Photon Netw Commun (2015) 30:403–415
DOI 10.1007/s11107-015-0553-8

On the design of 5G transport networks

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Received: 14 May 2015 / Accepted: 7 August 2015 / Published online: 29 August 2015

Abstract Future 5G systems will pave the way to a completely new societal paradigm where access to information will be available anywhere, anytime, and to anyone or anything. Most of the ongoing research and debate around 5G systems are focusing on the radio network segment (e.g., how to offer high peak-rates per subscriber, and how to handle a very large number of simultaneously connected devices without compromising on coverage, outage probability, and latency). On the other hand, understanding the impact that 5G systems will have on the transport network (i.e., the segment in charge of the backhaul of radio base stations and/or the fronthaul of remote radio units) is also very important. This paper provides an analysis of the key architectural challenges for the design of a flexible 5G transport infrastructure able to adapt in a cost-efficient way to the plethora of requirements coming from the large number of envisioned future 5G services.

The work described in this paper was carried out with the support of the Kista 5G Transport Lab (K5) project funded by VINNOVA and Ericsson.

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Keywords 5G transport · Backhaul · Fronthaul · Network sharing · Network function virtualization (NFV) · Flexible transport

1 Introduction

The fifth generation of mobile networks (5G) is seen as one of the enablers of what is referred to as the networked society [1], i.e., a future with user- and machine-centric communications where access to information and sharing of data is available anywhere and anytime to anyone and anything.

Even though the details of 5G are still the subject of ongoing research and debate, it is already clear that a future 5G system will need to offer not only high peak-rates per subscriber, but it will also be required to handle a large number of simultaneously connected devices, to provide better coverage, to offer highly reliable communications and low latency. Finally, the above objectives must be met at similar cost and energy consumption levels as today's networks [2,3]. As a result, it becomes evident that the 5G vision requires the definition of a new generation of mobile access systems that goes beyond the mere upgrade of the existing ones, i.e., 3G and 4G.

Most of the ongoing research efforts on 5G mobile networks target the radio technologies that will be part of 5G [4,5]. For example, 5G will include new and flexible spectrum resources (e.g., sub-6.5 GHz, mm-wave radio access technologies RAT), multi-antenna technologies with beam forming and massive multiple-input multiple-output (M-MIMO), as well as inter-site coordination for higher spectral efficiency. Increased capacity and coverage will also be achieved through continued radio site densification (e.g., through small cells).

Considering that a 5G system may also include different deployment architectures (e.g., integrated radio base station, centralized baseband, radio-over-copper solutions), it becomes also important to assess how 5G will impact the transport infrastructure. However, as of today not much is known about these implications. On the other hand, it is expected that with site densification as well as with larger numbers and variegated services to be provisioned, the role of the transport network, i.e., backhaul of radio base stations or fronthaul of remote radio units, will become more and more crucial [6].

The aim of this paper is to discuss the key challenges in designing a transport network for the future 5G mobile systems. First, the paper provides an in-depth overview of the set of services (and respective requirements) that a 5G transport network is expected to accommodate. This overview is then the basis to present a number of candidate transport architectures categorized according to the type of transport segment they belong to (e.g., small cell transport vs. metro/aggregation networks). The paper continues discussing a few transport design options, focusing mainly on how to accommodate high traffic volumes over specific geographical areas while providing transport resources in a flexible manner. Finally, two case studies are presented. Their purpose is to show how some of the key design concepts presented in the paper can be applied to deploy a transport infrastructure able to guarantee the required level of quality of experience of the various services to be provisioned at the lowest possible deployment and operational costs.

2 Related works

Initiatives related to 5G are already underway both in research projects and 5G-related consortia, mainly focused on the definition of new radio technologies. However, the transport part of the 5G infrastructure will play a key role as well. With continued site densification and with larger numbers and variegated services to be provisioned, the role of the transport network, i.e., backhaul of radio base stations or fronthaul of remote radio units, will become more and more crucial.

The COnvergence of fixed and Mobile BrOadband access /aggregation networks (COMBO) project [7] proposes and investigates new integrated approaches for fixed-mobile converged (FMC) broadband access/aggregation networks for different scenarios (dense urban, urban, rural). COMBO architectures are based on joint optimization of fixed and mobile access/aggregation networks around the innovative concept of Next Generation Point of Presence (NG-POP). Within COMBO, a first resource orchestration across DWDM optical transport, radio access networks (RANs) and cloud domains based on SDN has been experimentally demonstrated [8].

The Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS) project [2], which ended in March 2015, had as an objective to lay the foundation of 5G. Most of the attention of the METIS project is dedicated to define future scenario and requirements for 5G.

The 5G Infrastructure PPP (5G-PPP) is a 1.4 Billion Euro joint initiative between the European ICT industry and the European Commission to rethink the infrastructure and to create the next generation of communication networks and services that will provide ubiquitous super-fast connectivity and seamless service delivery in all circumstances. 5G-PPP released recently a vision document [9] for 5G infrastructure that defines key drivers, 5G disruptive capabilities, design principles, key enabling technologies, and timeline.

The iJOIN project [10] addresses the issue that wireless access and backhaul are individually designed and therefore not optimized jointly. The approach is based on the concept of RAN-as-a-Service (RANaaS), where RAN functionality is centralized through an open IT platform based on a cloud infrastructure. The SOftware-Defined Access using Low-Energy Subsystems (SODALES) project [11] aimed at offering transparent transport services for fixed and mobile subscribers to support 10 Gbps fixed access and radio technologies over a converged network architecture. The transport solution is based on low-cost 10 Gbps customer premises equipments (CPE) for FTTH and fixed radio access.

Some recent works focus on specific aspect of the 5G transport infrastructure. In [12], for example, an overview of the issues and requirements of next-generation mobile fronthaul architectures is provided. In particular, it is stated that the utilization of Common Packet Radio Interface (CPRI) might jeopardize the savings expected from the C-RAN architecture. Thus, possible ways of avoiding this are "the reduction in the digital fronthaul bandwidth requirements based on a modified RAN architecture (dual-site processing) or in quasi-analog optical transmission schemes for certain use cases."

3 Service requirements for 5G networks

5G networks will be required to support both the evolution of current services as well as completely new services. These services will imply new requirements on the RAN and consequently new requirements on the RAN transport network (backhaul and fronthaul). We analyze the requirements on 5G networks according to three groups of services: (1) end-user broadband services, (2) machine-type communications (MTC), and (3) cloud services. They are described in the following subsections.

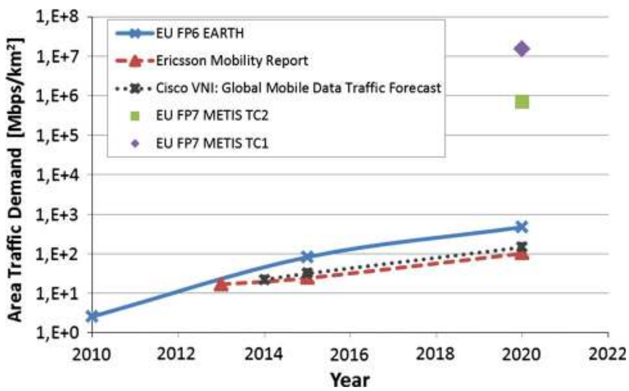

Fig. 1 Comparison among different mobile traffic forecasts. For the Ericsson Mobility Report and Cisco VNI, the area traffic demand was calculated from the average monthly generated traffic using the model presented in [13]

3.1 End-user broadband services

5G end-user broadband services represent an evolution of current broadband services. They are mainly driven by the continued request for an enhanced user experience (e.g., 8K television and 3D video conferencing) and they pose a challenge in terms of very high aggregated capacity to the transport network. End-user broadband services can be provided through either fixed or mobile access. 5G transport networks will be required to support both, realizing the so-called fixed-mobile convergence (FMC). In the following, we analyze separately mobile and fixed access traffic requirements.

Mobile access services The traffic in mobile access networks has been increasing exponentially over the last years, a trend that it is not expected to change in the near future. Traffic forecasts for mobile access are usually based on modeling end-user broadband services. According to the traffic forecast model presented in the EU FP6 project EARTH [13], the area traffic demand is expected to increase 100-fold in the decade between 2010 and 2020 reaching 474 Mbps/km^2 average at busy hours in dense urban areas. This prediction is in line with the latest estimates provided by the Ericsson Mobility Report [14] and the Cisco Visual Networking Index (VNI) [15]. A comparison among the different traffic forecast models is presented in Fig. 1. It is worth noting that the Ericsson Mobility and Cisco curves were derived from the values of the average monthly traffic per mobile terminal [14, 15] using the analytical formulation presented in [13].

More aggressive traffic scenarios have also been recently proposed and investigated [3, 16], e.g., the 5G test cases identified in the EU FP7 project METIS [3]. A driver for more aggressive traffic densities in the mobile access could be a possible replacement of the fixed access. METIS defines 5G in terms of five fundamental scenarios which the next-generation wireless access networks will have to support. Future applications may be associated with one or several of these scenarios imposing different challenges to the network. METIS also defines twelve specific test cases that are mapped onto the five scenarios. These test cases are used to sample the space of future applications. There are two test cases that are particularly challenging in terms of traffic requirements. The first one, called *dense urban information society* (i.e., METIS TC2), envisions a dense urban scenario where humans interact with the cloud (i.e., any type of content remotely stored) and the surrounding environment (e.g., sensors, video cameras) via high-capacity connections. As a result, the traffic requirements for this test case are in the order of 700 Gbps/km^2 (i.e., 1000 times higher than the traffic forecasted for 2020 by EARTH, Fig. 1). The other test case, called *virtual reality office* (i.e., METIS TC1), refers to the possibility to have high-resolution 3D tele-presence and virtual reality in indoor offices to remotely interact with colleagues. As a result, this test case drives the traffic requirements up to 15 Tbps/km^2 [3, 16], almost 100 times higher than TC2.

Fixed access services The fixed access traffic is also increasing, even if at a lower rate compared to its mobile counterpart. Fixed access services can be categorized in residential and business. According to the traffic forecast model presented in the EU FP7 project OASE [17], the residential traffic is expected to increase tenfold in the current decade and reach average values at busy hours of 16 Mbps per household. On the other hand, peak residential traffic is expected to increase at higher rate and reach 1 Gbps per household by the year 2020. Similar trends are forecasted for the business traffic, i.e., a tenfold increase in the current decade reaching average and peak values per business of 200 Mbps and 10 Gbps, respectively. In addition, business traffic introduces also strict availability requirements on the transport network, i.e., 99.99 % or higher.

3.2 Machine-type communications

MTC applications are expected to play an important role in the design of 5G transport networks. They introduce potentially new challenges which might go beyond the pure connectivity. Due to the large number of possible scenarios and use cases for MTC, it is difficult, if not impossible, to define a single set of requirements. In the following, we present a few examples coming from a selected number of use cases.

In MTC, devices interact among themselves without human intervention [18]. MTC applications can be broadly categorized as massive and mission critical [18]. Massive MTC applications are provided through the extensive deployment of connected devices (e.g., sensors and actuators), which perform a large number of different tasks (e.g., monitoring and surveillance). Each of these devices is expected to generate a relatively small amount of data. The large number of connected machines will create a challenge for the wireless network, due to the large overhead generated by the control information. On the other hand, massive MTC will most probably not affect significantly the transport network. This is due to the fact that the traffic generated by a large number of devices over a geographical area will be aggregated in the transport.

Mission critical MTC applications are used to perform specific tasks in an automated manner (e.g., industrial processes). Some mission critical MTC applications are expected to create major impact on transport networks due to the high availability and strict latency requirements. Different applications introduce different levels of challenges. An example of mission critical MTC application is traffic safety control. Cooperative active safety systems can warn drivers of dangerous situations and intervene through automatic braking or steering if the driver is unable to avoid an accident. The main requirement deriving from this MTC application is related to the latency that should be as small as possible to minimize the risk of accidents and damages to people. For instance, in case of automated braking, the maximum network reaction time should be lower than 10 ms [19] to minimize the risk of collisions.

3.3 Cloud services

Businesses and consumers are increasingly relying on cloud-based services. This is proven by the fact that the cloud traffic is increasing at a compound annual growth rate (CAGR) of 32 %, i.e., much faster than any other type of traffic [20]. Cloud services are very heterogeneous in nature and may impose a large number of different requirements on the transport network. As a consequence, 5G transport networks must be adapted in a flexible way (i.e., in terms of capacity and latency, etc.) in order to effectively support a large set of different requirements.

An example of a cloud application that has a severe impact on the transport network is cloud gaming. In this application, the entire game is hosted on a server in a data center while the user runs only a simple client transmitting game controller actions upstream to the game server. One single cloud gamer may require a guaranteed streaming bit-rate of up to 15 Mbps and round-trip delays (including processing in the data center) lower than 100 ms [21]. If we now consider that we can have several of them playing simultaneously on the same transport network segment, it is easy to understand how they can severely impact both the transport network and the data center performance. An even more extreme example is high-frequency trading (HFT) [22]. HFT is the trading of financial assets based on computerized strategies with brief holding time and high volume. At the heart of such a trading algorithm would be the computation of short-term stock correlation in real time. HFT introduces very strict requirements in terms of transport delay, since the lower the network delay the higher the potential revenues for the investors. In order for HFT to be effective, delays should be in the order of few hundreds of μs. This translates also in requirements on the bit-rate, which should be as high as possible in order to reduce the serialization delays (i.e., order of several hundreds of Mbps for the trader) [22].

4 RAN transport services

The service requirements described above trigger an evolution of both the RAN transport architecture and services. The latter includes the evolution of current LTE fronthaul [i.e., centralized RAN (C-RAN)] and backhaul functionalities as well as new service instances driven by the upcoming 5G radio technologies. LTE fronthaul and backhaul services are expected to evolve to support the increased amount of traffic generated per LTE base station (i.e., eNodeB). On the other hand, innovative 5G radio access technologies will drive new requirements for 5G transport networks. We identified three specific examples which are expected to impact the transport network design: (1) ultra-densification, (2) advanced radio coordination, and (3) massive multiple-input multiple-output (M-MIMO).

LTE backhaul services LTE radio interfaces are continuously evolving to more advanced configurations for supporting the increasing mobile traffic requirements. As a consequence, the backhaul traffic generated by an LTE base station also grows. In order to dimension the LTE backhaul network, the following general rule applies [23]. Given a number of sectors N (from one or more base stations), the backhaul capacity is given by the maximum between the peak bit-rate for a single sector and N times the busy hour average bit-rate. It is worth noting that the peak bit-rate for a single sector is generated when a single user-equipment (UE) is connected in close proximity of the base station, so that it experiences ideal channel conditions and obtains the highest possible transmission rate [23]. The peak bit-rate of a sector depends on the radio access network configuration (i.e., channel bandwidth, MIMO, etc.) as well as the UE category of the UE served by the sector [24]. It is worth noting that the average bit-rate per sector at busy hours of a small cell is usually higher than the one of a macro-cell [25]. The reason is twofold. First, small cells are usually deployed to cover a “hot spot,” thus they are more likely to have higher concentration of users toward the cell center and away from the edge, which improves the signal quality distribution. Second, small cells are likely to have better inter-cell isolation,

Table 1 Expected backhaul capacity requirements for a LTE base station

Base station	Downlink (Mbps)	Uplink (Mbps)
Macro (3 sectors)	228	126
Micro (1 sector)	90	50
Indoor (1 sector)	132	116

We consider the LTE configuration with highest possible spectral efficiency

Table 2 CPRI transport capacity for different radio configurations using a single 20 MHz carrier

Sectors	MIMO	CPRI bitrate
1	1	1.228 Gbps (option 2)
1	2	2.457 Gbps (option 3)
1	4	4.915 Gbps (option 5)
1	8	9.830 Gbps (option 7)
3	4	12.165 Gbps (option 9)

reducing interference and improving the signal quality distribution.

Table 1 shows the expected backhaul capacity for three LTE base station types calculated according to the dimensioning guidelines just described. We considered macro-cells, micro-cells, and indoor small cells. We assumed radio configurations with the highest possible spectral efficiency available for LTE [24] and we considered 20 MHz of channel bandwidth. In addition, we considered that macro-cells are equipped with three sectors, while micro- and indoor cells are omnidirectional (one sector) and we excluded the transport overhead.

Centralized RAN Centralized radio access network (C-RAN) is a relatively new architectural concept aimed at reducing the cost and at providing a better management of mobile networks [26]. Differently from conventional RANs, where radio units and the baseband unit (BBU) are colocated at the base station site, in a C-RAN architecture BBUs are decoupled from the base stations and centralized in a central office (CO) or in a BBU hotel. Radio units [also referred to as remote radio head (RRH)] are connected to BBU hotels via a fronthaul network using radio-over-fiber (RoF) transmission technologies. RoF transmission can be digital or analog. The main standards for Digital RoF (D-RoF) are the Common Public Radio Interface (CPRI) [27] and the Open Base Station Architecture Initiative (OBSAI) [28], while there is an ongoing work in IEEE 1904.3 to define a radio over Ethernet solution [29]. On the other hand, analog RoF (A-RoF) [30] solutions have not been standardized yet. RoF transmission poses strict latency and high-capacity constraints on the transport network. In the following, we will use CPRI fronthaul as an example to describe these constraints.

The constraint on the latency for the transmission between a RRH and a BBU comes from the LTE physical layer hybrid automated repeat request process [31] which requires a maximum round-trip delay of 3 ms, including both transport and BBU processing time. As a consequence, the higher the transport delay the lower the available time for BBU processing. A good practice is to limit the RoF transmission delay to around 100 µs, which in turn means that the maximum distance between a RRH and a BBU is limited to around 20 km.

The CPRI bit-rate can be calculated as a function of the radio configuration and the analog-to-digital conversion (ADC) resolution according to the following formula [27]:

$$B_{\mathrm{CPRI}} = N_S \cdot N_{\mathrm{Ant}} \cdot R_S \cdot 2N_{\mathrm{Res}} \cdot O_{\mathrm{CW}} \cdot O_{\mathrm{LC}}, \quad (1)$$

where N_S is the number of sectors, and N_{Ant} is the number of MIMO elements per sector. In addition, R_S is the sampling rate (typically 30.72 MHz for a single 20 MHz carrier) and N_{Res} is the number of bits per sample (typically 15 bits per sample). Finally, O_{CW} represents the overhead introduced by CPRI control words (typically one control word for 15 words of payload) and O_{LC} represents the line coding overhead (typically 10/8 or 66/64 Byte). Table 2 shows a few values of the transport capacity required by CPRI as a function of radio configuration using O_{LC} =10/8 Byte.

Ultra-densification Ultra-densification aims at increasing the radio network capacity via the dense deployment of low-cost and low-power small cells (indoor and/or outdoor) [32]. The small cells layer is added on top of the conventional macro-base station layer, which serves mainly for coverage purposes. As a result, the number of sites that need to be connected to the transport infrastructure becomes very high increasing substantially the complexity (mostly in terms of cost and power consumption) of the transport network. This will drive the need for more cost- and energy-efficient transport solutions [33,34].

Advanced radio coordination Advanced radio coordination solutions, such as coordinated multipoint (CoMP) and enhanced inter-cell interference coordination (eICIC), aim at improving the spectral efficiency in the radio network and in particular at the cell edges [35]. Different coordination levels (i.e., moderate, tight, and very tight) pose different constraints on the transport network. Moderate coordination techniques (e.g., eICIC) have no specific requirement in terms of transport performance. On the other hand, tight coordination techniques introduce strict latency constraints (i.e., between 1 and 10 ms), while they do not introduce very strict capacity constraints (i.e., lower than 20 Mbps). Finally, very tight coordination techniques introduce very demand-

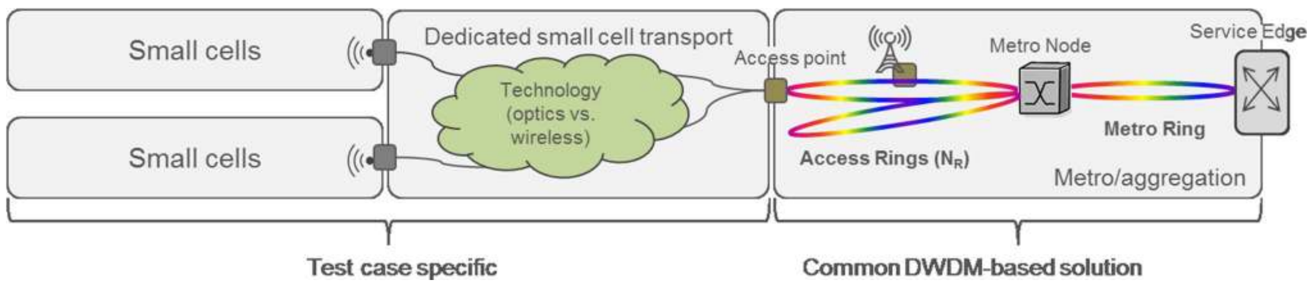

Fig. 2 Reference transport network architecture

ing constraints in terms of both latency (lower than 0.5 ms) and capacity (in the range of several Gbps using CPRI).

Massive MIMO The idea behind M-MIMO is to provide base stations with large spatial multiplexing gains and beamforming capabilities thanks to hundreds of antenna elements [36]. M-MIMO techniques allow for a better spectral efficiency and for smoothed channel responses thanks to the vast spatial diversity they can provide. As a result M-MIMO base stations are able to provide significantly higher data-rates to end-users. From the transport perspective, this translates in higher capacity that needs to be provided at each base station, i.e., M-MIMO drives for transport networks able to support very high transmission capacities. The required capacity per M-MIMO base station using backhaul services is in the range of several Gbps. On the other hand, the required capacity using CPRI fronthaul services is in the range of hundreds of Gbps or even a few Tbps depending on the specific radio configuration [see formula (1)]. This raises doubts about the feasibility of CPRI fronthaul for serving M-MIMO base stations.

5 Candidate transport network architectures

This section provides an overview of candidate technologies and architectures for 5G transport networks. One aspect of 5G transport is providing higher capacity to more densely deployed macro-sites. Another aspect is providing connectivity to a large number of small cells. There are different avenues along which the transport architecture could evolve. One scenario is the existence of a dominant/preexisting deployment of fixed access (DSL, PON, etc) that could be reused for connecting small cells and possibly new macro-sites. Such reuse could occur on an infrastructure level, reusing the installed base of copper/fiber or on a system level where fixed access systems provide packet backhaul to new cells. In this case, the existing fixed access infrastructure could reduce costs for connecting new cells, but it will also restrict the RAN deployment options depending on the structure of the existing infrastructure, e.g., limiting the possible degree of RAN centralization and coordination. Another scenario is a dedicated infrastructure (separate from the fixed access) to cater for the densification of macro- and small cells. Such a deployment could involve a large degree of wireless backhaul or it could be driven by RAN transport requirements that cannot be fulfilled by the fixed access infrastructure. This scenario would also be relevant for more aggressive scenarios where mobile access is the dominant access technology. In this work, we divide the transport network in two segments, i.e., *small cell transport* and *metro/aggregation* (Fig. 2). The small cell transport segment aggregates the traffic to/from the wireless small cells toward the metro/aggregation segment. The main challenge in deploying a transport segment for small cell lies in having to reach a large number of geographically disperse cell sites. These sites could be indoor (e.g., offices and/or residential premises) and might be difficult to be reached in an economically feasible way. For this reason, cost-efficient deployments are necessary. The metro/aggregation segment, on the other hand, connects different site types (i.e., macro, small cells, and/or fixed access points) among themselves and to the core network via the service edge (i.e., the node(s) used for interconnecting different network domains). Metro/aggregation networks are characterized by high-capacity requirements and thus high-speed transmission and switching technologies are required in this network segment.

5.1 Small cells transport

The best small cells transport network technology depends on the specific deployment scenario. The main technology options can be categorized as copper-, wireless- and fiber-based [33,34]. Recent copper-based technologies (such as G. fast [37]) are able to offer rates in the order of few Gbps over relatively short distances (i.e., few hundreds of meters). They represent an optimal solution for backhauling indoor LTE small cells in areas where there is an already installed copper infrastructure that can be reused (e.g., in order to save costs). In principle, advanced copper-based technologies could also be used for fronthaul (e.g., CPRI or analog radio over copper [30], but only for low bit-rate options (e.g., option 2 in Table 2) and given that the BBUs are located maximum few hundreds meters away from the RRHs.

Wireless-based solutions are an attractive option in locations where deploying a wired transport infrastructure is difficult (e.g., due to geographical conditions) or uneconomical. Advanced wireless-based technologies, i.e., millimeter wave (mmw) [38] and free space optics (FSO) [39], achieve very high transmission capacities (up to several Gbps) over short and medium distances (i.e., up to few km). As a result, they can be used both for backhauling LTE base stations and for fronthauling RRHs (when the maximum distance between RRHs and BBUs is limited to few km).

Fiber-based transmission technologies are able to provide very high data-rates (i.e., up to hundreds of Gbps) over long distances (i.e., tens of km or more). This is the reason why fiber-based solutions are seen as a good and long-term candidate for small cells transport. In particular, next-generation passive optical networks (PON) [40] technologies [such as ultra-dense wavelength division multiplexing PON (UD-WDM-PON) and time wavelength division multiplexing PON (TWDM-PON)] are particularly attractive due to their reduced energy consumption and potentially lower costs compared to active optical networks (AON). For a more detailed comparison of different optical and wireless technology options for small cells transport, the reader is referred to [6].

5.2 Metro/aggregation network

A promising candidate for the metro/aggregation segment is represented by dense wavelength division multiplexing (DWDM) networks [41,42]. An example of DWDM metro network based on optical DWDM rings is shown on the right-hand side of Fig. 2. In this network, several optical DWDM access rings (N_R) collect the traffic from a large number of access points (i.e., macro-base stations plus small cells and fixed access points) and transmit it to the metro node. The metro node aggregates the traffic from the various access rings and forwards it to the metro ring and the service edge. The access points as well as the service edge have electronic packet aggregation functionalities to allow for the multiplexing of low rate traffic. On the other hand, for the metro node a number of different possible architectures can be used, as described next.

Optical metro node With this solution, switching at the metro node is done completely in the optical domain thanks to active optical elements such as wavelength-selective switches (WSSs) and reconfigurable optical add–drop multiplexers (ROADMs). This solution is referred to as DWDM-centric[42]. An advantage of this approach is that the architecture of the metro node is simple and can potentially reduce the cost and the energy consumption levels as well as allow for an easy maintenance. On the other hand, since the traffic in the access rings cannot be statistically multiplexed in the direction toward the metro ring, this solution might require several fibers in the metro ring.

Electronic metro node In this solution, packet aggregation is employed in the metro node to statistically multiplex the traffic toward the metro ring, e.g., by using a high-capacity Ethernet packet switch. Electronic packet aggregation allows for electronic traffic grooming, i.e., a large number of wavelength channels in the access rings can be multiplexed over a lower number of higher capacity channels in the metro ring. As a consequence, this solution might reduce the number of fibers required in the metro ring compared to the solution based on optical switching at the metro node. However, an electronic packet switch might consume more power in addition to having high deployment and maintenance costs.

Micro-data center In this last approach, the electronic metro node not only performs packet aggregation, but it is also directly connected to a micro-data center that allows for advanced processing and storing functionalities inside the transport network. For example, cache servers can be placed in the micro-data center to provide video delivery services to the end-users. In this way, part of the traffic is terminated locally at the metro node and is not transmitted toward the service edge, i.e., offloading the metro ring. This solution may potentially reduce the number of fibers required in the metro ring (i.e., with respect to electronic aggregation-only solution) and it also provides better quality of experience (QoE) levels for the end-users. On the other hand, the extra IT equipment installed at the metro node increases both costs and energy consumption.

6 Flexible transport networks

In this section, we discuss the pros and cons of a number of design strategies for 5G transport networks. There are two different approaches that can be used while deciding where to deploy resources in a transport infrastructure. The first one is based on the *overprovisioning* concept, i.e., dimensioning for the worst-case traffic scenario (i.e., peak traffic). This is the approach mobile operators have been mainly using so far. Its main advantage is the relatively low complexity since no dynamic control of transport resources is required. With overprovisioning the 5G transport, capacity constraints are satisfied thanks to the ubiquitous availability of transport resources. However, this solution comes with high cost in terms of equipment and suffers from an inefficient use of transport resources.

The second design approach allocates transport resources on-demand to support specific transport needs, that may vary over time. This can be achieved using advanced network functionalities, such as *dynamic resource sharing* and *network function virtualization (NFV)* [43]. Dynamic resource sharing is based on the intuition that the same transport resource can be dynamically shared over time for different transport purposes. The type of resources and how they can be shared depend on the specific transport service, the deployment scenario, the radio deployment architecture, and on the choice of transport technology. Examples of transport resources that can be dynamically shared are: optical fibers (e.g., using dynamic wavelength allocation), wavelength channels (e.g., using time-division multiplexing), and spectrum (e.g., using time, frequency, or code division multiple access).

NFV provides flexibility by dynamically placing network functions in different locations depending on the specific need of a service, e.g., close to the users to exploit traffic locality. Dynamically pushing network functions closer to the users enables to serve requests locally and to offload the central part of the network infrastructure, thus reducing the risk of congestions. In addition, NFV allows for reduced end-to-end service delays, fulfilling the extreme latency requirements imposed by some critical MTC applications. The network functions that can be dynamically virtualized can be categorized in: (1) radio network functions, (2) transport functions, and (3) IT functions. Radio network functions may include, for instance, the virtualization of the Evolved Packet Core (EPC) functionalities for local breakout [approach referred to as Virtual EPC (vEPC [44])]. The vEPC will be an important feature in 5G transport as it enables to terminate the mobile traffic, and to serve mobile service requests locally. Transport functions may include the virtualization of packet aggregation, while IT functions may include the virtualization of computing and storing functionalities, e.g., network caching. On the other hand, NFV requires the availability of an IT infrastructure, e.g., micro-data centers, located within the transport network. One important aspect to consider for NFV is also the business model in place in a specific transport network instance. If the transport- and the wireless-service providers are two separate entities, then the type of network functions that can be virtualized depends on the specific agreements between these two entities.

The use of dynamic resource sharing and NFV means also moving some of the complexity from the data plane to the control plane. There are several options for realizing a control plane able to support dynamic resource sharing and NFV. On the other hand, the best performance can be achieved by a control architecture able to jointly orchestrate transport, radio, and IT resources. The implementation of such an advanced control plane is an extremely challenging task. One possible option for realizing this integrated multi-domain and multi-technology control architecture is software-defined networking (SDN). In [8], a proof of concept of an SDN-based control plane for joint orchestration of radio and transport resources has been presented, while further demonstrations are currently a major research focus.

7 Case studies

This section presents two case studies aimed at evaluating the impact on the transport performance of some of the concepts introduced in the paper so far. In the first case study, we analyze the cost and energy consumption levels of different architectural options for the metro node (i.e., optical metro node, electronic metro node or micro-data center) in a DWDM transport network. In the second case study, we evaluate the potential benefits of using advanced network functionalities against a pure overprovisioning-based design approach.

7.1 Case study 1: impact of metro node design

In this case study, we consider a dense urban scenario with mobile and fixed users. The mobile traffic requirements are the ones defined in METIS TC2 [3] (see Fig. 1). We assume that mobile traffic is served using an ultra-dense heterogeneous radio network composed of indoor small, micro-, and macro-base stations. The traffic generated per base station type is defined in Table 1. The area under consideration is 2 km^2. The traffic from the wireless base stations is collected at the access points (APs) of the DWDM network (see Fig. 3). The macro-base stations are directly connected to the APs, while the small base stations (i.e., indoor small and micro-base stations) are connected to the APs via dedicated small cells transport networks. The specific architecture of the small cells transport networks is outside the scope of this study. In the metro network, four access rings with 15 APs each (the area in total has 60 APs) collect the traffic from all the wireless base stations and sends toward the metro node (MN). Moreover, the fixed users are served by residential and business access networks. The average traffic generated per household and per business location is derived from [17] (see Sect. 3). The traffic from the fixed access networks is aggregated directly at the MN of the DWDM network (see Fig. 3), so that it bypasses the access ring. The total number of wireless base stations and fixed access points as well as their traffic requirements for the considered scenario are reported in Table 3.

Three possible architectures can be considered for the metro node. The first architecture is based on an optical metro node [i.e., with wavelength-selective switches (WSS)] with wavelength channels operating at 10 Gbps in both the access and in the metro rings. The second architecture is based on an electronic metro node (i.e., an Ethernet packet switch) and wavelength channels operating at 10 Gbps in the access ring and at 100 Gbps in the metro ring. In this way, the traffic from the fixed access and the wireless base stations can be aggregated to a lower number of higher-rate channels. The third architecture is similar to the second one, but allows for the addition of a micro-data center in the MN that is used for

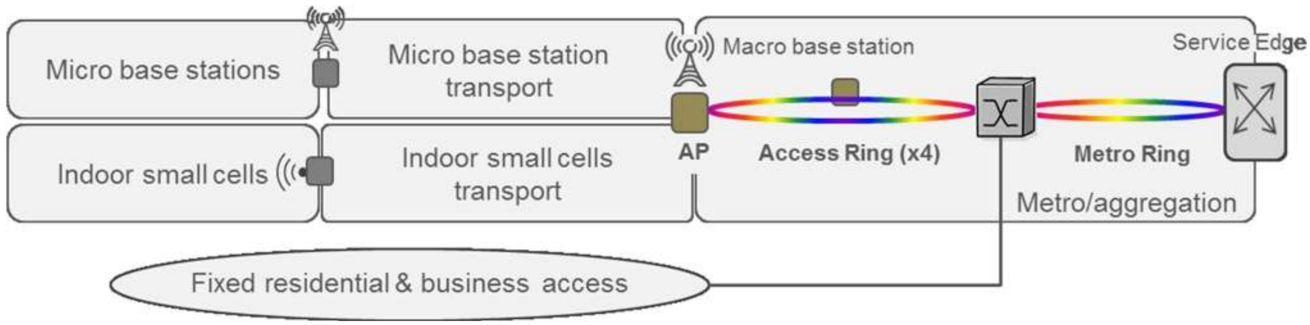

Fig. 3 Transport network architecture for case study 1

Table 3 Traffic requirements for case study 1 assuming an area of 2 km^2

Mobile	Tot.	× AP	Traffic × AP	Traffic × MN
Macro	60	1	0.23 Gbps	13.7 Gbps
Micro	600	10	0.90 Gbps	54.0 Gbps
Indoor	6000	100	13.20 Gbps	792.0 Gbps
Fixed	Tot.	× AP	Traffic × AP	Traffic × MN
Household	20,000	–	–	320 Gbps
Business	4000	–	–	808 Gbps

AP access point; *MN* metro node

video content delivery. The micro-data center is equipped with cache servers that provide local delivery of content-based traffic, i.e., in this specific case YouTube and Netflix video clips.

Figure 4 shows the power consumption, equipment cost, and number of wavelengths in the metro ring for the three different metro architectures. In order to calculate the power consumption and equipment cost, we employed the models and the input values presented in [45]. The equipment cost is expressed in Cost Unit (CU) where each CU corresponds to half the cost of a 10 Gbps Ethernet interface. In order to estimate the amount of traffic that can be served locally using the Youtube and Netflix cache servers, we used the same offloading traffic ratios as presented in [45]. It can be observed in Fig. 4 that having an optical MN is by far the most energy- and cost-efficient option (i.e., both energy consumption and equipment costs are 2–3 times lower than in the other architectures). This is due to the simplified architecture of the MN, which comprises only WSSs and requires substantially less power-consuming and costly network components compared to an electronic-based MN. The relatively high cost of the reconfigurable WSSs is compensated by avoiding the large number of expensive optical transponders and electronic packet switching elements required in the electronic MN. However, the architecture with optical MN requires a very large number of 10 Gbps wavelength channels in the metro ring (i.e., as high as 233). This high number of channels might not be supported using a single fiber, so that more fibers might be needed in the metro ring. As a result, in a fiber-scarce scenario a solution based on electronic switching is potentially a better option. In fact, using statistical multiplexing and 100 Gbps transponders in the metro ring, it is possible to reduce the number of wavelength channels required by a factor of 10. Among the solutions based on electronic packet switching, the one with micro-data center provides both slightly lower equipment cost and potentially higher user performance. The lower costs are due to the fact that, by allowing traffic locality, this solution requires a lower number of 100 Gbps channels in the metro ring (i.e., 16 vs. 20). Given the high costs of 100 Gbps interfaces, this reduction is sufficient to compensate for the extra cost of the cache servers. In addition, the local delivery of video content can potentially allow for a better QoE for the end-users. Unfortunately, due to the high power consumption of the cache servers, the solution based on micro-data center is the most energy-consuming.

7.2 Case study 2: benefits of deploying flexible transport networks

A virtual reality (VR) office [3] is a top-modern (virtual) office space where the work involves the interaction with high-resolution 3D scenes. The 3D video traffic drives the average traffic density per VR office to 0.1 Gbps/m^2 (assuming an average office size of 20 m^2 the traffic volume is 20 Gbps per VR office). On the other hand, the peak traffic volume density per VR office can be as high as 0.5 Gbps/m^2 (i.e., 100 Gbps per VR office). In terms of wireless deployment, the project METIS envisions an ultra-dense small cell network (UDN) solution [3]. The overall impact of this test case on the metro transport depends on how many VR offices an office building has. If we assume up to 50 VR offices, then we can expect an average aggregated backhaul traffic of 1 Tbps and a peak of 5 Tbps per building, respectively. In this scenario, it is reasonable to assume that each building is directly connected to an access point of the DWDM metro network (see Fig. 5), which in this case study is supposed to be equipped with wavelength channels operating at

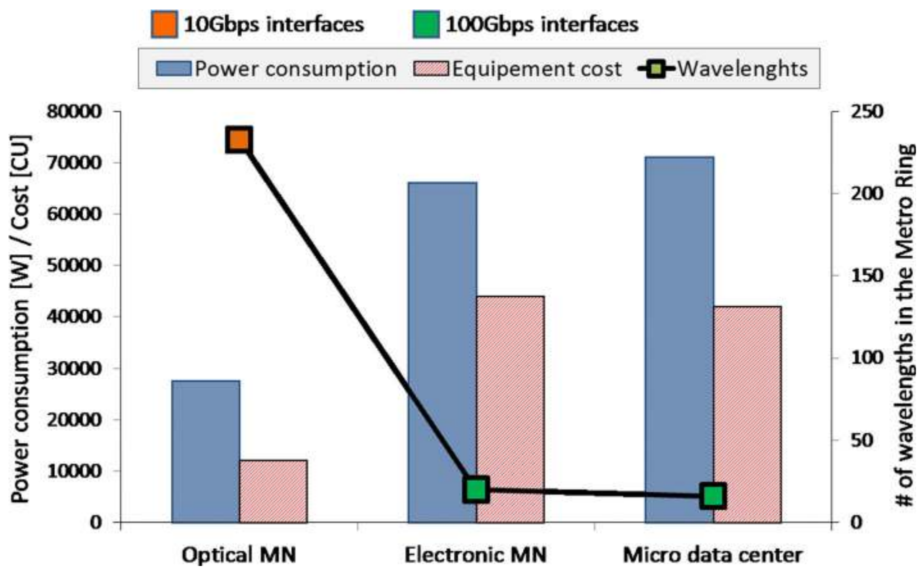

Fig. 4 Power consumption, equipment cost and number of wavelength channels required in case study 1 for different metro architectural options

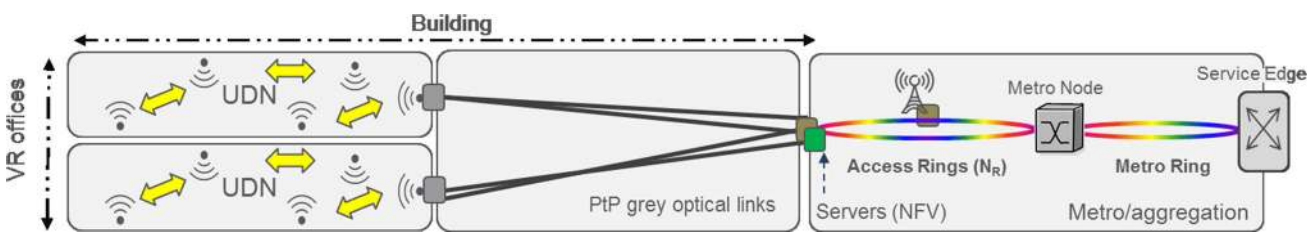

Fig. 5 Transport network architecture for case study 2

100 Gbps (both in the access and metro rings). Using a pure overprovisioning-based design approach, the metro network should be dimensioned for the peak traffic scenario, so that 50 wavelengths per building are required. As a consequence, in order to serve a metropolitan area with 100 office buildings a total of 5000 wavelength channels (i.e., 10,000 transponders operating at 100 Gbps) are required, leading to an enormous costs for the network operator. On the other hand, using a SDN control plane and an efficient dynamic wavelength allocation policy, it is possible to dimension the metro network for the average traffic scenario, so that the area can be served using 1000 wavelength channels. This reduces the number of required transponders to 6000 (it is worth noting that the number of transponders inside the buildings must always be calculated according to the worst-case scenario). As a consequence, using a flexible transport network design instead of overprovisioning the operator can reduce its equipment cost by 40 %. Additional benefits can also be achieved by placing IT resources servers at the access points or at internal nodes of the transport network (Fig. 5) and by exploiting NFV. The servers can be controlled by an SDN-based control plane, so that some network functions, such as caching of data files or processing of 3D video traffic, can be dynamically virtualized and pushed closer to the VR offices in order to save capacity inside the metro network. A possible policy could be to monitor the traffic generated in each office building and to activate the local servers when the traffic exceeds a certain threshold. In this way, the amount of traffic that needs to flow through the metro network can be reduced. In terms of the dedicated small cell transport network, optical solutions are the most suitable given the high capacity needed between the wireless UDN and the metro aggregation point (Fig. 5). Assuming that VR offices will be deployed in modern buildings equipped with an advanced fiber infrastructure, the use of gray point-to-point (PtP) optical links might be an effective technology option due to low-energy consumption and its relatively high maturity [6].

8 Conclusions

This paper discusses the efficient design of 5G transport networks. Firstly, the 5G transport services are identified and categorized in terms of broadband, RAN transport, MTC, and cloud services, respectively. For each category, the main requirements imposed on the transport network are defined. Then, several candidate technologies for 5G transport networks as well as three architectural options for optical DWDM metro networks (optical metro node, electronic metro node, and electronic metro node with micro-data center) are presented. In addition, two approaches for transport networks design are described. One is based on the overprovisioning of transport resources, while the second design approach is based on dynamic resource sharing and network function virtualization (NFV) in conjunction with a software-defined network (SDN)-based controller (referred to as flexible transport deployment). Finally, two case studies are presented to: (1) assess the cost and energy benefits of an all optical metro node solution and (2) present the potential savings brought by a flexible transport network deployments versus a pure overprovisioning-based design approach.

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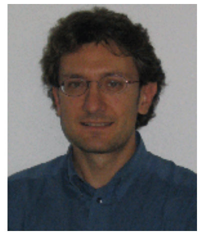

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