

Power and Cost Modeling for 5G Transport Networks

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ABSTRACT

Optical 5G transport networks are the subject of academic and industrial research aimed at identifying the best architectural and deployment options. In this regard, the optimization of both power consumption and equipment cost is a crucial aspect. This paper analyses a number of architectural options (i.e., all optical vs. intermediate electronic processing, with and without network caching) for optical 5G transport networks, with the objective of understanding which alternatives are the most promising in terms of total power consumption and equipment cost. The analysis presented in the paper shows that 10 Gbps transmission equipment combined with optical switching guarantees the best overall performance. On the other hand, 100 Gbps transmission equipment combined with electronic processing and network caching is also a promising approach, especially in fiber scarce scenarios.

Keywords: optical 5G transport, fronthaul, power modeling, cost modeling, electronic switching, optical switching, network caching.

1. INTRODUCTION

The *5th generation of mobile networks (5G)* is the next phase of mobile telecommunication. Thanks to a major redesign and rethinking of the mobile network interfaces and architectures, 5G is expected to enable a fully networked society (i.e., not only communication among humans but also interactions among (and with) inanimate objects) [1]. One important aspect to consider in the 5G paradigm is the *transport network* segment, which carries data traffic between radio base stations and the core part of the network. Transport networks must be able to deliver in a flexible and cost efficient way the connectivity needed to accommodate 5G services (i.e., part of which may now also be cloud-based), as well as to provide enough capacity to support the many-fold increase in data traffic [2]. While our research community is currently addressing the challenges posed by 5G on transport networks, a little work has been done so far on understanding the impact that power consumption and equipment cost have on transport network deployments.

In order to define suitable data plane architectures for 5G transport networks, this paper compares different technological and architectural options, ranging from solutions based on *transparent all-optical switching* to ones using *intermediate electronic processing*. Moreover, considering intermediate electronic processing, the paper also analyses the case where *caching* is placed at intermediate nodes to provide a better end-user experience, and to exploit *traffic locality*, i.e., utilizing network resources close to the end-user thus offloading the traffic (i.e., capacity) closer the core part of the network. The intuition behind our investigation is the following. As we move from a case with an all-optical solution to a case with intermediate electronic processing with caching, the complexity of the network increases (i.e., it results in a higher number of complex network components). At the same time, the amount of required fiber resources and optical channels in the network is reduced because of the possibility to have traffic aggregation in the electronic domain. This means that there is a clear performance trade-off between these different architectural options.

The study presented in the paper first considers three different deployments scenarios for optical 5G transport networks (i.e., based on the architectural options mentioned above) and then it evaluates their cost and power consumption performance. The capacity dimensioning for each option is done considering an estimation of the traffic requirements of 5G services in the short-term future (i.e., year 2020) in a dense urban scenario. Our analysis shows that an all-optical solution is the most promising in terms of power consumption and cost. However, intermediate electronic processing shows benefits over the all-optical solution in terms of a reduced amount of required fiber resources, thanks to statistical multiplexing and network caching. Hence, one may opt for this latter solution to save on precious fiber resources but at the expense of higher power consumption and cost levels. Moreover, it has been found that 10 Gbps equipment is effective both in terms of cost and power consumption, while with the increase in traffic levels expected for the near future, the most feasible solution would be to use a hybrid architectural option, with 10 Gbps equipment deployed in the access segment and 100 Gbps equipment installed in the metro segment of the transport network.

2. NETWORK ARCHITECTURE

The optical network architecture considered in this paper is based on the one proposed in [3] and relies on dense wavelength division multiplexing (DWDM) transmission technology. The network architecture can be classified

into *DWDM-centric* or *packet-centric* depending on whether DWDM or packet aggregation is used at intermediate nodes. However, both these network options employ packet aggregation at the edges of the network (i.e., at the access point, and at the service edge nodes). We assume that the transport network carries both mobile traffic and fixed access traffic, i.e., realizing fixed-mobile convergence scenario. In terms of mobile network deployment, we consider an ultra-dense wireless access network comprising macro, micro, and pico (i.e., indoor) Long-Term Evolution (LTE) base stations, which are able to provide the necessary capacity to support the traffic requirements of the envisioned 5G services. We propose three different network deployments for DWDM-centric and packet-centric networks, as shown in Fig. 1. They are described next.

In Deployment A (Fig. 1a) traffic is aggregated at the macro base station site in the access ring, i.e., the *access point (AP)*, and forwarded to the *metro node (MN)*. The MN aggregates the mobile traffic and the fixed traffic, i.e., from fixed residential and business customers, and delivers it to the *service edge (SE)*. The aggregation/switching at the MN is optical in the DWDM-centric network case while it is done electronically in the packet-centric one. Deployment B (Fig. 1b) is similar to Deployment A with the only difference that the indoor LTE mobile traffic from the pico base stations is aggregated together with the fixed traffic and it is carried by the fixed access infrastructure. Deployment C (Fig. 1c) is another alternative deployment in which all traffic (i.e., mobile and fixed) can be aggregated at the closest AP and forwarded to the MN.

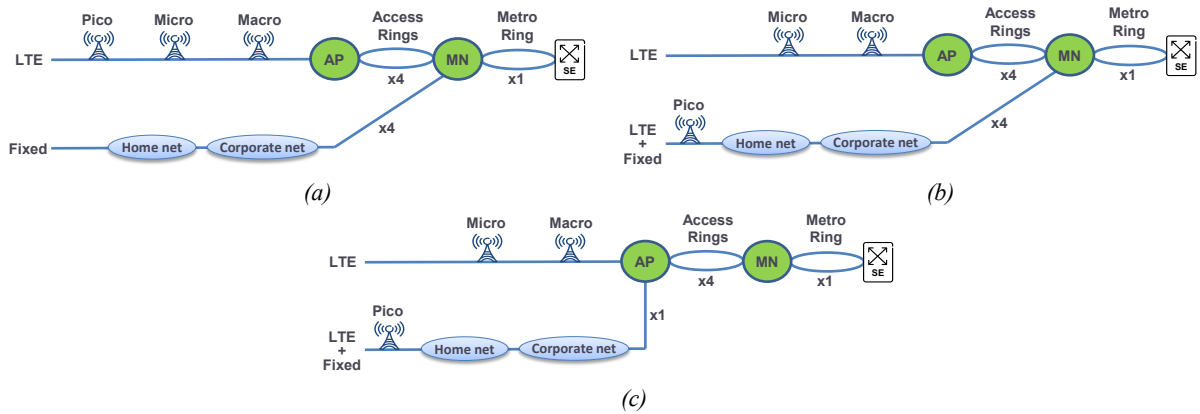


Figure 1. Network Deployment options: (a) Deployment A, (b) Deployment B, and (c) Deployment C.

3. POWER/COST MODELS

For packet-centric networks (Fig. 2a), the power and cost models are based on the assumption that power consumption and equipment cost increase linearly with the number of electronic ports required to perform switching at each AP, MN, and SE, as shown in Fig. 2a. For a particular scenario, the level of traffic demand determines how many ports are required at each node (i.e., AP, MN, and SE), thus making it possible to estimate the power/cost values of each network node. The total power consumption/equipment cost of the network is then the sum of the power/cost at all of the APs, MNs and SE, as explained next.

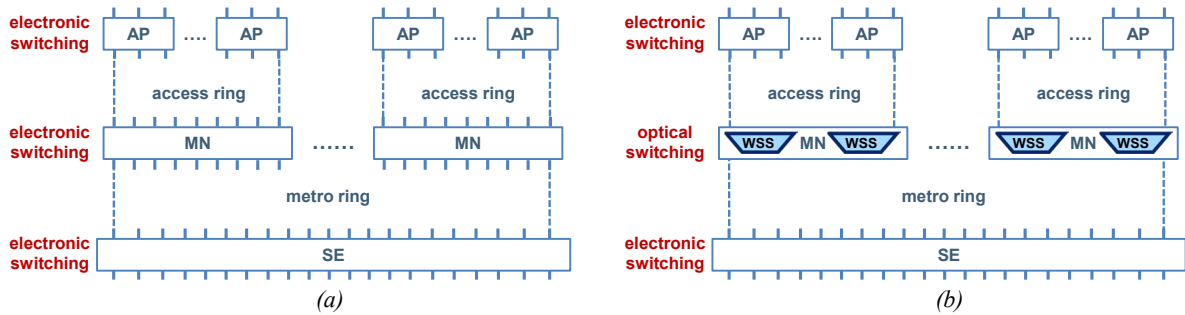


Figure 2. Power/Cost models with (a) electronic switching at MN (b) optical switching at MN.

$$P_{total} = (N_{in,AP}P_{AP} + N_{out,AP}P_{AP}) n_{AP} + (N_{in,MN}P_{MN} + N_{out,MN}P_{MN}) n_{MN} + (N_{in,SE}P_{SE} + N_{out,SE}P_{SE}) n_{SE} \quad (1)$$

and

$$C_{total} = (N_{in,AP}C_{AP} + N_{out,AP}C_{AP}) n_{AP} + (N_{in,MN}C_{MN} + N_{out,MN}C_{MN}) n_{MN} + (N_{in,SE}C_{SE} + N_{out,SE}C_{SE}) n_{SE} \quad (2)$$

The parameters used in equation (1) and (2) are described in Table 1.

For DWDM-centric networks (Fig. 2b), the MN employs optical switching instead of electronic switching. For such networks, it is not appropriate to model the MN as in the previous case. Hence, we propose a simple model for the MN with two 1×2 wavelength selective switches (WSS), which can interconnect one access ring to one metro ring. Moreover, another two WSSs are needed to interconnect the metro ring to the SE as well as

another two additional WSSs for each of the four links carrying the fixed traffic. The DWDM-centric architecture is depicted in Fig. 2b and its power and cost performance can be mathematically represented as:

$$P_{total} = (N_{in,AP}P_{AP} + N_{out,AP}P_{AP})n_{AP} + (N_{WSS,access}n_{access} + N_{WSS,metro}n_{metro} + N_{WSS,fixed}n_{fixed})P_{WSS} + \dots \quad (3)$$

$$(N_{in,SE}P_{SE} + N_{out,SE}P_{SE})n_{SE}$$

and

$$C_{total} = (N_{in,AP}C_{AP} + N_{out,AP}C_{AP})n_{AP} + (N_{WSS,access}n_{access} + N_{WSS,metro}n_{metro} + N_{WSS,fixed}n_{fixed})C_{WSS} + \dots \quad (4)$$

$$(N_{in,SE}C_{SE} + N_{out,SE}C_{SE})n_{SE}$$

The parameters used in equation (3) and (4) are described in Table 1.

Table 1. Description of symbols in equation (1), (2), (3) and (4).

Symbol	Description	Symbol	Description	Symbol	Description
P_{total} / C_{total}	Total power/cost of network	$N_{in,MN}$	No. of input ports per MN	n_{AP}	No. of APs
P_{AP} / C_{AP}	Power/cost per port of AP	$N_{out,MN}$	No. of output ports per MN	n_{MN}	No. of MNs
P_{MN} / C_{MN}	Power/cost per port of MN	$N_{in,SE}$	No. of input ports per SE	n_{SE}	No. of SEs
P_{SE} / C_{SE}	Power/cost per port of SE	$N_{out,SE}$	No. of output ports per SE	n_{access}	No. of access rings
P_{WSS} / C_{WSS}	Power/cost of WSS	$N_{WSS,access}$	No. of WSS per access ring	n_{metro}	No. of metro rings
$N_{in,AP}$	No. of input ports per AP	$N_{WSS,fixed}$	No. of WSS for each link of fixed traffic	n_{fixed}	No. of links at MN for fixed traffic
$N_{out,AP}$	No. of output ports per AP	$N_{WSS,metro}$	No. of WSS per metro ring		

4. CASE STUDY

In order to compare the power and cost performance of different architectural options for 5G transport networks, we consider the traffic requirements expected for the year 2020 in an extremely dense urban scenario, which is referred to as Megacity. In this scenario, high capacity connectivity is requested between humans and the cloud and also between machines (e.g., vehicles and sensors) and the cloud. The mobile traffic requirements are extrapolated from [4][5] and the traffic volume density is as high as 350 Gbps/km². On the other hand, the fixed traffic requirements are derived from [6] and correspond to 16 Mbps per residential household and 200 Mbps per business customer. We assume that the service area of a Central Office (CO) is 2 km² in which 60 APs are uniformly distributed. The number of macro, micro, and pico base-stations as well as the number of residential and business users per AP is listed in Table 2, along with the traffic generated by each one of them. These traffic requirements can be used to obtain the values of the various parameters in equations (1), (2), (3), and (4) in order to get the total power consumption and cost of one specific transport network. We consider a number of scenarios to evaluate which architectural option is the most promising in terms of total power consumption and cost when the different deployments shown in Fig. 1 are investigated.

Table 2. Traffic requirements for a Chinese megacity.

	Number per AP	Rate [Gbps]	Traffic [Gbps] per AP	Total Traffic [Gbps] for 60 Aps
LTE				
Macro	1	0.228	0.228	13.7
Micro	10	0.090	0.9	54
Pico	100	0.132	13.2	792
Fixed				
Residential	333	0.016	5.33	320
Business	67	0.201	13.47	808

4.1 Case I – Optical Switching at MN

This case refers to DWDM-centric networks where the MN performs optical switching. The power/cost model for this case is expressed by equations (3) and (4). The values of parameters P_{AP} , C_{AP} , P_{WSS} , C_{WSS} , P_{SE} and C_{SE} are already known and depend on whether 10 Gbps or 100 Gbps interfaces are employed in the network. The number of APs (n_{AP}) for the Megacity scenario is 60 while the number of SEs (n_{SE}) is assumed to be one. For all the three deployments shown in Fig. 1, the number of access rings (n_{access}) is 4 while the number of metro rings (n_{metro}) is one. As mentioned in Section 3, the proposed architecture for optical switched MN results in $N_{WSS,access}$, $N_{WSS,metro}$ and $N_{WSS,fixed}$ being equal to two. For the sake of simplicity, we assume that the most significant part of the power and cost is incurred in the access and in the metro ring. Hence, the number of input ports per AP ($N_{in,AP}$) and the number of output ports per SE ($N_{out,SE}$) are set to zero. The value of the remaining parameters in equation (3) and (4) vary for each of the three deployments considered.

For Deployment A and B, the fixed traffic is carried towards the MN through four dedicated links, hence n_{fixed} is equal to 4. For Deployment C, the fixed traffic is directly aggregated at the AP, hence n_{fixed} is zero in this case. The values of parameters $N_{out,AP}$ and $N_{in,SE}$ can be obtained by using the traffic requirement values in Table 2. For Deployment A, all the macro, micro, and pico traffic is aggregated at the AP resulting in a total of 14.328 Gbps per AP. This traffic can be accommodated using two 10 Gbps channels (i.e., $N_{out,AP} = 2$). When using 100 Gbps channels, the traffic at each AP can be carried by a single channel (i.e., $N_{out,AP} = 1$). The value of $N_{in,SE}$ can be found by counting the number of ports required to carry the mobile traffic and the number of ports required to carry the fixed traffic. The aggregated fixed traffic comes out to be 1128 Gbps, which can be accommodated with either 113 channels working at 10 Gbps, or with 12 channels at 100 Gbps. For the mobile traffic, we need either 120 channels (2 channels per AP) at 10 Gbps, or 60 channels (1 channel per AP) at 100 Gbps. Hence, $N_{in,SE}$ is equal to 233 in case 10 Gbps transceivers are used, or equal to 72, in the case of 100 Gbps interfaces.

For Deployment B, the values of $N_{out,AP}$ and $N_{in,SE}$ can be found in a similar way by taking into consideration that the pico traffic is carried along with the fixed traffic. Similarly for Deployment C, it must be considered that both mobile and fixed traffic are aggregated at the AP. The calculations for Deployment B and C are not given here for space reasons.

4.2 Case II – Optical Switching at MN, caching at AP

This case is an extension of Case I where we introduce caching at the APs. According to the work in [7], YouTube and Netflix dominate the Internet traffic around the world. The report suggests that YouTube contributes to 17.26% of all the mobile traffic and to 12.28% of all fixed traffic, whereas Netflix accounts for 4.55% of the mobile and for 31.09% of the fixed traffic. Thus, it is reasonable to consider the option of caching YouTube and Netflix traffic at some given nodes in the network and to move the data close to the end-users and to decrease the traffic in core part of the network.

According to the cache model for YouTube traffic presented in [8], the highest cache hit-rate is achieved when the cache size is equal to the total size of all the unique video clips requested in a 10 days period. After scaling the analysis of YouTube traffic in [8] to the Megacity values, we conclude that we can offload the YouTube traffic by 24% when the cache is placed at the AP. According to the cache model for Netflix traffic presented in [9], we find that by placing the top 100 watched movies in a cache at the AP, we can achieve an offloading factor of 77.7% for the Netflix traffic.

Based on the caching model described before, an analysis similar to the one in Case I is carried out by taking into consideration the placement of YouTube and Netflix caches at each AP. After subtracting the offloaded traffic at each AP, the reduced traffic values are used to calculate the total power consumption and cost of the network. However, the models in equation (3) and (4) are extended to take into account the power and cost introduced by the caching. The cache power consumption P_{cache} is given by:

$$P_{cache} = (N_{cache,AP} P_{AP} + P_c) n_{AP} \quad (5)$$

while the cache cost C_{cache} is given by:

$$C_{cache} = (N_{cache,AP} C_{AP} + C_c) n_{AP} \quad (6)$$

where $N_{cache,AP}$ represents the number of ports required to connect the cache with the AP, a number that is a function of how many 10 Gbps and 100 Gbps channels are enough to accommodate the offloaded YouTube and Netflix traffic. The parameter P_c represents the power consumed by the cache itself while C_c represents the cost of placing a cache at the AP.

4.3 Case III – Electronic Switching at MN

This case refers to packet-centric networks where the MN has electronic packet aggregation functionalities. In this case, the power and cost values can be computed using equations (1) and (2) respectively. The values of P_{MN} and C_{MN} depend on whether 10 Gbps or 100 Gbps transceivers are employed in the network while the value of n_{MN} is 4 (Fig. 1). The values of all the remaining parameters are the same as in Case I except for $N_{in,MN}$, $N_{out,MN}$ and $N_{in,SE}$.

The value of $N_{in,MN}$ is calculated by counting the number of ports needed to accommodate the mobile as well as for fixed traffic, which comes out to be the same as $N_{in,SE}$ in Case I. However, when the MN has electronic switching functionalities, it can aggregate all the incoming traffic electronically. Hence, the number of output ports of the MN is less than the number of input ports. The value of $N_{out,MN}$ can be found from Table 2 and it is equal to 199 (using 10 Gbps channels) and to 20 (using 100 Gbps channels). These values are the same for Deployment A, B, and C (i.e., the value of aggregated traffic towards the SE is always the same). The value of parameter $N_{in,SE}$ is the same as $N_{out,MN}$ because the same number of output ports of MN are used to connect to the input ports of SE.

4.4 Case IV – Electronic Switching at MN, caching at MN

This case is an extension of Case III where caching can be employed at the MN because of its capability to perform electronic switching. In such a case, large size caches can be placed at each of the MN unlike small caches placed at the APs in Case II. Referring again to the YouTube and Netflix cache models in [8] and [9], we get a higher offloading factor by employing large size caches, i.e., 100 TB. When the caches are placed at the MN, the offloading factor for the YouTube traffic is equal to 51%, while a Netflix cache pre-fetching the top 20% of the movies can offload up to 98% of the traffic.

Using a methodology similar to the one for Case II, and after subtracting the offloaded YouTube and Netflix traffic at the MN, we have a reduced number of output ports of the MN ($N_{out,MN}$) which also results in a reduction in the number of input ports at the SE ($N_{in,SE}$). However, there is an extra penalty in term of power consumption and cost due to the presence of the cache. As already done presenting Case II equation (1) and (2) have to be extended to account for the cache power consumption P_{cache} and cache cost C_{cache} , given by:

$$P_{cache} = (N_{cache,MN} P_{MN} + P_c) n_{MN} \quad (7)$$

and

$$C_{cache} = (N_{cache,MN} C_{MN} + C_c) n_{MN} \quad (8)$$

where $N_{cache,MN}$ is the number of ports required to connect the cache with the MN. Both the value of the cache power consumption (P_c) and the cost of the cache (C_c) are higher in this case because we have caches with larger sizes.

4.5 Case V – Electronic Switching at MN with hybrid 10G/100G

This case is another extension of Case III where we use both 10 Gbps and 100 Gbps interfaces. The idea is to employ lower rates (10 Gbps) at the APs, since the aggregated traffic at each AP is far less than 100 Gbps. On the other hand, the MNs and the SE employ 100 Gbps channels since the aggregate traffic they have to handle is much higher than 10 Gbps. As a result some ports at the MN and SE can be saved compared to the case when only 10 Gbps interfaces are used in the whole network.

4.6 Case VI – Electronic Switching at MN with hybrid 10G/100G, caching at MN

This case is a further extension of Case V where caching functionalities are added at the MN. The calculations for power consumption and cost are carried out in the same way as in Case IV but using 10 Gbps channels in the access segment and 100 Gbps channels in the metro segment of the transport network. The cache power consumption (P_{cache}) and cache cost (C_{cache}) values are computed using equations (7) and (8) respectively.

5. PERFORMANCE EVALUATION

In order to evaluate the cost and power performance of Cases I to VI described in the previous section, we use the power consumption and cost values listed in Table 3. The per-port power values for 10 Gbps and 100 Gbps electronic Ethernet interfaces are taken from [10] and they are considered to be independent of the load. The WSS power consumption value has been taken from [11]. The typical cost values for the years 2014 and 2018 (projections) are expressed in terms of Cost-Units (CU), where one CU is the market price of a 10 Gbps transceiver during the year 2014. The typical power and cost values for YouTube and Netflix caches depend on whether they are placed at the AP or MN. It is worth mentioning that all the per-port power and cost values in Table 3 include the power/cost of transmitting (i.e., transceiver, which is always assumed to be tunable) as well as of switching data. The total power consumption and cost values are shown in Fig. 3, 4, and 5.

Table 3. Typical power and cost values. The Ethernet ports include optical tunable transceiver and switch capabilities.

	Power Consumption [Watt]	Cost [CU] in Year 2014	Cost [CU] in Year 2018
Ethernet 10 Gbps port	38	1.56	0.89
Ethernet 100 Gbps port	205	28.89	10
WSS	20	5.56	3.89
Small YouTube/Netflix cache at AP	10	0.55	0.55
Large YouTube/Netflix cache at MN	600	2.22	2.22

A careful analysis of the results in Figs. 3, 4, and 5 can help to gather a significant amount of information. The different cases in Fig. 3 can be compared to find out which technology and deployment option are the most suitable in terms of total power consumption of the network. It is evident that Case I with optical switching at the MN is the most promising solution, i.e., the MN consumes very little due to low power consumption of the WSS. When we introduce caching at the AP in Case II, we observe an increase in the total power consumption of the network due to the power incurred by using YouTube and Netflix caches. However, the end-user may experience a better Quality of Service (QoS), an aspect that might justify an increase in the power consumption. Case III with electronic switching seems to be the least feasible solution, however it might be a good option if the

benefits associated with intermediate electronic processing at the MN, e.g., caching, buffering, statistical multiplexing, are taken into account. With caching at MN in Case IV, we have to pay a small penalty in terms of power consumption because of the YouTube and Netflix caches. In this case, even with a reduced number of ports at the MN, the added penalty (i.e., cache power consumption) results in a slightly increased power consumption levels at the MN. However, it can be observed that the power consumption at the SE is lower than in Case III due to the reduction in the number of ports connecting the MN to the SE. Cases V and VI with hybrid technology tend to be among the best contenders for the future as we may observe a significant amount of savings in power consumption than the cases with only 10 Gbps or 100 Gbps channels.

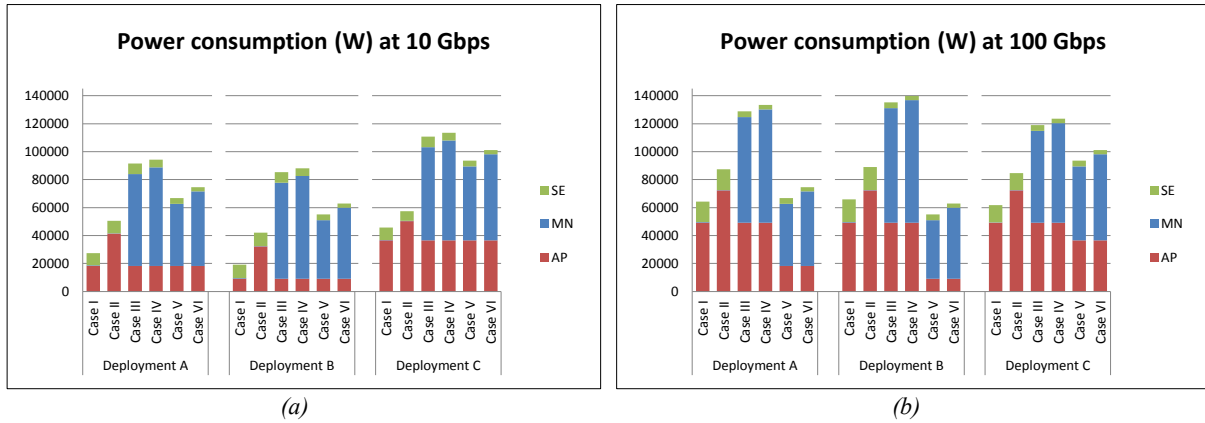


Figure 3. Total power consumption of the network using (a) 10 Gbps channels (b) 100 Gbps channels.

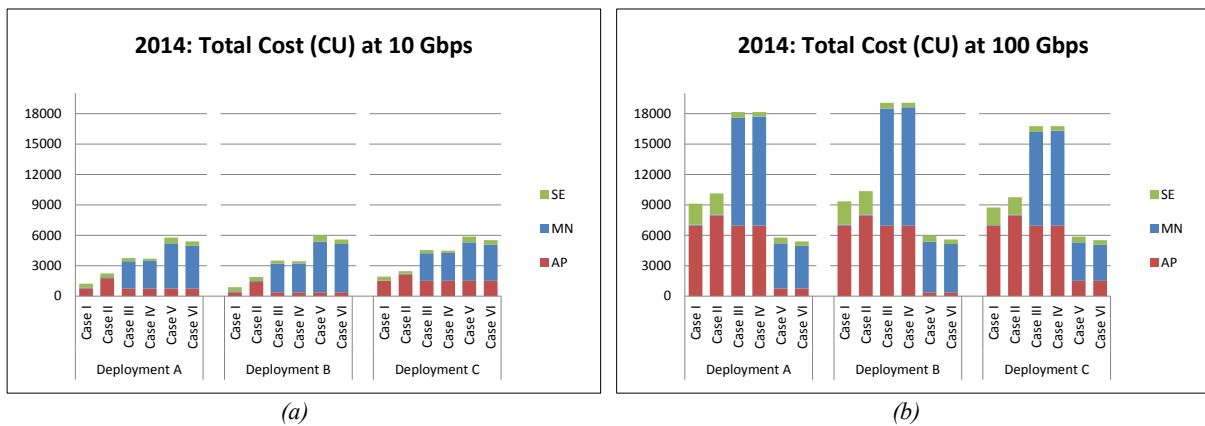


Figure 4. Total cost of the network during the year 2014 using (a) 10 Gbps channels (b) 100 Gbps channels.

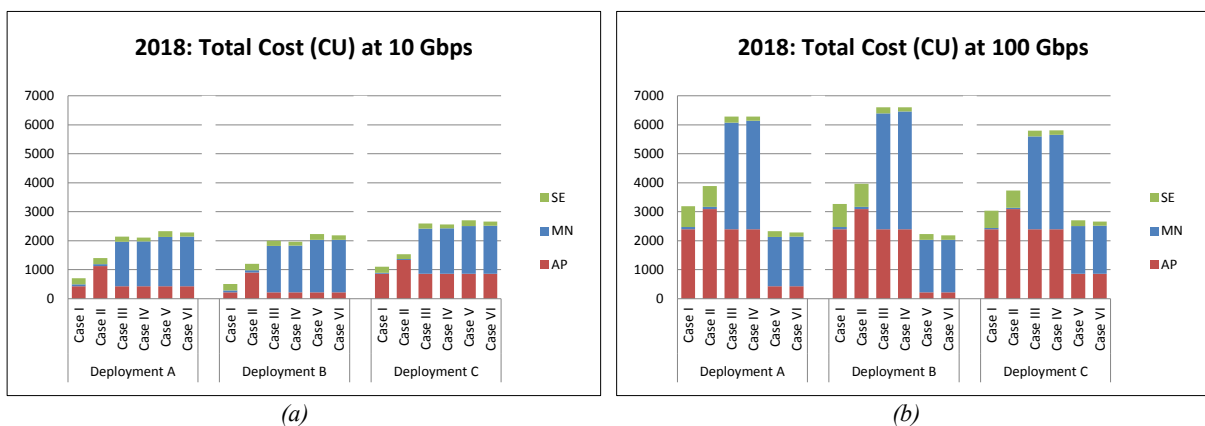


Figure 5. Total cost of the network during the year 2018 using (a) 10 Gbps channels (b) 100 Gbps channels.

By analyzing the results in Figs. 4 and 5, we may notice that the optical switching is still the best solution in terms of cost. However, electronic switching seems to be a good option if we employ only 10 Gbps interfaces, while 100 Gbps equipment is still very expensive. Hence, if a hybrid solution is selected (i.e., using both 10 and 100 Gbps interfaces) during the year 2014, it will result in a higher cost than using only 10 Gbps channels (Fig. 4a). However, as can be seen from Table 3, the price difference between 10 Gbps and 100 Gbps equipment is expected to decrease in 2018, limiting the cost penalty of using 100 Gbps transponders (Fig. 5a) and making the hybrid solution a viable option for the future. It is also worth noting that during the upcoming years, when

the increase in traffic volumes will force to migrate to 100 Gbps transponders, using 10 Gbps equipment in the access part of the network can still lead to a significant cost and power consumption savings.

6. CONCLUSIONS

This paper provides an analysis of a number of architectural options for 5G transport networks. Based on our results, we may conclude that optical switching is more efficient than electronic switching in terms of power consumption and equipment cost, i.e., 2 to 3 times lower. However, architectures with packet aggregation and network caching functionalities are able to reduce the number of required optical channels by up to a factor 10, thus representing a better option in fiber scarce scenarios. Moreover, we may conclude that considering 2020 traffic levels, 10 Gbps equipment is most suitable for the access segment, while 100 Gbps technology could be the best option for the metro/aggregation segment.

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