Upcoming applications driving the design of next-generation Metro Area Networks: dealing with 5G backhaul/fronthaul and edge-cloud computing

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ABSTRACT

This article provides insight on two of the most relevant applications driving the design of the future MAN: the implementation of 5G by means of C-RAN (Cloud - Radio Area Network) and the deployment of edge computing. The work addresses important questions such as the target latency budget for future MANs, the target bandwidth requirements for 2020-2030 induced by 5G midhaul and fronthaul traffic, and describes how optical and electronics layers can co-operate to meet the QoS targets of C-RAN and edge computing traffic. In the process, we identify the key architectural elements to meet the challenges of these applications in a cost-effective way.

Keywords: MAN, MAN design, 5G, Fronthaul, Midhaul, Edge Computing

1. INTRODUCTION

Besides supporting exponentially increasing transmission and switching rates, next-generation Metropolitan Area Networks (MAN) are expected to meet a number of challenges posed by any upcoming application scenarios. In this article we review two of these applications, selected as the ones inducing more changes on the way MAN technology is being conceived: 5G transport and joint edge/cloud computing. They share the need to simultaneously deliver ultra-low latency and Tb/s services in the data plane, and the need for an intelligent control plane able to exploit the elasticity of the optical layer.

We look into the characteristics of 5G backhaul and fronthaul traffic in section 2. 3GPP/ITU reports for 5G New Radio transport suggest a transport latency budget that would allow to push 5G baseband units up to 50Km into the MAN, much further than eCPRI and IEEE802.1cm specify. This opens the path to a very efficient way to centralize and share the processing of the radio signals from the myriads of active small cells in a MAN, provided that there is a lot of bandwidth and strict latency control mechanisms.

In section 3 we review aspects of edge computing and MAN connectivity requirements to cloud. The trend to push computing to the edge brought in by augmented/virtual reality services (AR/VR) and CDNs may reduce the traffic in the MAN but poses a number of challenges for a cost-efficient reliable deployment of micro-datacenters in central offices. Dynamic circuits and SBVT (Sliceable Bandwidth Variable Transceivers) seem to be a cost-effective solution to address them.

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Finally, section 4 reviews some of the key architectural elements that were introduced in the discussions, which are being developed in EU project PASSION,[1] and section 5 draws a few conclusions.

2. C-RAN

Cloud Radio Access Network (C-RAN) is an implementation option for 4G/5G base stations that introduces cloud processing of radio signals. In C-RAN,[2] RF signals received by the so-called Remote Radio Heads (RRHs) are downconverted, digitalised and transported to a pool of remote Baseband Units (BBUs) over the fronthaul (FH) network. Conversely, the BBUs synthesize the baseband signal to be upconverted and radiated by the antennas; this signal is transmitted over the fronthaul network to the RRHs. This scheme reduces the complexity of base stations and makes it possible to share signal processing resources among the many small cells that will populate metropolitan areas with the deployment of 5G.

From the technological alternatives to implement the fronthaul network, packet switching has been the focus of intense research and standardisation activity given its potential to exploit the statistical multiplexing of variable-rate fronthaul and backhaul traffic. There have been a few key milestones in the standardisation process of fronthaul over packet networks which are worth revising:

- **eCPRI**. Until recently, the Common Public Radio Interface (CPRI)[3] specification has been used as the most popular RRH-BBU interface. However, the digitalized RF signal of CPRI requires very high-capacity and ultra low-latency links, and more efficient schemes that rely on other functional splits of the radio processing chain are necessary to scale to 5G. In addition, the demand for a packet-switching-based fronthaul network[4] has led to an enhanced version of CPRI: eCPRI,[5] that is designed for packet networks, namely Ethernet and IP.
- **IEEE802.1CM**. This comprehensive standard published in 2018 includes important recommendations for the configuration of Ethernet for the transport of fronthaul traffic, and specifies relevant QoS targets for such transport. These parameters include the end-to-end latency budgets and the maximum Frame Loss Ratio (FLR) for each type of fronthaul traffic, which are used as design targets in this article. In addition, IEEE802.1cm suggests four timing distribution schemes to fulfill the synchronization requirements of the four timing Categories identified in[6] to implement 3GPP features (handovers, MIMO, CoMP, etc).
- **5G New Radio**. In December 2017 the numerology for the New Radio air interface for 5G was released by 3GPP in TS38.104[7] as Release 15. This document defines two frequency ranges: FR1 (under 6 GHz) with component bandwidths ranging 5-100 MHz and sub-carrier spacings 15/30/60 KHz; and FR2 (24-86 GHz) with component bandwidths ranging 50-400 MHz, and sub-carrier spacings 60/120 KHz. In addition, 8 possible functional split options are further defined in TR38.801.[8] This leads to a wide range of very-high-rate fronthaul traffic patterns with different QoS requirements. However the focus is set on two options of practical interest: Option 2 (F1 interface that processes up to RLC (Radio Link Control) layer) - which relieves part of the BBU packet processing work- and Option 7 (intra-Phy, being 7.a equivalent to eCPRI split I_U/II_D) -given the interest in a split that produces fronthaul traffic proportional to the cell load, unlike CPRI (Option 8 in 3GPP architecture)-. The use of both splits has led to the possibility of having the original BBU functionality split into CU (Central Unit) and DU (Distributed Unit). Finally the original RRH concept is named RU (Remote Unit) in 3GPP terminology. This has given way to three types of traffic: fronthaul (RU-DU), midhaul (DU-CU) and backhaul (CU-NGC). In terms of rate, midhaul and backhul traffic are similar.

How does this architecture fit into the MAN? Figure 1 shows a schematic view of the hierarchical levels of a big reference MAN topology (the topology is not shown in the picture, but its characteristics can be seen in[9]) based on real network data. Five hierarchical levels (HL) are defined, with differentiated functionalities. HL1 and HL2, connected in a mesh topology, make up the top level in the hierarchy and are treated as a single level since HL3 nodes connect directly to either HL1 or HL2 nodes to reach the core, where the traffic is routed to/from either service gateways (e.g. IPTV or CDN caches at HL2) or to the appropriate WAN routers (at HL1) for Internet and other global connectivity services. At the next level, HL3 are aggregation and transit nodes.

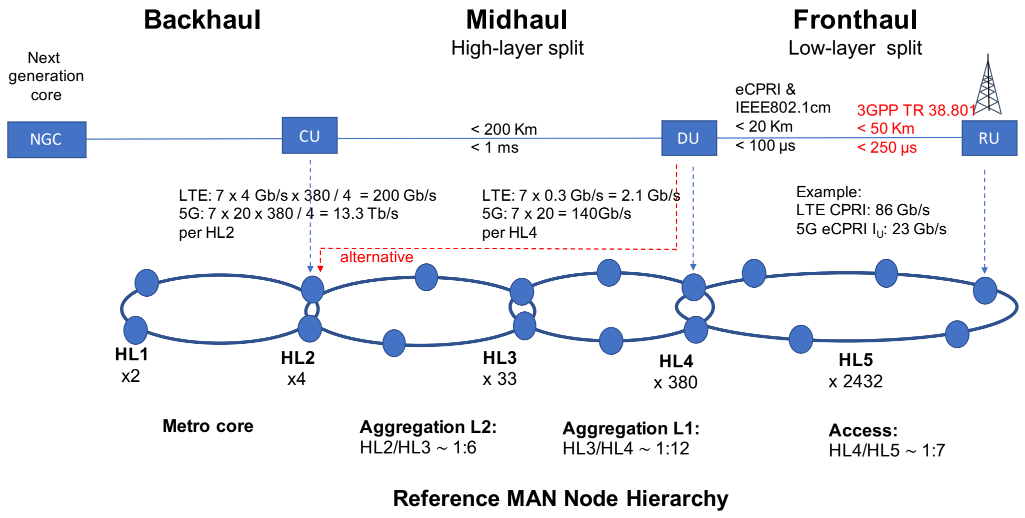

Figure 1. Location of CU, DU and RU in a hierarchy of MAN nodes.

HL5 consists of Base Stations and small COs (Central Office) hosting OLTs and DSLAMs, whereas HL4 are bigger COs that distribute/aggregate HL5 traffic. The picture shows where CU, DU and RUs are located in the node hierarchy and the latency budgets allowed for each C-RAN segment. The Figure also shows the rates of midhaul traffic generated at each DU, assuming that all HL5 nodes whose traffic is aggregated in the HL4 DU, are 5G base stations featuring an end-user peak rate of 20 Gb/s (5G target). This implies a peak data rate of 13Tb/s offered to each HL2 node hosting pools of CUs in this reference topology.

Regarding latency, the organisations developing the standards show some discrepancies regarding the budget for intra-PHY fronthaul (see segment DU-RU in Figure 1). eCPRI/IEEE802.1CM sets 100μs (or 20 Km) whereas 3GPP suggests 250μs in report.[8] This budget includes propagation and queuing delay. If the 3GPP budget becomes a standard, this would mean that the DU functionality may get deeper into the MAN and improve baseband processing resource sharing degrees. In our reference topology, this would mean that CU and DU could run at HL2 in many practical settings. However, as 5G develops its potential in the next years the fronthaul rates and OFDM symbol burst size become very large and hence, the transport through the MAN becomes challenging.

To give an idea of such traffic volume, Figure 2 tries to show the effect of antenna arrays, one of the radio features to be fully exploited in 5G, on fronthaul rate. The parameters used to calculate the rate and burst size of the figure for each graph, namely: RF channel bandwidth, subcarrier spacing, number of subcarriers and bits per sample are summarised in Table 1. Figure 2 reveal rates up to 2.9Tb/s for base stations with 256 antenna elements with a single 400MHz RF channel. Some more average settings that may be considered as a reference in the deployment of 5G from the current 20MHz of LTE to 400MHz, are included on the right of Table 1.

The needs in terms of burst size are also remarkable. The 400MHz case requires transporting 380KB bursts every 8 μs which can be very challenging over 1.5KB ethernet frames. The reassembly and jitter compensation time of all those frames is likely to take a lot of the latency budget, which means less distance between RU and DU, hence reducing the centralisation capability.

Forecasting the way this traffic will grow in the next decade is complex as it depends on the pace at which operators deploy 5G, which will be determined mainly by competition and by the return-of-investment from new vertical applications enabled by 5G. As Figure 1 shows, assuming that all base stations are LTE macro cells currently providing 300Mb/s of peak rate access that evolve to 5G gNodeB featuring 20Gb/s rates in 10 years, the peak traffic would grow 67 times, i.e. CAGR = 52%.

If the design choice is co-locating the CU/DU functionality at HL2, the fronthaul traffic will grow much more. Even without the massive deployment of new small cells the rates become very high. If each HL5 base

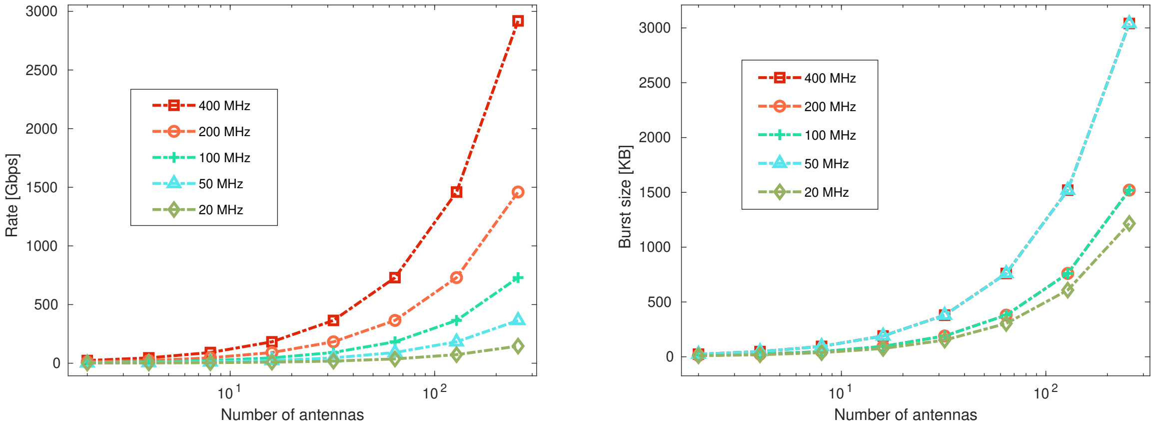

Figure 2. Rate (left) and burst size (right) for fronthaul data for split I_U and 100% radio resource utilisation.

Table 1. Parameters used in Figure 2 for each channel bandwidth: subcarrier spacing (Δf), sampling period, bits/sample.

B [MHz]	Δf [KHz]	Usable SC	N. SC	Ts [ms]	Bits/sample	Antennas	R [Gbps] per RF Channel	Burst Size [bytes]
20	15	0.95	1267	0.06667	15	2	1.1403	9503
50	15	0.95	3167	0.06667	15	4	5.7006	47505
100	60	0.95	1584	0.01667	15	8	22.8096	47520
200	120	0.95	1584	0.00833	15	16	91.2384	95040
400	120	0.95	3167	0.00833	15	32	364.8384	380040

station follows the evolution depicted in Table 2 in 10 years upgrading to 400MHz channels, the annual growth rate must be 78%. Then, HL2 nodes should support 222 Tb/s, for the whole cellular network working at 100% utilisation. This amount can be proportionally reduced according to the real maximum utilisation.

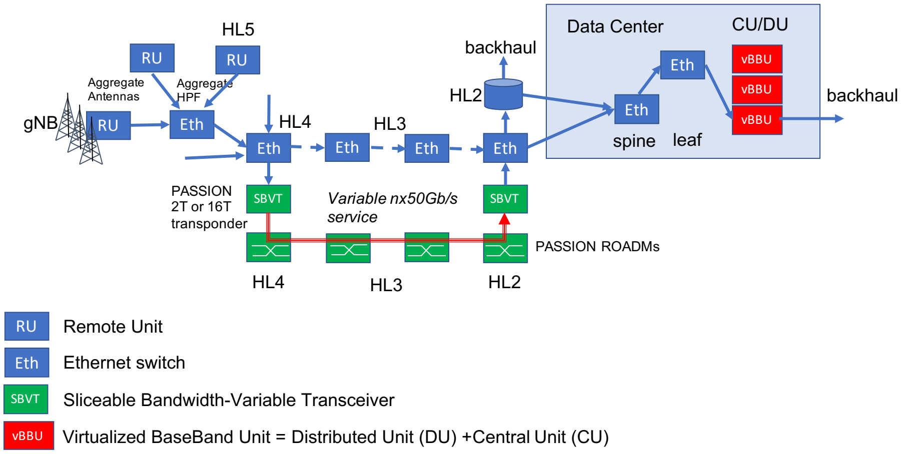

Figure 3. Hybrid packet-circuit fronthaul transport with Ethernet an Elastic Optical Networking.

If Ethernet is the packet switching technology of choice, all this 10-100Tb/s traffic needs to be transported as HPF (High Priority Fronthaul) in the maximum available priority class, and coexist with regular telecommunication traffic (SDH, Internet, VPN, etc). Given the complexity of operation of this volume of high priority traffic and the need to over-provision links to meet the latency requirements, the convenience of using optical circuits comes out naturally. Moreover, the HPF rates quickly saturate standard 100G and 400G Ethernet interfaces, which make statistical multiplexing hardly possible.

The approach envisioned in EU project PASSION for this use case is depicted in Figure 3. Packet switching is used in the access to aggregate very variable traffic at low cost and at the data center to distribute the traffic over the BBU pool. On the other hand, dynamic circuit switching is used to transport trunks of HPF with no jitter when the load justifies optical by-passing of packet switches.

3. EDGE-CLOUD COMPUTING

Another relevant new application with impact on the technology supporting the next generation MAN is the advent of edge computing as a means to enable ultra-low latency network applications. Although, in principle, edge computing is expected to reduce the amount of traffic in the MAN and core, the connectivity between edge and cloud needs to be maintained, especially what regards CDN caching. The scenario, described in,[10] is depicted in Figure 4. The scenario assumes that the edge cache is serving up to 1 Tb/s of content to the subscribers and is updated at 100Gb/s from higher level cache nodes.

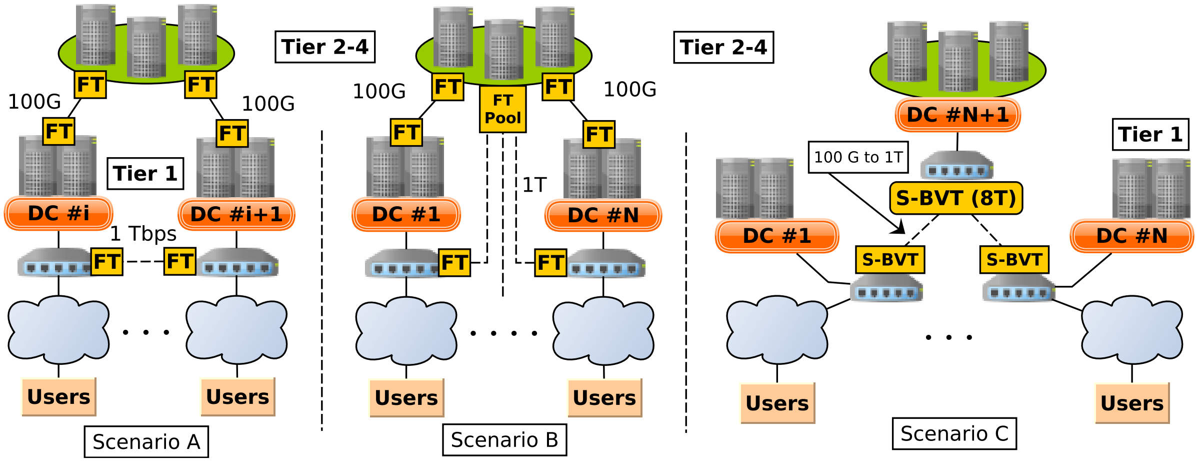

Figure 4. Options for dynamic restoration of CDN caches[10] (A) Pair-wise backup, (B) Hierarchical backup with Fixed Transceivers (FT),(C) Hierarchical backup with SBVT. Dashed lines represent dynamic connections and the solid lines refer to the permanent ones

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Figure 4 compares three implementations of CDN caching with dynamic restoration. In (Scenario A), edge data center (DC) i is backuped by another edge data center i+1 at the closest CO using 1 Tb/s Fixed Transceivers (FT). Conversely, data center $i+$ is backuped by DC i. This requires DC i and $i+1$ to be equipped with double computing resources. Better multiplexing gains can be obtained if edge data centers are grouped into clusters and all the cluster members are backuped by the same DC in an upper layer in the MAN hierarchy. This can be done with FTs (Scenario B) or with SBVTs (Scenario C). SBVTs solves the question in a more efficient way as a single transceiver serves both the normal state (100Gb/s) and the failure state (1Tb/s) in the edges. Furthermore, the capacity used will fit the actual demand exactly with SBVTs and hence we shall need fewer 1Tb/s-SBVTs in the hub than if implemented with FTs thanks to statistical multiplexing. In the Figure, the hub in scenario (C) simply has one SBVT of 8Tb/s,[1] whose slices can serve multiple edge data centers at the same time.

Another interesting use case to develop is the transport of the overflow of traffic from an edge data center to another data center, either in the cloud or in the edge, to deal with the resource limitations of edge DCs. In general, distributed computing (between edge data centers and between edge and cloud) and edge computing resilience require features that affect mainly the control plane, namely:

- Ability to automatically migrate a full edge CDN node to another backup location with muilti-Tb/s optical circuits.
- Fast multi-channel (re-)configuration (in the order of seconds) when an urgent traffic demand or a re-route demand is issued.
- Fast multi-channel provisioning and reconfiguration (in the order of minutes) to better adapt to traffic variability during a day
- Efficient routing and wavelength/spectrum assignment RWA/RSA algorithms to attain low blocking probabilities even at high loads.
- Full control of end-to-end latency for all paths set up in order to keep the delay within the budget of the services being re-accommodated
- Agile switch-over and switch-back capability handled either by a centralized SDN controller or by a distributed mechanism that does not rely on the connectivity with the controller.
- Multi-layer SDN control integrating real-time knowledge of packet (IP) network usage as well optical network domain. The aim is to leverage the best of both worlds attaining the most efficient use of all the network resources (packet ports, optical spectrum, transceivers devices, etc.)

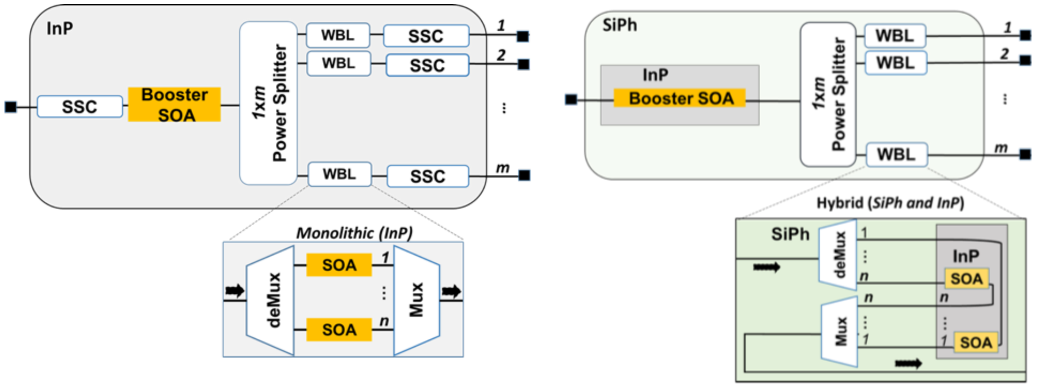
4. ARCHITECTURAL ELEMENTS IN SUPPORT OF UPCOMING APPLICATIONS

In order to support the above-mentioned applications, high levels of flexibility as well as cost-effective switching solutions are required. As reviewed in the previous sections, SBVTs seem to be a versatile option to address high capacity and elasticity at a low cost. This, together with a smart control plane and fine-grained switching capability, can provide the required elasticity to place Tb/s capacity wherever needed in the MAN.

The adoption of Vertical-Cavity Surface Emitting Lasers (VCSELs) together with dense photonic integration is a promising choice in terms of cost and power consumption. The general advantages of SBVTs in the MAN for an operator are: a) *Pay-as-you-grow* can be achieved with a license-based scheme for VCSEL activation, with no extra upgrade cost: no manual intervention is required, featuring a lower OPEX and a shorter downtime; b) Faster recovery from laser failures (other VCSEL gets activated): no manual intervention, lower OPEX, lower downtime; c) Disaggregation of transponders and ROADMs; d) Flexibility to tradeoff distance for rate and used lambdas; e) Smaller Form Factor than FTs: less space, less cost, more energy efficiency; f) Ability to connect to multiple destinations at the same time. In the context of MAN, where 90% of the traffic is hierarchical, this means that a node can connect to its two same-level neighbours at low speed and to the two upper nodes with a single transponder.

The SBVT being developed in H2020 project PASSION[1] is composed of several BVT modules incorporating an array of direct-modulated VCSELs to create a bandwidth variable transmitter. On the other hand, the bandwidth variable receiver features coherent or direct detection. Additionally, a fine spectral manipulation is possible by making use of adaptive digital signal processing. Combining all these elements, multiple flows can be aggregated or distributed in a SBVT with a spectrum selective switch. The performance of BVT modules has been demonstrated recently, achieving capacities above 30 Gb/s in back-to-back and greater than 20 Gb/s up to a 2-hop path of 185km, with flexgrid spectral occupancy of 25 GHz (DMT) and 12.5 GHz (SSB-OFDM).[11] The target is building two types of SBVTs. One featuring up to 2Tb/s and another for 8 or 16 Tb/s (using PDM)[12][13][14] . SBVTs, as well as the underlying optical switching technology are controlled by an intelligent SDN controller[15] capable of finding multiple paths to route the wavelengths making up a demand.

The other key architectural element enabling elastic Tb/s services is ROADMs, where wavelength selective switches (WSS) play a major role and a major impact on cost. In EU project PASSION,[1] WSSs are implemented in a modular fashion. Two schemes of integration are followed to realize low optical loss and high optical signal-to-noise ratio (OSNR). The first one is monolithically integrated WSS based on Indium phosphide (InP) and the second one is based on hybrid integrated WSS based on low-loss on Silicon photonics (SiPh) passives and InP actives. The schematic representation of the monolithic and hybrid integrated n-channel, 1xm WSS modules



(a)

(b)

Figure 5. Schematic representation of 1xm WSS module with n WDM channel (a) monolithic integration on InP (b) hybrid integration of SiPh passives and InP actives

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are given in Figure 5 (a) and (b) respectively. The design is based on broadcast-and-select scheme, in which the signal is broadcast by a 1xm splitter and is selected by m wavelength blockers (WBLs) at the output ports. The WBL is constituted by de-multiplexing/multiplexing circuitry and SOA switching gates as illustrated in Figure 5. The SOA switching gates are used to pass/block the desired wavelength at each of the output ports. The monolithic integration consists of all the passives and active circuitry on InP. At the input/output ports a spot-size-converter (SSC) waveguide is used to efficiently couple with a single mode fiber. A booster SOA is used to compensate on-chip losses of passive circuitry. The hybrid integrated approach involves the integration of all passive circuitry (splitter, deMux/Muxs) on low-loss SiPh combined with SOA actives on InP. A booster SOA on InP chip is used to compensate the splitter losses in the SiPh circuitry. The hybrid WBL is based on SiPh deMux/Mux circuits and SOA switching gates on InP chip. The integration scheme uses cavities on SiPh chip to flip-chip bond the InP chips after fabrication.

5. CONCLUSIONS

This paper provides insight on two relevant applications driving the design of the future MAN: the implementation of 5G RAN as a C-RAN (Cloud - Radio Area Network) and the deployment of edge computing. The study answers relevant questions such as the target latency budgets in the MAN depending on the C-RAN implementation option selected, the target bandwidth requirements for a 5G deployment through 2020-2030 and identifies key architectural elements optimized for the MAN scenario where 90% of traffic is aggregation/distribution. SBVTs and cost-effective WSSs controlled by a versatile control plane seem to be an adequate way to fulfill the elastic multi-Tb/s service required to meet the challenges of both applications.

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