different wavelengths are first multiplexed at the transmitter end, then amplified using EDFA and then finally de-multiplexed at the receiver end [20]. The basic block diagram of the DWDM concept is shown in Figure 8. The DWDM system consists of various building blocks which include OA, OXCs, OADM and wavelength converters.

**Wavelength assignment procedure in DWDM Networks:**

A lightpath is an optical connection which corresponds to an optical channel trail between any two nodes that carries the entire traffic within a wavelength [25]. Once a path has been chosen for each connection, wavelengths have to be assigned to each to each lightpath where any two lightpaths that pass through the same physical link are assigned different wavelengths. Moreover, if intermediate switches do not have wavelength conversion, lightpath has to operate on the same wavelength throughout its path. There are three wavelength assignment procedures used in DWDM networks in order to assign the wavelengths (resources) for a connection request from point one node to another.
Figure 8: Basic DWDM network architecture [20]

First and the most simple of the three is the fixed shortest path wavelength assignment procedure [26] in which the traffic from start node to end node always takes a fixed shortest path. The shortest paths between the start node and the end node could be calculated using the Dijkstra's algorithm using the path costs between different nodes present in the network [22]. In the fixed shortest path wavelength assignment procedure, shortest paths are calculated in advance for each source-destination node pair and any connection between a specified node pair is established using a pre-determined route using shortest path algorithms like Dijkstra's algorithm. The advantage of using this procedure is that the network administrator does not require to process any network updates as the routes are pre-determined. However, as illustrated in Figure 9, the disadvantage is that this procedure has the worst blocking performance (number of blocked requests vs. total connection requests) among the three as the connection gets blocked if the wavelengths along the fixed path are busy.

The second wavelength assignment procedure is the fixed alternate routing [26] in which each node maintains a routing table that contains a list of fixed routes to each destination. K-shortest path algorithm is used to calculate the different shortest paths between the source and destination nodes [23]. The fixed routes include the shortest path, second shortest path, third shortest path and so on. Whenever a connection request arrives, the source node attempts to establish a connection according on the shortest path. However, if no wavelength resource is available on the shortest path, then the second shortest path is chosen and so on. Finally, a connection request gets blocked if no wavelength resources are available on any of the shortest paths. The blocking performance of this procedure is better than the fixed shortest path wavelength assignment procedure.

The third wavelength assignment procedure is the adaptive routing in which the routes between any two nodes are calculated dynamically [26]. In doing so, the ongoing connection requests are taken into consideration. Each time a connection request arrives, the routes have to be determined according to the free wavelength resources on the physical optical links. The disadvantage of this procedure is that the whole network state must be available to the network administrator at all times which results in high signaling costs. However as illustrated in Figure 9, the advantage of this procedure is that it has the best blocking performance among all the three wavelength assignment procedures.
Figure 9: Average Number of Blocked requests vs. Connection requests for 8 resources, 50 experiments and 50 connection requests per experiment

From Figure 9 it is evident that the average number of blocked requests in case of adaptive shortest path routing are less than fixed shortest routing because in adaptive shortest path routing, an alternate path (if available) is chosen whenever a link is out of resources and that alternate path would be the shortest amongst other available alternate paths [26]. But in case of fixed shortest path routing, as the path is fixed between the source and the destination, if any of the link traversing that path is out of resources, the lightpath from the source to destination will no longer exist. Moreover as the number of connection requests keep increasing with fixed number of resources, the number of average blocked requests tend to one as both the provisioning scenarios are unable to serve all the requests due to unavailability of free links between the source and destination.

As we increase the number of resources, the blocking probability and hence the average number of blocked requests for adaptive shortest path routing is less than with less number of resources as there are more resources now, so the possibility of alternate paths in adaptive shortest path routing increases. In case of fixed shortest path routing the performance in terms of blocked connection requests is a little better than one with less number of resources as now the probability of finding an unblocked fixed path increases with the increase in the number of resources, but not better than adaptive shortest path routing.

2.3 Software defined networking (SDN)

The main idea behind Software Defined Networking (SDN) is pulling out all the networking intelligence away from the hardware such as the routers and the switches. In this way, the hardware devices could function mainly on the data plane whereas the control plane is operated by a remote management system, thereby making the networking much more intelligent with added quality of service. Therefore, by pooling the networking intelligence or the control planes of all the hardware devices into one management system allows handling of network management features in a more efficient manner. With SDN, there is scope for dynamically shaping and modelling of data traffic depending on the service requirements. The basic concept of SDN architecture is illustrated in Figure 10, according to which, the
SDN controllers centralize entire networking intelligence logically which allows the SDN controllers to maintain a global view of the whole network [24].

The networking function can be separated into the control plane and the data plane as shown in Figure 11. The data plane consists of the networking hardware like the switches and the routers that allow transfer of data packets from one point to another. The control plane is however a set of management servers that communicate with all of the different networking equipment on the data plane and decides how data should move in the data plane thereby prioritizing one set of data traffic from another. Hence, the different networking infrastructure can be separated to be dealt separately.

![Figure 10: SDN Architecture (Image courtesy – Open networking foundation) [24]](image)

![Figure 11: Control Plane VS. Data Plane](image)
As illustrated in Figure 12, the services plane consists of the networking services (e.g. firewall) which can be separated from the physical equipment present in the data plane and can be placed in high volume servers so as to deal with them more efficiently. The control plane consists of the control function that manages the services and data. Finally, the management plane makes sure that all the control functions in the control plane function as they are supposed to according to the required QoS. Finally, by doing such a separation of the networking features which allows networking hardware, which at present contains all the networking intelligence and programming, from not to process complex networking protocols. Therefore, the whole network features can now be managed efficiently.

![Figure 12: Separation of services from Networking Equipment](image)

### 2.4 Network Functions Virtualization (NFV)

Network Functions Virtualization (NFV) is highly complementary to SDN [25]. SDN and NFV are mutually beneficial implementations but however, independent of each other and can be implemented separately without using each other [25]. Therefore, network functions can be virtualized and deployed without SDN and vice versa. NFV has been introduced to address the issues faced by the mobile operators while deploying their network infrastructure. Network infrastructure deployment includes installation of a large number of hardware appliances like firewalls, routers, switches, servers, load balances, media servers, etc. However, from the telecom operators’ point of view, this appears to be rather inflexible with higher CAPEX and OPEX, high power requirements, scarce availability of installation space and difficult configuration and maintenance of an overall complex environment [25]. Hence, NFV is a newly emerged concept according to which the service providers could convert their hardware appliances into virtual machines or stacks of high capacity servers which can store and access data large traffic volumes. The network services can thus be placed in data centers along with other network nodes. Moreover, the more important functions that should be virtualized require cooperation from the data plane with SDN with a control function like Openflow. This allows the high capacity serves also to monitor and control the traffic according to the service requirements.
2.5 Self-O rganizing Networks

Self-organizing networks (SONs) in general are defined as the networks which have the capability to dynamically adapt changes in the networks in order to optimize their performance with the help of automated features. These features include dynamic topology management, resource management etc., in order to achieve a faster and efficient handling and maintenance of complex networks. The need for SONs arise from the fact that in the course of new technologies like LTE, 5G etc., the number of nodes in increasing at a rapid rate migrating towards ultra-dense networks. Moreover, it’s also because of the introduction of a high degree of heterogeneity and complexity, that such networks could save a lot of OPEX in addition to optimizing the performance. SONs for LTE have been recognized by NGMN and some of the test cases have been discussed in various 3GPPP releases for LTE and LTE-Advanced (LTE-A) [27].
3 Mobile backhaul dimensioning

This chapter explains the mobile backhaul dimensioning methodology. In order to achieve the expected QoS for the end users, mobile backhaul dimensioning plays an important role in the transport network. The primary output from transport dimensioning is the bandwidth required for the transmission link closest to the RBS, referred to as the last mile. The last mile refers to the transmission link connecting the cell site with the next aggregation level in the network. The mobile backhaul dimensioning methodology and key concepts have been strictly referred only from Ericsson sources.

Before moving on, there are various key concepts which should be understood before performing the mobile backhaul dimensioning which include:

- **Cell peak rate**, the maximum data throughput achieved in one cell of an RBS under ideal radio conditions
- **Cell throughput in a loaded network**, the maximum throughput per cell when all cells are at their dimensioned load, both interfering cells as well as the cell affected by interference
- **Average cell throughput during busy hour**, the average throughput per cell in the network during busy hour
- **Busy hour displacement**, is represented by the percentage of RBSs not having a busy hour during the network busy hour
- **Mobile backhaul**, the mobile backhaul connects the RAN with the core network
- **Last mile**, the last mile refers to the transmission link connecting the cell site with the next aggregation level in the network
- **Transport overhead**, is contributed by the encapsulation data from the protocols. Calculations hereafter assume that IPSec is used.

Mobile backhaul dimensioning could be performed using one of the following methods:

- **Overbooking** allows more users than the dimensioned quantity, assuming the entire bandwidth is available only to a subset of users at a time.
- **Overdimensioning** method is implemented by multiplying the average required dimensioned capacity by a factor known as overdimensioning factor.
- **Peak allocation**, is used when the backhaul links have to be dimensioned for the maximum possible bit rate. Hence, the upper bound of the capacity throughput requirement is used in this method.
- **Overprovisioning** method allows for link monitoring in terms of capacity usage. The limit is generally set to 50% of the peak and when the limit exceeds this threshold, the link capacities are upgraded.
The method is generally chosen taking into account the business considerations. However, overbooking method will be used for all backhaul dimensioning activities in this report because of the considerations of ultra-dense network scenarios and high peak rates. Also, this method uses the full available bandwidth in the mobile backhaul, by allowing usage to exceed the allocated bandwidth assuming that only a subset of users is active simultaneously.

Mobile backhaul dimensioning – overbooking methodology

This section explains the mobile backhaul dimensioning methodology used today to calculate the link capacities at various aggregation levels starting from the RBS all the way to EPC.

Figure 13: Mobile backhaul dimensioning methodology

Figure 13 shows a basic network deployment setup of a predefined size where the link capacity requirements are calculated on each aggregation level. Each aggregation level corresponds to traffic aggregation from a geographical point of view. For example, aggregation node A1 aggregates traffic in a local area, A2 aggregates traffic in a wide area for example a city as a whole, A3 aggregates level globally for example a country as a whole and then passes on the traffic to the evolved packet core or EPC to route the traffic globally in IP cloud.

RBS – A1 level: The bandwidth required for the last mile to the RBS is calculated by multiplying the cell peak rate by the transport overhead. Cell peak rates are used in this calculation assuming that only one cell will provide peak rates at a time instead of all the three cells.

A1 level – A2 level: The capacity calculations are done by multiplying the cell throughput in a loaded network multiplied for the number of cells which also refers to the RBS throughout in a loaded network.
A2 level – A3 level: This link capacity is calculated using the average RBS throughput during the busy hour which is considered to be 50% of the load compared to the cell throughput in a loaded network according to simulations.

A3 level – EPC: As most of the RBSs are not fully loaded at all times, a displacement factor of 0.8 is multiplied with the sum of the link capacities aggregated at A3 level to calculate the link capacity.

In the following subsections, mobile backhaul dimensioning exercise is performed in order to investigate the last mile and backhaul requirements using current LTE RAT for today’s deployment scenarios with those of UDN 5G deployment scenarios of 2020 (METIS). Moreover, a quantitative analysis is also performed for the mobile backhaul dimensioning capacity outcomes using 5G radio access technology (RAT).

### 3.1 Mobile backhaul dimensioning – LTE – Today

This section explains on how the mobile backhaul dimensioning is performed today with LTE technology. Following are the assumptions that were made to perform the backhaul dimensioning for a network as shown in Figure 13:

- 3 aggregation levels A1, A2 and A3
- A1 is the first aggregation level grouping 10 LTE RBSs per A1 node
- Two A2 nodes aggregate traffic from 10 A1 nodes each
- A3 is located at the EPC site and aggregates the traffic of two A2 nodes and implicitly all 200 RBSs
- 50% of the RBSs are configured with 3 × 10 MHz cells and 50% are configured with 3 × 20 MHz cells
- The 10 and 20 MHz RBSs are randomly distributed
- A factor of 1.27 is used for transport overhead (including IPsec).
- Peak allocation is used for the last mile to ensure that a user can achieve the maximum possible throughput
- A reference network of a predefined size is used where aggregation gain is assumed
- All the radio specifications are based on simulations and provided by Ericsson resources
- Cell throughput during busy hour: 50% of the value obtained for Cell throughput in a loaded network.
- The bandwidth required for the uplink is assumed to be 50% of the downlink capacity.
- Overbooking Method used.
Table 1 shows the radio considerations taken into account as an input to perform the mobile backhaul dimensioning. In addition to these specifications, a busy hour displacement factor of 0.8 (β) is assumed for all RBSs while dimensioning the link after the A3 level.

<table>
<thead>
<tr>
<th>Radio specifications</th>
<th>LTE – 20 MHz Cells</th>
<th>LTE – 10 MHz Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration</td>
<td>3x1</td>
<td>3x1</td>
</tr>
<tr>
<td>Cell Peak Rate (λ_p)</td>
<td>150 Mbps</td>
<td>75 Mbps</td>
</tr>
<tr>
<td>RBS throughput in a loaded (λ_l) network</td>
<td>100 Mbps</td>
<td>50 Mbps</td>
</tr>
<tr>
<td>Average RBS throughput during busy hour (λ_{bh})</td>
<td>50 Mbps</td>
<td>25 Mbps</td>
</tr>
<tr>
<td>Average cell throughput during busy hour</td>
<td>25 Mbps</td>
<td>25 Mbps</td>
</tr>
<tr>
<td>Cell peak throughput in a loaded network</td>
<td>35 Mbps</td>
<td>17 Mbps</td>
</tr>
<tr>
<td>Transport overhead (Including IPSec) expansion factor used for the last mile (α)</td>
<td>1.27</td>
<td>1.27</td>
</tr>
</tbody>
</table>

Table 1: Radio specifications - LTE

3.1.1 Mobile backhaul dimensioning calculations and output– LTE – Today

If the Number of RBSs per A1 node = N_r, Number of A1 levels per A2 level = N_{a1}, ΣA2 represents the sum of link capacities aggregated at A2 level and β represents the busy hour displacement factor, then Table 2 shows the calculations to find out the link capacities.

<table>
<thead>
<tr>
<th>Aggregation Level</th>
<th>Formula</th>
<th>Link Capacity (20 MHz Cells)</th>
<th>Link Capacity (10 MHz Cells)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBS (Last Mile)</td>
<td>λ_p * α</td>
<td>190 Mbps</td>
<td>95 Mbps</td>
</tr>
<tr>
<td>A1 – A2</td>
<td>λ_l * α * N_r</td>
<td>1.3 Gbps</td>
<td>0.7 Gbps</td>
</tr>
<tr>
<td>A2 – A3</td>
<td>λ_{bh} * α * N_r * N_{a1}</td>
<td>6.4 Gbps</td>
<td>3.2 Gbps</td>
</tr>
<tr>
<td>A3 – EPC</td>
<td>ΣA2 * β</td>
<td>7.7 Gbps</td>
<td>7.7 Gbps</td>
</tr>
</tbody>
</table>

Table 2: Backhaul dimensioning calculations – LTE today

Figure 14 shows the link capacities at different aggregation levels starting the RBS until the EPC. It is therefore clear that the upper-bound of the last mile is roughly around 200 Mbps and the lower-bound is around 100 Mbps for today’s deployments of a similar setup as assumed to perform the mobile backhaul dimensioning.

Moreover, the above calculations hold true only if aggregation gain is assumed for all the RBSs at all aggregation levels. If the aggregation gain is not considered then RBS throughput in a loaded network is to be used in order to calculate the link capacity A2 – A3 and the displacement factor is to be omitted while calculating the link capacity A3 – EPC.
3.2 Mobile backhaul dimensioning – 5G RAT – 2020

In this section, mobile backhaul dimensioning is performed with a similar deployment scenario of the same size as in Figure 13 and having the same assumptions as explained in section 3.1, but instead of the LTE RAT, 5G RAT specifications are used to calculate the different link capacities.

Table 3 illustrates the 5G RAT specifications used to perform the mobile backhaul dimensioning. The cell peak rate has been taken from the NTT DOCOMO trial with Ericsson [29]. RBS throughput in a loaded network has been assumed to be 1 Gbps being fair to the METIS test case TC1 – virtual reality office where it is assumed that 1 Gbps should be the minimum downlink throughput requirement (in 95% office area) during the peak working hours. The RBS average throughput during busy hour is assumed to be 50% that of the RBS throughput in a loaded network as mentioned in section 3.

<table>
<thead>
<tr>
<th>Radio Parameters</th>
<th>5G – 15 GHz frequency band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration</td>
<td>3x1</td>
</tr>
<tr>
<td>Cell peak rate</td>
<td>10 Gbps</td>
</tr>
<tr>
<td>RBS throughput in a loaded network</td>
<td>1 Gbps</td>
</tr>
<tr>
<td>RBS average throughput during busy hour</td>
<td>0.5 Gbps</td>
</tr>
<tr>
<td>Transport overhead (including IPSec)</td>
<td>1.27</td>
</tr>
</tbody>
</table>

Table 3: Radio specifications 5G RAT

3.2.1 Mobile backhaul dimensioning calculation and output – 5G RAT

If the Number of RBSs per A1 node = N₁, Number of A1 levels per A2 level = N₂, and ∑A2 represents the sum of link capacities aggregated at A2 level and β represents the busy hour displacement factor then Table 4 shows the calculations to find out the link capacities.
### Aggregation Level | Formula | Link Capacity
--- | --- | ---
RBS (Last Mile) | $\lambda_p \alpha$ | 12.7 Gbps
A1 – A2 | $\lambda_i \alpha N_t$ | 12.7 Gbps
A2 – A3 | $\lambda_{bs} \alpha N_t N_{a1}$ | 63.5 Gbps
A3 – EPC | $\sum A2 \beta$ | 102.4 Gbps

Table 4: Mobile backhaul dimensioning calculations - 5G RAT

Figure 15 shows the link capacities at different aggregation levels starting the RBS until the EPC. It is therefore clear that the last mile requirement is roughly 12.7 Gbps for today’s deployments of a similar setup as assumed using 5G RAT to perform the mobile backhaul dimensioning.

Moreover, the above calculations hold true only if aggregation gain is assumed for all the RBSs at all aggregation levels. If the aggregation gain is not considered then RBS throughput in a loaded network is to be used in order to calculate the link capacity A2 – A3 and the displacement factor is to be omitted while calculating the link capacity A3 – EPC.

#### 3.2.2 Mobile backhaul dimensioning calculation and output – 5G RAT – with small cells

Assuming that 10 small cells aggregate traffic onto each of the macro RBSs and thus introducing an extra aggregation level A0, the dimensions of the different links at different levels are calculated as shown in Table 5. The small cells are assumed to have the same 5G RAT as that of the macro RBSs. If the Small cell peak rate = $\lambda_{ps}$; Small cell RBS throughput in a loaded network = $\lambda_{ps}$; Number of small cells per macro= $N_s$; Number of macro RBSs per A1 node = $N_t$; Number of A1 nodes per A2 node = $N_{a1}$ and Number of A2 node per A3 node = $N_{a2}$, then the link capacities at various aggregation levels could be calculated as shown in Table 5.

<table>
<thead>
<tr>
<th>Aggregation Level</th>
<th>Formula</th>
<th>Link Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small cells</td>
<td>$\lambda_{ps} \alpha$</td>
<td>12.7 Gbps</td>
</tr>
<tr>
<td>A0 – RBS (Macro)</td>
<td>$\lambda_{ps} \alpha N_s$</td>
<td>127 Gbps</td>
</tr>
</tbody>
</table>
3.3 Mobile backhaul dimensioning – LTE – METIS TC2

This section describes the mobile backhaul dimensioning using today’s LTE-A RBSs to be able to meet the METIS TC2 – Dense urban information society as illustrated in Figure 37 in Appendix I. The dense-urban information society corresponds to a combined indoor and outdoor ultra-dense network deployment scenario which is mainly concerned with providing connectivity to all the users at any place and any time in a dense urban environment [8]. The environmental and traffic models used to create the framework have been referred from the METIS D6.1 document [28] also summarized in Appendix I and Appendix II.

Table 6 illustrates the radio specifications calculated for LTE-A cells using the deployment parameters as mentioned in Table 16 in Appendix II. The radio specification in Table 6 are calculated using the concept of career aggregation for LTE-A. The reference numbers for these radio specifications are taken from

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**Table 5: Mobile backhaul dimensioning calculations - 5G RAT with small cells**

| RBS (Macro) – A1 | \((\lambda_p + \lambda_s * N_s) * \alpha\) \((\lambda_p + \lambda_m * N_m) * \alpha\) | 25.4 Gbps | 139.7 Gbps |
| A1 – A2 | \((\lambda_1 * N_i + \lambda_{bh} * N_r * N_s) * \alpha\) | 139.7 Gbps |
| A2 – A3 | \((\lambda_{bh} * N_r + \lambda_s * N_s * N_r) * \alpha\) | 1.3 Tbps |
| A3 – EPC | \(\lambda_{bh} * N_r * N_{s1} * N_{s2} * \alpha * \beta + \lambda_{bh} * N_s * N_r * N_{a1} * N_{s2}^* \alpha\) | 2.5 Tbps |

---

Figure 16 shows the backhaul dimensioning output with link capacities on each link. In Figure 16, it can be seen that the addition of small cells add an extra load on the overall backhaul capacity for the macro RBS. In addition, as mentioned in earlier cases as well, the link capacity calculation can be done either by using the cell peak rate or RBS throughput in a loaded network for the small cells results in in two values as shown in Table 5 (marked in red and black respectively). In addition, the aggregation gains are again not considered for small cells.
Table 1 for 20 MHz cells and thus multiplied by 1 for Indoor small cells and macro cell and by 4 for outdoor small cells only for the downlink.

<table>
<thead>
<tr>
<th>Radio Parameters</th>
<th>Indoor Small (Femto) Cells</th>
<th>Outdoor Small (Micro) Cells</th>
<th>Macro Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>20 + 20 MHz (UL+DL)</td>
<td>80 + 80 MHz (UL+DL)</td>
<td>20 + 20 MHz (UL+DL)</td>
</tr>
<tr>
<td>Cell peak rate (DL)</td>
<td>150 Mbps</td>
<td>600 Mbps</td>
<td>150 Mbps</td>
</tr>
<tr>
<td>RBS throughput in a loaded network (DL)</td>
<td>100 Mbps</td>
<td>400 Mbps</td>
<td>100 Mbps</td>
</tr>
<tr>
<td>Average throughput during busy hour (DL)</td>
<td>50 Mbps</td>
<td>200 Mbps</td>
<td>50 Mbps</td>
</tr>
<tr>
<td>Transport overhead</td>
<td>1.27</td>
<td>1.27</td>
<td>1.27</td>
</tr>
</tbody>
</table>

Table 6: Radio specifications - METIS TC2 with LTE-A

In order to perform the backhaul dimensioning, a simplified model version of METIS TC2 is used as shown in Figure 18. As can be seen from the Figure 18, this model comprises of four square shaped buildings with 2 outdoor (micro) small cells on two of the buildings and a macro cell on one of the buildings.

In addition, Figure 17 represents the indoor small cell layout on each floor, according to which, ten small cells are to be uniformly distributed on each floor (odd number floors and even number floors).

### 3.3.1 Mobile backhaul dimensioning using calculations and output

The following assumptions were made for mobile backhaul dimensioning using the METIS TC2:

- Four Buildings with 5 floors each and each floor having 10 indoor small cells uniformly distributed as shown in Figure 17.
- Buildings 2, 3 and 4 have an indoor small cell aggregation point.
- Micro cells and indoor small cells aggregate traffic at the intermediate small cell aggregation point of building 2 and 4. It is important to note that this aggregation point is deployment dependent and is practically same as A0 which means that this could be a fiber chunk aggregating traffic and not an active device. This is because there is a high probability that all the small cells in that particular region will aggregate traffic in the macro and no more logical aggregation levels exists beyond A0.
- Aggregation node A0 aggregated traffic from all the indoor small cells of building 1 and all traffic coming from building 2, 3 and 4.
- The traffic from A0 is logically aggregated into the macro RBS.
- All the traffic coming from all the buildings, small cells and the macro cell is aggregated in aggregation node A1.
- The higher aggregation levels are ignored as the capacity of the link between the macro cell and A1 is the point of focus which constitutes the backhaul dimension for the whole deployment model.
- Aggregation gain is not assumed for the small cells and micro cells.
- All the calculations hold true only for the downlink.

Furthermore if, Number of small cells per floor = \( \mu_s \); Number of floors = \( N \); Number of micro cells per building = \( N_{mi} \); Micro RBS throughput in a loaded network = \( \lambda_{lmi} \); Small cell throughput in a loaded network = \( \lambda_{ls} \); Micro RBS cell peak rate = \( \lambda_{pm} \); Small cell peak rate = \( \lambda_{ps} \), then Table 7 shows the calculations to find out the link capacities.

<table>
<thead>
<tr>
<th>Aggregation level</th>
<th>Formula</th>
<th>Link Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro RBS</td>
<td>( \lambda_m \cdot \alpha )</td>
<td>190 Mbps</td>
</tr>
<tr>
<td>Micro (Outdoor small cell)</td>
<td>( \lambda_{pm} \cdot \alpha )</td>
<td>762 Mbps</td>
</tr>
<tr>
<td>Intermediate indoor small cell aggregation node (for buildings 1, 2, 3 and 4)</td>
<td>( \lambda_{ps} \cdot \alpha \cdot \mu_s \cdot N )</td>
<td>9.3 Gbps</td>
</tr>
<tr>
<td>Building 1 – A0</td>
<td>( \lambda_{ps} \cdot \alpha \cdot \mu_s \cdot N )</td>
<td>9.3 Gbps</td>
</tr>
<tr>
<td>Building 2 – A0</td>
<td>( N_{mi} \cdot \lambda_{lmi} \cdot \alpha + \lambda_{ls} \cdot \alpha \cdot \mu_s \cdot N )</td>
<td>7.2 Gbps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.5 Gbps</td>
</tr>
<tr>
<td>Building 3 – A0</td>
<td>( \lambda_{ls} \cdot \alpha \cdot \mu_s \cdot N )</td>
<td>6.2 Gbps</td>
</tr>
<tr>
<td></td>
<td>( \lambda_{ps} \cdot \alpha \cdot \mu_s \cdot N )</td>
<td>9.3 Gbps</td>
</tr>
<tr>
<td>Building 4 – A0</td>
<td>( N_{mi} \cdot \lambda_{lmi} \cdot \alpha + \lambda_{ls} \cdot \alpha \cdot \mu_s \cdot N )</td>
<td>7.2 Gbps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.5 Gbps</td>
</tr>
<tr>
<td>A0 – RBS (Macro)</td>
<td>( (Building 1 – A0) + (Building 2 – A0) + (Building 3 – A0) + (Building 4 – A0) )</td>
<td>26.8 Gbps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>39.6 Gbps</td>
</tr>
<tr>
<td>RBS – A1</td>
<td>( \lambda_p \cdot \alpha + A0 – RBS ((Macro)) )</td>
<td>27 Gbps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>39.8 Gbps</td>
</tr>
</tbody>
</table>

Table 7: Mobile backhaul dimensioning capacity calculations - METIS TC2 – LTE A

Again as can be seen from Table 7 that the aggregation gain is omitted for the small cells and micro cells which is why their respective throughputs in a loaded network are used to calculate the link capacities for higher aggregation levels after the first aggregation level. In addition, Table 7 shows two link capacities (with black and red markings) which are calculated using the cell peak rates and RBS throughput in a loaded network in order to investigate the impact on the link capacity when either of them is used and to give an idea onto which methodology, to use the peak rates or throughputs in loaded networks, could be used beneficially to dimension the links. Since, the intermediate small cell aggregation point is logically same as A0, the small cell peak rates are used for micro and indoor small cells to dimension the links and
the RBS throughput in a loaded network is used to dimension the link between macro BS and A1. Figure 19 shows the backhaul dimensioning output with link capacities on each link. In Figure 19, it can be seen that the links are logically connected to the macro cell which aggregates traffic from all the small cells (indoor and outdoor), when wireless backhaul is used for the small cells (indoor and outdoor).

Figure 19: Mobile backhaul dimensioning output-TC2 (Example with logical links; wireless backhaul for small cells)
4 GAP Analysis – Mobile backhaul dimensioning

In this section, the backhaul requirements of today are compared to that of 2020 5G scenarios with example deployment strategies and an investigation is carried on how the 2020 5G scenarios would impact the transport network. Finally, the amendments in the existing mobile backhaul dimensioning methodology are also discussed in the context of 20202 5G scenarios. The backhaul capacity measurement included in Table 8 assumes that the RBS throughput in a loaded network values are used to calculate the numbers for small cells. It is important to note that the TC2 backhaul capacity calculations were just an exercise to evaluate the backhaul requirement for an indoor/outdoor dense urban scenario. Hence, that particular column has been colored as shown in Table 8 as it does not fit in the comparison.

Table 8 summarizes the findings in chapter 3; thereby giving a clear view on the backhaul capacity requirements for each of the mobile dimensioning exercises.

<table>
<thead>
<tr>
<th>Maximum Capacity</th>
<th>LTE - Today</th>
<th>5G RAT (w/o small cells)</th>
<th>5G RAT (with small cells)</th>
<th>TC2 – LTE A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backhaul per Macro BS</td>
<td>190 Mbps</td>
<td>12.7 Gbps</td>
<td>25.4 Gbps</td>
<td>27 Gbps</td>
</tr>
<tr>
<td>Small cell traffic</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 8: Backhaul capacities for different backhaul dimensioning exercises

Therefore from Table 8 and from the mobile backhaul dimensioning exercises, the following conclusions can be drawn assuming that the same dimensioning methods and formulae are employed as today:

- The last mile requirement for 2020 5G (w/o small cells) would be 68 times more than today.
- Considering 10 small cells aggregated to one Macro, the backhaul requirement for 2020 5G would be double than without small cells.
- Majority of the traffic can be generated from the small cells, assuming small cells deployment for offloading and macro cells for coverage.
- Capacity calculations for higher levels would depend on whether the aggregation gain for small cells is considered or not.
- Tradeoff between small cell peak rates and small cell RBS throughput in backhaul dimensioning because of which mobile backhaul dimensioning techniques can be adapted depending on user behavior and operator interests.

In addition the 5G scenarios would provide a huge impact on the transport network links and it would be vital to dimension the backhaul links in an efficient way and make efficient usage of the available resources in order to save additional costs and at the same time delivering good QoS to the end users.

Figure 20 shows a square shaped building as in METIS TC2 with dimensions 120m x 120m in width and breadth. If such a building has to have virtual reality offices of dimension 20m x 10m, as mentioned in METIS D6.1 Annex section 9.1.1, then there would be 6 * 12 = 72 virtual reality offices per floor. Considering a traffic volume density of 0.1 Gbps/m² again as mentioned in METIS TC1, the total traffic volume generated per office = 0.1 Gbps/m² * 20m * 10m = 20 Gbps and total traffic volume generated per building with 5 floors = 20 Gbps * 72 * 5 = 7.2 Tbps.
As mentioned in METIS TC2, the total average traffic volume generated in a minimal layout as shown in Figure 37 is 175 Gbps. Therefore if one of the square shaped buildings happens to contain virtual reality offices in five floors, there would be an addition of 7.2 Tbps over an existing transport link for METIS TC2. In order to fulfill such heavy traffic requirements it is important to analyze the user behavior throughout the day and dynamically allocate the traffic resources to provide an economical solution in handling such heavy traffic. In addition, the backhaul dimensioning schemes should be efficient enough in order to handle large traffic.
5 Integrated backhaul management:

This chapter deals with the investigation for the need and mechanisms for mobile backhaul management techniques in ultra-dense network scenarios. This includes both the nomadic node attachment algorithm for the moving networks as well as dynamic resource allocation and sharing between various ultra-dense network scenarios.

Moving networks – driver for network adaptation

Moving networks can be seen as nomadic nodes requiring access to the existing mobile network. METIS test case 6, traffic jam is used as a reference while investigating the moving networks as shown in Figure 40 in Appendix I. The reason behind choosing the METIS traffic jam test case was that it represents a good reference for a realistic scenario of moving networks in the 2020 5G UDN context. Figure 40 also illustrates the test case definition and KPI requirements in a traffic jam scenario. With an increasing use of mobile smart phones and tablets, it becomes essential that operators provide required QoS for end users who are on the move even in the situation of a traffic jam [8]. Furthermore, with a user density of 4000 users/Km², the high data rate requirement on most of the real time services adds extensive load on the existing network infrastructure which results in a sudden increase in capacity requirements when a traffic jam occurs. Allocating more resources only to meet the traffic in a highly localized traffic jam would prove very expensive for the operators. Therefore, in order to motivate the need for dynamic network adaptation features, a simple scenario of moving networks was analyzed as explained in the next section.

5.1 Moving networks analysis

In this section, a moving network scenario with the same test case definition and service requirements as TC6 traffic jam in METIS (Figure 40) is analyzed assuming a hypothetical deployment situation. It is therefore important to note that the deployment details mentioned in this scenario are hypothetical and not realistic. The motive of this exercise is mainly to investigate the impact of a UDN scenario (traffic jam) onto an existing mobile network infrastructure and to motivate the need for dynamic resource allocation mechanism in 2020 networks. Figure 21 shows the deployment scenario taken into consideration along with the assumed peak traffic hours. It is assumed that traffic jam happens during peak on-road traffic hours which occur between 07:00 – 09:00 and 17:00 – 19:00 during each working day (working days are assumed 7 days a week).

Figure 21 also illustrates the dimensions considered for the length of the roads and the width of the whole scenario. The whole scenario could be divided into four roads, having multiple lanes in both the directions. However, in order to investigate the impact of traffic jam on the existing network infrastructure, one single road, having multiple lanes on both sides, of width 250m and length 3600m is assumed as shown in Figure 22. Please note that the cars assumed in this analysis are potential small cell base stations and these can connect only to the existing macro or micro base station alongside the road and not to each other (avoiding the complexity of mesh networks).
Following is a summary of all the assumptions considered during the investigation:

- Road length of 3600m
- Range of Macro Cell for threshold throughput = 500m
- Range of Micro Cell for threshold throughput = 200m
• User density = 4000/Km$^2$
• Number of Randomly Distributed Cars along the length of the Road = 3600
• Minimum Data Rate requirement of Cars = 100 Mbps (METIS TC6)
• 2 Traffic Aggregation points Agg1 and Agg2.
• Wavelength resources ($\lambda_s$) equivalent to an interface of 10 Gbps

The macro and the micro base stations are considered to have a threshold range of 500m and 200m respectively. It is assumed that the cars connect to one of these base stations if they are within their range. It is also assumed that the cell throughput is uniform within the entire threshold range of each cell and there is a quick handover at the cell edges, which means that the cars connect quickly to the other base station if it is no longer in the threshold range of the first base station. Furthermore, with a user density of 4000 users/ Km$^2$ (METIS TC6), a total of 3600 cars would be present on the entire road (on all the lanes in both the directions), during an event of a traffic jam. Aggregation node Agg1 aggregates traffic from Macro1, Micro1 and Micro2 whereas aggregation node Agg2 aggregates traffic from Macro2, Micro3 and Micro4. However, traffic from Micro1 and Micro2 is logically aggregated in Macro1 and traffic from Micro3 and Micro4 is logically aggregated in Macro2. The micro base stations could be connected with the macro base stations with wired or wireless backhaul links depending on the traffic requirements and deployment considerations, more of which would be discussed in section 5.5. It is assumed that the wavelength resources ($\lambda_s$) can provide an interface of 10 Gbps in wired optical transport link spanning from the macro base stations to the aggregation nodes. Finally, it is also assumed that a car cannot request network access to a base station if it is not in its coverage range (range of threshold throughput). As the cars are considered to be moving constantly at a speed of 3-10 Kmph, depending upon the position of the car, three cases could be considered as illustrated in Figure 23. Figure 23 shows how a car can get access to the network by connecting directly to the macro base station or by connecting to one of the micro cells.

Simulation Considerations:

Using the parameters of the deployment considerations mentioned as above, a simulation setup was created in order to find out the actual impact on the transport links due to a traffic jam. Following is a summary of the simulation guidelines which were followed;

• 3600 cars (points) randomly distributed across the length of the road.
• Entire duration of peak hours divided into 100 snapshots
• Each snapshot gives the position of the car, number of cars blocked and no. of cars
• During each snapshot, the cars change position and there are always 3600 cars within the length of the road during the peak traffic jam hours.
• Number of maximum accessible fixed resources per macro = 70 $\lambda_s$ = 70
• Number of maximum accessible fixed resources per micro = 20 Gbps (20 $\lambda_s$ if fixed optical fronthaul is used for micro base stations).
Figure 23: Illustration of node attachment cases to different cells
Simulation results:

Figure 24 illustrates the total number of blocked cars by Macro1 and Macro2 and Figure 25, the total number of blocked requests coming from the cars by Micro1, Micro2, Micro3 and Micro4 in each snap shot within the entire duration of the traffic jam event. With 70 fixed $\lambda$s (resources), each macro base station would reject the attachment request of 300 cars on an average in every snap shot considered. Similarly, with 20 fixed $\lambda$s, each micro base station would reject the attachment request of 200 cars on an average in every snap shot considered. Moreover, Figure 26 shows the trend of the average number of car attachment requests blocked during each day every month during a traffic jam event.

![Performance of Node Attachment](image1)

![Performance of Node Attachment](image2)

*Figure 24: Car connection requests blocked by Macro1 and Macro2 in each snap shot during peak hours*
Figure 25: Car connection requests blocked by Micro1, Micro2, Micro3 and Micro4 in each snap shot during peak hours
Firstly, as illustrated in Table 9 with 3600 cars requiring access to the existing mobile network infrastructure, with an expected throughput of 100 Mbps, an extra traffic of almost 360 Gbps is burdened on the transport links connected to the macro base stations (180 Gbps per macro). But dedicating these many resources only for a traffic jam scenario is not an economically viable solution.

<table>
<thead>
<tr>
<th>RBS Type</th>
<th>Average connection requests per day</th>
<th>Maximum number of dedicated λ, required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro1</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>Macro2</td>
<td>400</td>
<td>40</td>
</tr>
<tr>
<td>Micro1</td>
<td>400</td>
<td>40</td>
</tr>
<tr>
<td>Micro2</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>Micro3</td>
<td>400</td>
<td>40</td>
</tr>
<tr>
<td>Micro4</td>
<td>400</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 9: Wavelength resource requirements per cell in a day

On the other hand, if less number of resources is dedicated during an event of a traffic jam, for example 70 for the macro base stations and 20 for the micro base stations, there would be 1000 cars that would be blocked during every snapshot and hence 10,000 cars will not get access throughout the event of a traffic jam per day and hence the end users would definitely not be satisfied with the services of the operator. Therefore, it becomes essentially important to assign additional resources when such an event occurs which requires more resources than assigned. In order to achieve this, an algorithm was explored which could be used to dynamically attach nomadic nodes into the existing mobile network infrastructure as per request which is explained in the next section.

5.2 Nomadic node attachment algorithm

In a moving network scenario as described above, the demands imposed to the deployed access/aggregation network are plenty. In particular to backhaul provisioning, the addition of several new nodes can imply e.g. in traffic overload. In the latter case, the over dimensioning of networks are not an option to prevent such problems since it would not be economically viable. Furthermore, the dynamic
nature of the add/drop connections of nomadic nodes offers an additional challenge, since the network has to constantly adapt accordingly. Therefore, firstly it becomes essential to understand a few terms before exploring the actual handshake process between the moving nodes and the network infrastructure.

**Nomadic node:** It is a moving node (basically other moving nodes like cars having small cell base stations installed) requesting access to the existing mobile network.

**Anchor node:** It is a node which is considered integrated or with the current status of attached in a network with operational backhaul capabilities. It could either be a nomadic node (car) which is already attached to the mobile network or a base station as explained in section 5.1.

**Network control entity:** It could potentially be an aggregation node or a central office which monitor the network configuration and allocates resources by dynamically accepting, denying attachment requests.

**Resources:** Resources refer to the data throughput in bits/sec, required to fulfill a service requirement. These resources could be proved by both wired (optical/copper links) or wireless means.

The proposed nomadic node attachment algorithm is illustrated as follows:

<table>
<thead>
<tr>
<th>Step 1: Attachment REQUEST (Nomadic Node ‘N’)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEND information about actual data traffic/service demands to nearest anchor node(s).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 2: Acknowledgment (Anchor node redirects request to Network Control Entity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHECK new node N connection allowance based on the existing transport network resources</td>
</tr>
<tr>
<td>IF network (local and/or global) is able to fulfill ‘N’s requirements THEN</td>
</tr>
<tr>
<td>ACCEPT attachment. END</td>
</tr>
<tr>
<td>NOT able to fulfill ‘N’s requirements THEN</td>
</tr>
<tr>
<td>ALLOCATE additional network resources</td>
</tr>
<tr>
<td>IF resource allocation is NOT available</td>
</tr>
<tr>
<td>DENY attachment. END</td>
</tr>
<tr>
<td>IF resources allocation is possible</td>
</tr>
<tr>
<td>ACCEPT attachment. END</td>
</tr>
<tr>
<td>END</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 3: SEND final decision (Network Control Entity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attachment ACCEPTED or DENIED.</td>
</tr>
</tbody>
</table>

**Step 1:** In the first step, the nomadic node requests access (in terms of resources to attach to the network) to the mobile network from the nearest anchor node. The nomadic node also conveys a list of service specific KPI requirements and data traffic demands so that the resource allocation could be done accordingly.

**Step 2:** In the second step, the nearest anchor node redirects the request to the network control entity. After receiving the request, the network control entity checks whether or not the requested service
demands could be fulfilled with the available chunk of resources. If the available resources in the mobile network infrastructure are able to fulfill the service requirements, then the nomadic node gets access and is attached to the network. However, if the available resources are not able to fulfill the service requirements, the network control entity looks for additional network resources. If additional resources are available, then these resources are allocated and the attachment request is accepted, but if not, then the attachment request is rejected by the network control entity.

Step3: In this step, the network control entity replies with its final decision to accept or deny the attachment request to the nomadic node via the nearest anchor node. If the attachment request is accepted, the nomadic node also becomes a potential anchor node for the next attachment request.

In step2 of the algorithm, additional network resources are checked for which can be allocated in case if all the resources are used up. These additional resources could be shared by different use cases or scenarios that require different amount of network resources at different time instants. To achieve this, a dynamic resource allocation procedure has to be analyzed which could switch resources between one system to the other on an eventual trigger basis (request arrives only during an event and not in a scheduled fashion). However, to motivate the need for a dynamic resource allocation mechanism to fulfill the sudden increase in service demands in the existing mobile network infrastructure, the impact of a traffic jam scenario (METIS TC6) on a dense urban scenario (METIS TC2) was investigated as explained in the next section.

5.3 Impact of traffic jam on dense urban scenario

This section is dedicated to investigate the impact of mapping one 2020 UDN test case over the other (in this case, METIS TC6 over METIS TC2) in terms of increase in the overall traffic in the transport links. The previous section was investigated using an arbitrary hypothetical deployment situation, whereas in this section, a realistic deployment reference case is considered. The minimal layout of a dense urban information society (METIS TC2), along with the positioning of macro and micro base stations, as already shown in Figure 27, would be used for this investigation. Moreover, a traffic jam scenario (METIS TC6) would be mapped over TC2 in order to investigate the architectural impact. Also, it is important to note that, only the outdoor data traffic requirements would be considered for this investigation. Appendix II illustrates the dimensions assumed for the METIS TC2 minimal layout.

Two models would be considered for this investigation. In Model1, only one of the roads within TC2 minimal layout is assumed to have a traffic jam as shown in Figure 27 and Model2, where all the roads with TC2 minimal layout are assumed to have a traffic jam.
In addition, while mapping the requirements of traffic jam TC6 onto one of the roads in TC2, the following assumptions hold true.

**Model 1:** Traffic jam only on one of the roads;
- Road length of 552m
- Width of the road including parking lanes = 12m
- Cars connect to
  - Micro 1 if distance from origin d of the car is $0 \leq d < 207$
  - Micro 2 if distance from origin d of the car is $207 \leq d < 375$
  - Macro if distance from origin d of the car is $375 \leq d < 552$
- Total Area of the road = $6624 \text{ m}^2$; User density = 4000/Km$^2$
- No. of Randomly Distributed Cars along the length of the Road = User density* Total Area = 26
- Minimum Data Rate requirement of Cars = 100 Mbps (METIS TC6)
- Agg refers to the traffic aggregation point.

**Model 2:** Traffic jam on all the roads;
- Total Area of the all roads = $40440 \text{ m}^2$; User density = 4000/Km$^2$
- Number of Randomly Distributed Cars on TC2 minimal layout = User density* Total Area = 161
- Minimum Data Rate requirement of Cars = 100 Mbps (METIS TC6)
Hence, 26 cars would be distributed on the length of the road taken into consideration in accordance to the user density mentioned in TC6. Therefore, with 26 cars requiring a minimum average data throughput of 100 Mbps, there would be an extra traffic load of almost 2.5 Gbps (percentage increase in outdoor data traffic = 5.7 %) on the outdoor data traffic requirement in TC2 as shown in Figure 28. But, in the case of Model2, where all the roads within the TC2 minimal layout are assumed to have a traffic jam, an extra traffic requirement of 15.7 Gbps (percentage increase in outdoor data traffic = 35.8 %) would be imposed on the network infrastructure for TC2 as shown in Figure 28 summing up to 59.5 Gbps in the backhaul link.

Hence from the above illustration it is evident that the mobile network infrastructure has to be adaptive enough to cope with such sudden increase in traffic demands. This can be achieved by allocating resources dynamically during the event of a sudden increase in service requirements. The following section shows how dynamic resource allocations could be achieved in different use cases depending upon their KPI requirements and the corresponding gains obtained.

5.4 Dynamic resource allocation and & Quantitative analysis of optical switching

In this section, a resource allocation scheme is investigated where wavelength resources (λ) are dynamically allocated to different METIS test cases depending upon the requirements. In this investigation, following assumptions are taken into considerations;

- METIS Test Cases used
- Six A1 Aggregation levels in one access ring
- Each A1 aggregates traffic from each test case
- Each test case is assumed to have an area of 1 Km² except TC1

![Figure 28: Illustration of impact of mapping traffic jam scenario over TC2](image-url)
• Area of TC1 = 3200 m² comprising of 10 Virtual reality offices

• Each wavelength resource ($\lambda$) is assumed to have an interface of 10 Gbps

As shown in Figure 29, the local access ring consists of six first level of aggregation nodes (A1) while each of them aggregating traffic from each METIS test case. This seems like a hypothetical deployment situation, but the main focus here is to investigate the dynamic resource allocation and hence this assumption is considered. The KPI requirements of each of these METIS test cases could be found in Appendix I. In addition, for this investigation, only the required traffic volume density KPI parameter is considered in order to calculate the total traffic volume required for each of the test cases as shown in Table 10.

![Figure 29: Dynamic resource allocation system model description with each TC connected to an aggregation node](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TC1</th>
<th>TC2</th>
<th>TC3</th>
<th>TC4</th>
<th>TC6</th>
<th>TC9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic volume density</td>
<td>0.1 Gbps/m²</td>
<td>700 Gbps/Km²</td>
<td>170 Gbps/Km²</td>
<td>0.1 Mbps/m²</td>
<td>480 Gbps/Km²</td>
<td>900 Gbps/Km²</td>
</tr>
<tr>
<td>Area</td>
<td>10*320 m²</td>
<td>1 Km²</td>
<td>1 Km²</td>
<td>1 Km²</td>
<td>1 Km²</td>
<td>1 Km²</td>
</tr>
<tr>
<td>Total traffic volume</td>
<td>320 Gbps</td>
<td>700 Gbps</td>
<td>170 Gbps</td>
<td>100 Gbps</td>
<td>480 Gbps</td>
<td>900 Gbps</td>
</tr>
<tr>
<td>No. of dedicated resources</td>
<td>32</td>
<td>70</td>
<td>17</td>
<td>10</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>(Weekdays)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of dedicated resources</td>
<td>0</td>
<td>70</td>
<td>17</td>
<td>10</td>
<td>48</td>
<td>90</td>
</tr>
<tr>
<td>(Weekends)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 10: System model considerations - traffic volume and area for each test case
Moreover, as can be seen in Table 10, the total traffic volume required by each of the test cases has also been categorized in terms of weekday data traffic requirement and weekend data traffic requirement. This categorization is done in order to investigate wavelength granularity to perform a quantitative analysis of for optical switching of resources among the aggregation nodes. Figure 30 illustrates the traffic profile consideration and corresponding variation in required number of wavelength resources (λs) for each test case during the weekdays. The traffic volumes for each of the test cases are assumed for the non-peak hours whereas for the peak hours the traffic volume KPIs for each test case is used. The assumed traffic volumes for each of the test cases during the each hour of the day and the motivation behind it could be found in Appendix III. In addition, it is noteworthy that TC1 does not generate any traffic during the weekends as it is assumed that the offices are closed during the weekends whereas during TC9 does not generate any traffic during the weekdays as it is assumed that the open air festivals occur only in the weekends.

![Figure 30: Traffic profile and λ – variation for weekdays](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak traffic volume (All TCs)</td>
<td>1650 Gbps</td>
</tr>
<tr>
<td>Maximum number of λs required</td>
<td>165</td>
</tr>
<tr>
<td>Total Number of Dedicated λs (for all TCs w/o Dynamic Resource Allocation)</td>
<td>177</td>
</tr>
</tbody>
</table>

Table 11: Total number of wavelength resources - Weekdays

According to the traffic profile in Figure 30 it can be seen that the overall peak traffic volume usage occurs between 09:00 – 11:00 and 16:00 – 19:00 consuming a total traffic volume of 1650 Gbps. Table 11 illustrates the total peak traffic volume required during each weekday. It can also be seen from the Table 11 that the maximum number of wavelength resources (λss) need to be dedicated to provision each test case maximum requirement is 177, while the maximum number of wavelength resources required to fulfill only the peak traffic volume requirement is 165. This means that if a dynamic resource allocation procedure is employed which would allocate resources to each of the test cases based on their requirements then a total of 12 wavelength resources of 10 Gbps interface can be saved (almost 7%).

However, if a different traffic profile and a corresponding wavelength resource variation, as shown in Figure 31, are considered for the weekends, then the overall peak traffic volume usage occurs between 16:00 – 22:00 consuming a total traffic volume of 2150 Gbps (Appendix III). Table 12 illustrates the maximum number of wavelength resources required to serve this peak traffic which is equal to 215.
However, 235 wavelength resources would be required if each test case has to be dedicatedly allocated wavelength resources to serve each peak traffic volume requirement. Hence, with dynamic resources allocation, 20 wavelength resources could be saved which results in a saving of almost 8.5%.

From the above results, it is evident that if the dynamic resource allocation mechanism is employed during each day of the weekday or weekend, there is no significant amount of saving in terms of resources. However, as shown in Table 13, the total number of wavelength resources consumed can be combined both for the weekdays and weekends and hence evaluate the percentage saving if the dynamic resource allocation procedure is employed between weekdays and weekends rather than during any day.

This percentage saving can be evaluated by using the fact that assuming 215 resources are used both in the weekdays and weekends which is equal to max (total maximum resources consumed in weekdays, weekends), instead of the sum of total maximum required number of dedicated resources for both weekdays and weekends which is equal to 267, then a significant saving of almost 20% could be achieved. This means that the fiber network deployment could be done so as to support 215 resources instead of 267 wavelength resources by which this 20% amount could be saved, which is a huge saving in terms of cost if we assume that the wavelength resources in the future would have higher capacity interfaces. In addition, among these 215 resources only 165 could be used in the weekdays which account for another 30% saving, which is again significant in terms of cost.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak traffic volume (All TCs)</td>
<td>2150 Gbps</td>
</tr>
<tr>
<td>Maximum number of $\lambda$, required</td>
<td>215</td>
</tr>
<tr>
<td>Total Number of Dedicated $\lambda$, (for all TCs w/o Dynamic Resource Allocation)</td>
<td>235</td>
</tr>
</tbody>
</table>

Table 12: Total number of wavelength resources - Weekends

<table>
<thead>
<tr>
<th>Days</th>
<th>Total maximum required number of dedicated $\lambda$ $(\lambda_{r_{\text{max}}})$</th>
<th>Total maximum resources consumed $(\lambda_{c_{\text{max}}})$</th>
<th>Percentage saving $(\lambda_{r_{\text{max}}} - \lambda_{c_{\text{max}}}) / \lambda_{r_{\text{max}}} \times 100$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekdays</td>
<td>177</td>
<td>165</td>
<td>7.27%</td>
</tr>
<tr>
<td>Weekends</td>
<td>235</td>
<td>215</td>
<td>8.5%</td>
</tr>
<tr>
<td>Weekdays + Weekends</td>
<td>267</td>
<td>Max (215, 165) = 215</td>
<td>$\approx$20%</td>
</tr>
</tbody>
</table>

Table 13: Percentage resource saving calculation weekdays/weekends

Figure 31: Traffic profile and $\lambda$ – variation for weekdays
Finally this section could be concluded by highlighting the need for an evolution of SDN controllers in DWDM aggregation networks [30] with $\lambda$ – controlling functionalities which can be used in the access rings to optimize the dynamic resource allocation mechanism between different systems. By doing so, the operators could save cost on huge resources (10 Gbps interfaces are costly) and introduce more dynamicity by auto integration of new nodes in a system giving access and blocking according to the node attachment algorithm.

5.5 Moving network analysis – Fronthaul architecture

So far, the discussion mainly focused on the impact of mapping a traffic jam scenario (TC6) over a minimal layout of a dense urban information society scenario (TC2). Hence, it can be concluded that there would be considerable added capacity requirements on the existing infrastructure of TC2 if a traffic jam is mapped over it. With multi folds capacity requirements in the backhaul, leads to the need for an investigation on how the architectures for 2020 UDN networks should look like. Further motivation behind this investigation lies in the fact that with UDN deployments, cost would be vital parameter in both in terms of CAPEX and OPEX which acts as a firm driver toward new architectural solutions. There could be two types of architectures, one being the traditional backhaul and other being the centralized fronthaul architecture (C-RAN). In order to investigate the fronthaul architecture, it is important to understand that how the CPRI capacity calculation is done today for the optical fiber links in the fronthaul.

CPRI link capacity calculation

The CPRI link capacities are calculated using the following formulae;

Bitrate per sector = (Bitrate per antenna) x (Number of carriers) x (MIMO antennas per sector)

Bitrate per site = (Bitrate per sector) x (Number of sectors)

Where bitrate per antenna = (Sample rate) x (Bits per sample)

For typical 20 MHz LTE bandwidth; Sample rate = 30.72 MHz and Bits per sample = 16 (x2 for I and Q).

Therefore, Bitrate per antenna for single 20 MHz LTE carrier = 30.72 Mbps x 16 x 2 = 983.04 Mbps (for IQ-data only). Table 14 illustrates the CPRI link capacity calculation and for TC2 with LTE advanced calibration case [28] as well as the transport link capacities calculated from mobile backhaul dimensioning methodology. From Table 14 it can be seen that the CPRI link capacity per site is much higher compared to the required backhaul link capacity. Therefore, if fronthaul architecture is used in this case with CPRI link capacities (Figure 32) as calculated in Table 14, then the useful part of the capacity would be very less compared to the actual CPRI link capacity. This would result in wastage of resources as CPRI link capacities are fixed and are always ON even if they are not used. Backhaul capacity requirement for Macro and Micro are calculated similarly using the same formulae as in section 3.3 and 3.4 using the same radio considerations considering the fact the 12 micro cells logically aggregate traffic into the macro cell and cell throughput in a loaded network is used for micro cells while calculating the overall backhaul requirement for the macro link.
Table 15 illustrates the CPRI link capacity calculation and for TC2 with assumed 5G RAT deployment calibration details as well as the transport link capacities calculated from mobile backhaul dimensioning methodology. The bandwidth used for 5G RAT is assumed to be 10 times of LTE 20 MHz and 1 TX/RX MIMO is considered. The figures for the capacities are calculated by scaling the CPRI link capacities by a factor of 1. According to these assumptions and from the Table 15 it can be seen that the CPRI link capacity per site is comparable to the required backhaul link capacity. Therefore, if fronthaul architecture is used in this case with CPRI link capacities (Figure 33) as calculated in Table 15, then the most of the useful part of the capacity would be used as the fronthaul link capacity is in the same level as for required backhaul capacity. This would never result in wastage of resources as CPRI link capacities are fixed and are always ON even if they are not used. Hence, the fronthaul C-RAN architecture would be more beneficial to use for the 5G RAT UDN scenarios requiring high data rates as compared to today’s LTE scenarios. In addition, this would also add all the advantages, as discussed in section 2.1.1, into the system and from the operators’ perspective by using C-RAN in such scenarios.
<table>
<thead>
<tr>
<th>Deployment Parameters</th>
<th>Macro</th>
<th>Micro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency [MHz]*</td>
<td>15 GHz</td>
<td>15 GHz</td>
</tr>
<tr>
<td>Bandwidth [MHz]* (DL)</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Antenna configuration*</td>
<td>1 TX/RX MIMO</td>
<td>1 TX/RX MIMO</td>
</tr>
<tr>
<td>Sectors per site*</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>CPRI Link Capacity per sector</td>
<td>9.6 Gbps</td>
<td>9.6 Gbps</td>
</tr>
<tr>
<td>CPRI Link Capacity per site</td>
<td>28.8 Gbps</td>
<td>9.6 Gbps</td>
</tr>
<tr>
<td>Required transport link capacity for backhaul dimensioning per site</td>
<td>28 Gbps</td>
<td>12.7 Gbps</td>
</tr>
</tbody>
</table>

Table 15: CPRI Link capacity calculation for TC2 using assumed 5G RAT (Assuming same Bit Rate per Antenna as 20 MHz LTE and assuming 10 20 MHz carriers form 200 MHz bandwidth)

Figure 33: C-RAN for LTE-A calibration in TC2 deployment
6 Views on techno economics and fiber deployments

In this section, the techno economic aspects of 2020 UDN networks are discussed. From the above discussions, it is evident that the traffic capacity requirement on the transport links would be huge as compared to today’s networks. Therefore, it becomes extremely important for the operators to fulfill this high capacity demand by smart deployment solutions also considering the cost factors. As illustrated in Figure 34, in network segments with larger data rates, DWDM becomes more economically favorable than packet aggregation in both the access and aggregation links [31]. This is because, with the increase in traffic volumes, packet processing would also become costlier as huge numbers of packets have to be processed. Although fiber deployment is much costlier, the fiber deployment would be more cost effective when it comes to high traffic volume processing and hence the overall cost effectiveness of deploying DWDM centric transport networks would be much better than packet processing.

On the contrary, the optical fiber DWDM networks might cause a negative impact on the end user services through an unwanted trombone effect. Trombone effect refers to a situation when data traffic traverses long distances in the network, just because of the fiber deployment, which in turn causes additional deterioration of the service KPIs like latency, delay etc. [32]. The main reason of the traffic trombone effect to exist is that the fiber ducts and cables are deployed before the actual placement of access nodes and hence the fiber connectivity would be entirely different from logical connectivity as shown in Figure 35. Therefore, the data packets might have to travel longer distances than expected according to the logical connectivity, which leads to an increase in delay and latency and thereby a decrease in service quality. It is therefore essentially important for operators to take this into consideration while designing and deploying their networks.
Figure 35: An optimized PON configuration for small-cell backhaul [33]
7 Conclusions and Future work

This section summarizes the entire thesis work with a list of conclusions and possible scope for future work. The conclusion section includes a list of concluding remarks from each of the activities performed during the thesis including an overall summary of the conclusions.

7.1 Conclusions

1. Backhaul dimensioning for 2020 Dense-urban scenarios

The ultra-dense small cells deployments add an extra level of aggregation in the mobile backhaul dimensioning methods and a new approach for network planning was investigated (“cell peak rate” vs “cell throughput in a loaded network” parameters for dimensioning the A0 level). Hence, it could be concluded that new dimensioning mechanisms are required to dimension the 2020 UDN networks and a tradeoff between the use of cell peak rates and cell throughput in a loaded network should be considered so as to optimize the backhaul capacity dimensioning.

2. Gap analysis between 4G vs 5G RAN deployments

The last mile requirement for 2020 5G can be 68 times more than today. In addition, UDNs would also add on extensive load on the backhaul requirements. As the backhaul capacity requirement is almost double when small cells are added in 2020 5G networks, therefore, it can also be concluded small cells would generate a very high portion of the overall traffic generation.

3. Integrated Backhaul Management

3.1 Network adaptation

Moving networks (TC6 Traffic Jam) represents a considerable extra load for the network and also can be seen as a driver to network adaptation. Moreover, a need for new adaptive schemes was analyzed by investigating the implementation of nomadic node attachment algorithm in moving networks.

3.2 Dynamic resource allocation

The nomadic node attachment procedure illustrates a step where the mobile network entity checks for additional network resources. It was introduced in order to optimize the performance of moving networks which add extensive load on existing network infrastructure and avoid the rejection of nodes by the network due to the lack of resources. This method exemplifies the need to introduce dynamicity in allocating resources not only within the geographical areas but also among various service requests. And with further investigation on the granularity of wavelength resources, it can be seen that if the allocation of wavelength resources is done on the basis of weekdays and weekends there would be significantly more saving of 20% in the amount of wavelength resources and hence cost according to the investigation where traffic models did not include daily variation.

3.3 Architectural impact

With higher data rate requirements and improved access (LTE to 5G RAT), the fronthaul C-RAN architectures would be more beneficial than the traditional backhaul architectures for the transport
network. This is because the CPRI link capacities for LTE-A were found to be much higher compared to the backhaul requirements while for 5G RAT (with 1 Tx/Rx MIMO) the two capacities were comparable for the same number of cells deployed serving same services. Hence, by doing so the transport network for 2020 UDN scenarios would have added advantages of centralized C-RAN architectures. However, further investigations on the feasibility of fronthaul deployment can be done with massive MIMO.

4. Techno economics with fiber deployment

2020 5G UDN network would introduce high data rates not only in the transport but also in the access network. Hence it could be concluded that optical DWDM aggregation would be more beneficial than traditional packet aggregation both in the access as well as in the transport networks. However, the 2020 UDN networks are expected to have extensive service requirements which include delay, latency etc. that are very low as compared to today’s networks. Deploying optical fiber networks could introduce a negative trombone effect and hence, every UDN scenario would have to also consider the tradeoff between wireless and optical access networks (cost vs performance) from the deployment perspective. Therefore, an optimal solution would be a combing both depending upon the service requirements.

The above set of conclusions can be summarized as follows;

With an expected tsunami of mobile data traffic and increasing network demands for new emerging services, the 2020 5G mobile transport network infrastructure has be more agile, dynamic and adaptive as today in order to fulfill the end user QoS demands efficiently. This includes new mechanisms for proficient network planning, auto-attachment/detachment of nodes, dynamic resource allocation and deploying cost-effective network architectures.

7.2 Answers to Research Questions

1. What is the impact of 5G 2020 network deployment in the access backhaul links, assuming in particular the capacity requirements introduced by UDN and corresponding 1000x more traffic values?

   After comparing the backhaul dimensioning results for a similar reference deployment scenario using both the LTE and the 5G RAT results shows, e.g., that the estimated increase of backhaul traffic between LTE and 5G deployments can increase up more than 65 times.

2. In 2020, will traffic increase and RAN scenarios will be so different that new techniques for access network planning will be needed?

   Small cells deployment are right now in its early stages and by 2020, ultra dense deployment are expected in order to meet the foreseen coverage and capacity requirements for end-users. From typical backhaul dimensioning methods, i.e., assuming that the last mile fixed link is the macro station backhaul, a new aggregation level was proposed to represent the small cell traffic aggregation. In addition, it was identified that the dimensioning backhaul method for macro and small cells will be deployment dependent and will be based on a tradeoff between the “cell peak rates” or “cell throughput in a loaded network” parameters, in order to dimension the macro links, when small cell traffic is also aggregated, and to avoid overprovisioning and consequently increased network costs.
3. In terms of capacity requirements, will 2020 UDN deployments demand flexible and adaptive networks? What can be the foreseen gains?

Different 2020 deployments that might motivate large traffic variations were investigated. These include six METIS test cases: TC1 virtual reality office, TC2 dense urban information society, TC3 Shopping mall, TC4 Stadium, TC6 Traffic Jam and TC9 Open Air Festival. Furthermore, DWDM-centric transport architecture was considered, such as a network resource allocation (optical wavelengths) based on traffic demands could be managed automatically by the network. Results show that, if optical wavelength is a parameter to be optimized/saved in order to guarantee a low cost and scalable access/aggregation network, estimated savings of about 20% of resources/wavelengths (10Gbps optical interfaces), can be reached in access networks assuming the before mentioned METIS test cases deployments. For the latest, reallocation of optical wavelengths between different geographical areas and between weekends and weekdays was assumed (traffic models did not include daily variation).

4. What is the impact of the introduction of moving networks in the fixed access backhaul links? Is there motivation to introduce automatic node integration and self-managing backhaul networks schemes? (Instead of approaching the problem as pure radio access matter)

The introduction of moving networks in a dense urban scenario represents an additional random load to be considered while dimensioning networks. This thesis studied a particular capacity challenging scenario for moving networks, entitled METIS test case traffic jam, when the deployment of base station in cars can create a situation that the traffic load of a macro station can increase more than 30% during traffic busy hours. It was verified that to over dimensioning the backhaul links only based on possible traffic jams can be avoided. The proposal was to optimize the problem of nomadic node integrations to the network, considering also the availability of resources from the transport backhaul links, in addition to the possibility of reallocating new resources on demand, i.e., optical wavelengths to increase the corresponding backhaul link capacities. Thus, as discussed in chapter 4, the nomadic node attachment algorithm along with the dynamic resource allocation procedures could incorporate auto integration and self-managing features in moving networks (METIS TC6 – traffic jam scenario).

5. Assuming the increase in traffic in the access networks by 2020, what are the foreseen pros/cons of packet and optical based backhaul?

It depends, because in the future network like 2020 5G UDNs, the service requirements are so diverse that the mobile data traffic volume is expected to increase 1000 times and as was discussed in chapter 5, that as the data volume increases DWDM aggregation becomes more cost effective than packet aggregation. In addition, optical transport also simplifies network operation and fulfills latency requirements better than packet based networks. So by this argument it can replace. But fiber deployments also introduce unwanted trombone effects which could make the operators to go for an optimal solution with both wireless and optical DWDM aggregation networks in the access and in the transport.

7.3 Future work

The work to underline the full impact of the new 5G service requirements in the 2020 networks is just the beginning. This thesis focused, among other things, to perform a network feasibility study in terms of
capacity, considering the most recent 5G scenarios proposed in the literature. Another challenge for the networks will possibly be latency; energy efficiency etc. and a similar feasibility study can be considered, assuming different use cases, such as Tactile Internet.

Also, the traffic variation models for the scenarios were limited in terms of daily variation, especially for moving networks, different geographical areas in dense urban centers, etc. Once more detailed models are available, more precise investigations can be performed to determine, and e.g., the level of dynamicity required from network resource allocation schemes.

In addition, this thesis assumed 5G RAT considerations based on current industry or proof of concept demos. However, more refinements in the backhaul requirements could be done for specific use cases with actual 5G RAT deployment parameters, when available. This would also lead to a more explicit outcome regarding the feasibility of CPRI links in terms of capacity requirements for deploying optical fiber fronthaul. In addition, further investigations on the feasibility of fronthaul deployment can be done with massive MIMO.

Finally, this thesis included a very brief discussion on the techno-economic aspect of fiber deployments. This study could also be extended in order to investigate the cost structure for fiber deployments in different METIS test cases and find out the economic viability for the operators.
8 References


[9] Dave Cavalcanti and Dharma Agrawal, University of Cincinnati, Carlos Cordeiro, Philips Research Usa, Bin Xie And Anup Kumar, University Of Louisville “Issues in Integrating Cellular Networks, WLANs, and MANETs: A Futuristic Heterogeneous Wireless Network” 1536-1284/05 IEEE Wireless Communications • June 2005


[27] http://www.3gpp.org/technologies/keywords-acronyms/105-son


[31] Björn Skubic, Ming Xia, Stefan Dahlfort, Ericsson Research “Evolution towards DWDM in Access/Aggregation” ECOC 2014


[34] “SUGGESTIONS ON POTENTIAL SOLUTIONS TO C-RAN BY NGMN ALLIANCE”03-JANUARY-2013 VERSION 4.0


[37] 5G radio network architecture white paper; Radio Access and Spectrum FP7 Future Networks Cluster http://www.ictras.eu/
Appendix I

METIS Test Cases

This section describes the METIS test cases used as ultra-dense 2020 5G reference use cases [8] for evaluating the backhaul requirements and investigating the integrated backhaul management mechanisms. Following is a summary of the test case definitions and the KPI requirements relevant to this report.

TC1: Virtual Reality Office

**Test Case Definition**
- User/device average density is 1/10 m² per floor
- Traffic Volume of 36 TB/User/Month
- Office Area per floor 16x20 m²

**Performance Targets**
- Availability of 1Gbps at 95% office space (DL & UL)
- Availability of 5Gbps at 20% office space (DL & UL)

- Indoor live 3D tele-presence use case
- Very high data throughputs and low latency requirements

![Figure 36: METIS TC1 - Virtual reality office - Test case definition and KPIs [8]](image)

TC2: Dense Urban Information Society

**TC2 Definition**
- Buildings dense urban: Square 120m x 120m x 5 floors
- Minimal layout of 0.25 km²
- Considering global user density of 200 000 users/km²
- Total number of UEs to simulate on such minimal layout is 50 000 users
- For Indoor Coverage, ISD can be as low as 10m

**Users location probabilities**
- Indoor 75%
- Outdoor 25%

**Traffic Model**
- Considering of global traffic volume density of 700 Gbps/km², 175 Gbps have to be served on this minimal layout
- Outdoor 25%
- Actual average traffic volume area 15% lower than the METIS target.

![Figure 37: METIS TC2 - Dense Urban Information Society - Test case definition and KPIs [8]](image)
TC3: Shopping Mall

**Test Case Definition**
- Average human user density = 0.1 / m²
- Average device density = 0.7 / m²
- Total user traffic volume during busy hours = 5.6 Tbyte/hour (4 Tbyte in DL and 1.6 Tbyte in UL)

**Performance Targets**
- Experienced user throughput = 300 Mbps DL and UL
- Traffic volume density = 170 Gbps/Km² DL and UL
- Reliability 95% of time for commercial data traffic and 99.9% for safety-related sensor applications
- Availability 95% of indoor shopping mall area for commercial data traffic and 99% for safety-related sensor applications

Mobile broadband communication services in the heterogeneous indoor environment of a shopping mall, e.g. shops, catering areas, galleries.

*Figure 38: METIS TC3 - Shopping Mall - Test case definition and KPIs [8]*

TC4: Stadium

**Test Case Definition**
- User/device density = 20 – 50 Thousands in 50000 m²
- Traffic volume = 9 [Gbyte/h] per subscriber DL+UL in busy period

**Performance Targets**
- Traffic volume per subscriber = 9 [Gbyte/h] per subscriber DL+UL in busy period (peak of traffic during the sport event)
- Traffic volume per area = 0.1-10 [Mbps/m²] / (stadium area 50,000 m²)
- Experienced user data rate = 0.3-20 [Mbps] DL+UL
- Average user data rate during busy period = 0.3-3 [Mbps]
- Reliability: Throughput offered only during events in the stadium
- Availability of 95% within the stadium

Huge amount of traffic is generated during a quite short duration of the event, while the traffic is normal or very low for the rest of the time.

*Figure 39: METIS TC4 - Stadium - Test case definition and KPIs [8]*
TC6: Traffic Jam

Test Case Definition
- User/device density = 4000 users/Km²
- Traffic volume = 53 Gbyte/hour/device

Performance Targets
- Experienced user throughput = 100 Mbps/user DL and 20 [Mbps/user] UL
- Traffic volume density = 480 Gbps/Km²
- Reliability > 95%
- Availability > 95% of users
- Latency < 100 ms

- Sudden increase in capacity demands in traffic jam
- Challenge to maintain QoE of public cloud and infotainment services

Figure 40: METIS TC6 - Traffic Jam - Test case definition and KPIs [8]

TC9: Open Air Festival

Test Case Definition
- User/device density = Max. 4 subscribers/m²
- Traffic volume including Video clips sharing, internet access, and sensor device communication with total traffic volume per area: 900 Gbps/km²

Performance Targets
- Experienced user throughput > 30 Mbps DL and UL
- Average user data rate during busy period = 9 Mbps DL and UL
- Traffic volume density = 900 Gbps/Km² DL + UL
- Traffic volume per subscriber = 3.6 Gbyte per subscriber during busy period
- Reliability > 99%; less than 1 % outage. Wireless access offered only during the festival events.
- Availability of 95% of festival space for users and 100% for sensor applications

- Open Air Festival organized in a rural area
- Normally small numbers of sites are deployed due to low user density
- Challenge to meet data traffic demands during such festivals

Figure 41: METIS TC9 - Open Air Festival - Test case definition and KPIs [8]
Appendix II

METIS TC2 - Dense Urban Information Society – Test case explanation

Figure 37 shows the minimal layout of an ultra-dense information society METIS test case TC2 [28]. The environmental model and traffic model considerations for this test case can be found in METIS document D6.1 section 9.2 [28].

**Deployment Parameters:** Table 16 shows the deployment parameters as explained in METOS D6.1 Sec 3.3.3 for LTE-A calibration test case [28].

<table>
<thead>
<tr>
<th>Cell Deployed</th>
<th>Career</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro BS</td>
<td>800 MHz</td>
<td>20 + 20 MHz (UL + DL)</td>
</tr>
<tr>
<td>Micro BS (Outdoor small cell)</td>
<td>2.6 GHz</td>
<td>80 + 80 MHz (UL + DL)</td>
</tr>
<tr>
<td>Femto BS (Indoor small cell)</td>
<td>2.6 GHz</td>
<td>20 + 20 MHz (UL + DL)</td>
</tr>
</tbody>
</table>

Table 16: Deployment calibration parameters - TC2 [28]

The minimal layout of TC2 has the following dimensions of all the buildings, roads, parking lanes and sidewalks METIS D6.1 section 9.2.1[28];

- Layout Dimensions 552m (N-S) x 387m (E-W)
- Square shaped buildings and park; 120m x 120m
- Rectangular shaped buildings; 120m x 30m
- Width of the road including parking lanes = 12m
- Gran Via sidewalk. Double (6 m wide) sidewalk between Gran Via road lanes.
- Sidewalks surround every building and are 3 m wide.
- Calle Preciados sidewalk is of 21 m wide between rectangle shaped buildings.
- Roads are 3 m wide and are always one lane for one direction accompanied by parking lanes.
- Gran Via road has no parking lanes on both sides and there are three road lanes in each direction.
- Total Area of the all roads = 40440 m²
Appendix III

Assumed traffic volumes during the each hour of the day
This section includes the traffic profile considerations for investigating the dynamic resource allocation procedure in section 5.4 of the report. Separate traffic profiles were created for weekdays and weekends by making realistic assumptions. However, the main focus of this exercise was to evaluate the peak data volume requirements during the weekday and weekends in order to investigate the impact of implementing the dynamic resource allocation technique. Both traffic profiles assume peak data traffic volumes for each of the test cases referred from METIS [8].

Weekdays: Table 17 illustrates an hourly traffic profile during the weekdays for five METIS test cases [8]. The virtual reality office (TC1) has eight peak hours during the day. It is assumed that the office hours are from 09:00 until 18:00 (including a recess of one hour, makes it nine hours) and hence the peak traffic data volume requirement is allocated to these hours. The traffic volume for non-peak hours are assumed to be more realistic, but as mentioned earlier it does not matter as the main concern of this exercise is to investigate the peak data traffic volume requirements. For the dense urban information society (TC2), the peak hours are assumed to be 07:00 until 22:00 as it concerns with both outdoor and indoor data traffic for all types of buildings. For the shopping mall (TC3) the peak hours are assumed from 10:00 until 22:00. In case of a stadium (TC4), the peak hours are considered only from 19:00 to 0:00 (assuming stadium hosts games only during these hours). Finally the traffic jam (TC6) is assumed to occur during the peak rush hours in the morning 07:00 – 10:00 and in the evening 18:00 – 20:00.

<table>
<thead>
<tr>
<th>Time</th>
<th>TC 1(Gbps)</th>
<th>TC 2(Gbps)</th>
<th>TC 3(Gbps)</th>
<th>TC 4(Gbps)</th>
<th>TC 6(Gbps)</th>
<th>Total Traffic (Gbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00 – 1:00</td>
<td>50</td>
<td>100</td>
<td>20</td>
<td>10</td>
<td>50</td>
<td>230</td>
</tr>
<tr>
<td>1:00 – 2:00</td>
<td>50</td>
<td>100</td>
<td>20</td>
<td>10</td>
<td>50</td>
<td>230</td>
</tr>
<tr>
<td>2:00 – 3:00</td>
<td>50</td>
<td>100</td>
<td>20</td>
<td>10</td>
<td>70</td>
<td>250</td>
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<tr>
<td>3:00 – 4:00</td>
<td>50</td>
<td>100</td>
<td>20</td>
<td>10</td>
<td>150</td>
<td>330</td>
</tr>
<tr>
<td>4:00 – 5:00</td>
<td>50</td>
<td>200</td>
<td>20</td>
<td>10</td>
<td>150</td>
<td>430</td>
</tr>
<tr>
<td>5:00 – 6:00</td>
<td>100</td>
<td>400</td>
<td>20</td>
<td>10</td>
<td>200</td>
<td>730</td>
</tr>
<tr>
<td>6:00 – 7:00</td>
<td>150</td>
<td>600</td>
<td>50</td>
<td>10</td>
<td>200</td>
<td>1010</td>
</tr>
<tr>
<td>7:00 – 8:00</td>
<td>200</td>
<td>700</td>
<td>60</td>
<td>10</td>
<td>480</td>
<td>1450</td>
</tr>
<tr>
<td>8:00 – 9:00</td>
<td>200</td>
<td>700</td>
<td>80</td>
<td>10</td>
<td>480</td>
<td>1470</td>
</tr>
<tr>
<td>9:00 – 10:00</td>
<td>320</td>
<td>700</td>
<td>100</td>
<td>10</td>
<td>480</td>
<td>1610</td>
</tr>
<tr>
<td>10:00 – 11:00</td>
<td>320</td>
<td>700</td>
<td>170</td>
<td>10</td>
<td>400</td>
<td>1600</td>
</tr>
<tr>
<td>11:00 – 12:00</td>
<td>320</td>
<td>700</td>
<td>170</td>
<td>10</td>
<td>400</td>
<td>1600</td>
</tr>
<tr>
<td>12:00 – 13:00</td>
<td>320</td>
<td>700</td>
<td>170</td>
<td>10</td>
<td>300</td>
<td>1500</td>
</tr>
<tr>
<td>13:00 – 14:00</td>
<td>320</td>
<td>700</td>
<td>170</td>
<td>10</td>
<td>200</td>
<td>1400</td>
</tr>
<tr>
<td>14:00 – 15:00</td>
<td>320</td>
<td>700</td>
<td>170</td>
<td>10</td>
<td>200</td>
<td>1400</td>
</tr>
<tr>
<td>15:00 – 16:00</td>
<td>320</td>
<td>700</td>
<td>170</td>
<td>20</td>
<td>300</td>
<td>1510</td>
</tr>
<tr>
<td>16:00 – 17:00</td>
<td>320</td>
<td>700</td>
<td>170</td>
<td>40</td>
<td>400</td>
<td>1630</td>
</tr>
<tr>
<td>17:00 – 18:00</td>
<td>320</td>
<td>700</td>
<td>170</td>
<td>60</td>
<td>400</td>
<td>1650</td>
</tr>
<tr>
<td>18:00 – 19:00</td>
<td>200</td>
<td>700</td>
<td>170</td>
<td>80</td>
<td>480</td>
<td>1630</td>
</tr>
</tbody>
</table>
Table 17: Traffic volume generation consideration per hour - Weekdays

Weekends: Table 18 illustrates an hourly traffic profile during the weekdays for five METIS test cases [8]. The virtual reality office (TC1) is absent in the table as it is assumed that offices don’t function in the weekends. But, for the dense urban information society (TC2), the peak hours are assumed to be 07:00 until 22:00 as it concerns with both outdoor and indoor data traffic for all types of buildings and the traffic profile is assumed similar for the weekends as well. For the shopping mall (TC3) the peak hours are assumed from 10:00 until 22:00 similar to weekdays. In case of a stadium (TC4), the peak hours are considered only from 19:00 to 0:00 (assuming stadium hosts games only during these hours), similar to weekdays. The traffic jam (TC6) is assumed to occur during the peak rush hours not in the morning 07:00 – 18:00. Finally, an open air festival (TC9) is assumed to occur in the weekends between 18:00 – 23:00 in the evening which was not present in the weekdays as it is assumed that open air festivals occur only in the weekends.
<table>
<thead>
<tr>
<th>Time</th>
<th>Volume</th>
<th>Rate</th>
<th>Capacity</th>
<th>Traffic</th>
<th>Load</th>
<th>Traffic Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>22:00 – 23:00</td>
<td>600</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>900</td>
<td>1800</td>
</tr>
<tr>
<td>23:00 – 0:00</td>
<td>400</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>800</td>
<td>1450</td>
</tr>
</tbody>
</table>

Table 18: Traffic volume generation consideration per hour - Weekends