Smart Provisioning of Sliceable Bandwidth Variable Transponders in Elastic Optical Networks

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***Abstract*—Prior provisioning of optical source technologies have techno-economic importance for the operator during the design and planning of optical network architectonics. Advancement towards the latest technology paradigm such as Elastic Optical Networks (EONs) and Software Defined Networking (SDN) open a gateway for a flexible and re-configurable optical network architecture. In order to achieve the required degree of flexibility, a flexible and dynamic behaviour is required both at the control and data plane. In this regards, SDN-enabled flexible optical transceivers are proposed to provide the required degree of flexibility. Sliceable Bandwidth Variable Transponders (SBVTs) is one of the recent type of flexible optical transceivers. Based on the type/technology of optical carrier source, the SBVTs are categorized into two types; Multi-Laser SBVT (ML-SBVT) and Multi-wavelength SBVT (MW-SBVT). Both architectures have their own pros and cons when it comes to accommodate traffic request. In this paper, we propose a selection model for the SBVTs before its actual deployment in the network. The selection model consider various design and planning phase network characteristics. In addition to this selection model, the comparison of centralized Flex-OCSM architecture is also presented with the already discussed SBVT types. The analysis in this work is performed on random network (20 nodes) and the German Network (17 nodes).**

Keywords*—*Elastic Optical Networks; Slice-able Bandwidth Variable Transponders; Software Defined Networking

I. Introduction

The dramatic increase in the internet traffic due to the emerging innovative bandwidth intensive applications attracts the widespread research interest towards dynamic and flexible optical network architecture [1]. In order to provide that degree of dynamics and flexibility, new technologies and network architectures are proposed for both the control and data plane. Technologies such as Elastic Optical Networks (EONs) and Software Defined Networking (SDN) are introduced, with striking feature of adaptive and dynamic provisioning of network resources.

Flexibility in EON is achieved through the exploitation of novel set of transponders called bandwidth variable transponders (BVTs). BVTs are special type of a transponders that have the ability to dynamically operate the optical bandwidth and transmission reach. The transmission reach in the classical BVTs is adjusted by tuning the characteristics parameters such as modulation format, Forward Error Correction (FEC) coding, baud rate and adaptive spectral shaping of optical spectrum. BVTs provide an effective trade-off between spectral efficiency and transmission reach using distance adaptive modulation formats. These features enable BVTs to provide flexible transmission bandwidth independently dedicated to a single traffic request and operated in a fixed segments using software modules in order to provide a best match to the actual traffic demand and transmission reach [2].

To exploit the complete available bandwidth, BVTs should be operated up to a maximum value of transmission bandwidth. A traffic request which is smaller than the maximum transmission bandwidth of BVT results in the operation at lower transmission rate than its maximum capacity, thus a part of available bandwidth is wasted due to mismatch issues. In order to overcome the bandwidth wastage problem and provide higher degree of flexibility, Sliceable Bandwidth Variable Transponders (SBVT) or multi-flow transponders have been proposed. SBVTs can generate multiple optical flows and route them to different destinations or/and synchronously distributed over several portions of the optical channels [3].

SBVT is capable of virtualization a single transponder into multiple sub-transponders (SDN-enabled multiple optical flows) and each sub-flow can be specified to different destinations, hence enabling multiple in-flows and out-flows [4]. The provisioning of connectivity between the SBVTs is the responsibility of the deployed SDN controller. On top of this, the SDN controller establishes an optical connection in order to configure the candidate SBVT. SDN-enabled SBVT has the striking feature of *slicing* that enables it to slice the spectrum at finer granularity level (flexible-grid) than the BVT and therefore limiting the bandwidth wastage issue.

The segmentation ability also enables SBVT to use a single transponder device to accommodate multiple lightpaths (LPs) requests generating or terminating at a candidate node and therefore reducing the number of transponders required in the network.

Further to this, the flexibility in the traditional SBVT architecture is achieved by a tunable conventional laser, used to generate each particular carrier. This class of SBVT architecture is referred as multi-laser SBVT *(ML-SBVT)*. Recent research proposed, a novel SBVT architecture based on optical frequency combs [5]–[9] in which a single multi-wavelength source is used to generate multiple carriers. This new class of SBVT architecture is referred as multi-wavelength SBVT *(MW-SBVT)*. MW-SBVT architecture is potentially a promising solution in terms of inventory cost as it can save *N-1* number of lasers and improved the *super-channel* spectrum efficiency because the frequency comb lines are intrinsically locked in frequency domain, avoiding the guard band (≈*2 GHz*) between adjacent channels [10]. In addition to this, all lines of the frequency comb can be simultaneously tuned in wavelength and has been proven to be useful in *Hit-less Spectral De-fragmentation* [11]. Apart from that improvement MW-SBVT offered, it also imposed a unique constraint in Routing and Spectrum Assignment (RSA), particularly, using ML-SBVT each carrier can be tuned independently over the whole spectrum while traditional MW-SBVT introduces a limit on the maximum spacing between the carriers. Whereas the SDN based MW-SBVT proposed in [12] offers a more viable solution. In this the channel spacing is programmed separately by extended SDN control plane. This new solution of channel spacing to MW-SBVT generated much research interest towards the comparison of ML-SBVT and MW-SBVT. A few works have already been reported, which provided different kind of comparison among these two traditional SVBT architectures. The authors in [13] proposed a centralized Flexible Optical Carrier Source Module (Flex-OCSM) architecture, to exploit the cost and power efficiency benefits of high line count optical frequency combs. In [14]–[16] the authors describe the performance of MW-SBVT compared to ML-SBVT in terms of limited parameters and shows that former performs better in terms of higher traffic requests but not suitable if lower blocking probability is required. In [16], author showed that MW-SBVT has better performance in the presence of *super-channels*, in which lower blocking probability is achieved. The authors in [15] introduced various schemes to determine the RSA based on transponder assignment. The work in [15], [16] shows detailed comparison of both types of SBVTs for the online scenario. However, it is also imperative from the customer point of view to investigate and compare the impact of such hardware technology on the overall network performance during designing and planning phases of optical network architecture.

In this paper we proposed a novel model for the selection between the three types of SBVTs before their actual deployment in the network. In this paper, for the very first time we present a comprehensive performance comparison analysis of ML-SBVT, SDN based MW-SBVT and Flex-OCSM. The selection model consider various design and planning phase network characteristics such as number of nodes, node degree, heterogeneous/homogeneous traffic request and optical reach for better prediction of SBVT types for the new network. In addition to this, the comparison of centralized Flex-OCSM architecture is also presented with already discussed SBVT types. The analysis in this work is performed on Random network (20 nodes) and the German Network (17 nodes). The promising results of both networks show that centralized Flex-OCSM architecture provides comparable performance to ML-SBVT and overcoming the constraints related to dedicated MW-SBVT.

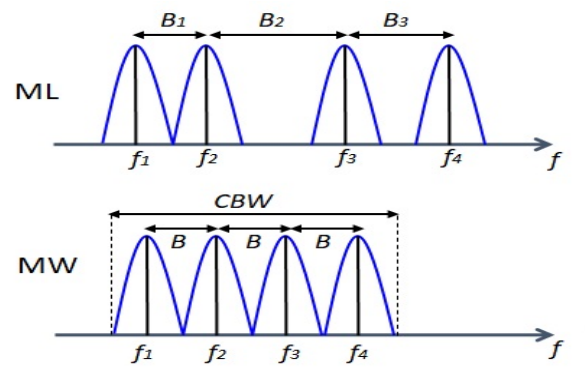

Fig. 1: Spectrum of ML and MW

II. Network Model

In this work, we are considering Internet Protocol (IP) over flexible-grid optical network. The physical topology is mapped by the directed graph where nodes 'N' are connected by the bi-directional physical links. IP routers and Re-configurable Optical Add/Drop Multiplexer (ROADM) are placed at every node. Every bi-directional physical link originating from source 's' and terminating at destination 'd' is represented by a physical length L_{sd} (km), such that L_{sd} = L_{ds}.

The traffic requests from source to destination are fulfilled in the form of optical LPs. These LPs are mapped onto the physical links within one or multiple hops depending on the physical paths available. For a single traffic request that is spanned over multiple hops, the optical LPs are bypassed at the intermediate nodes with the help of flexible ROADMs. The traffic request that exceeds the spectrum capability of the link is accommodated by multiple consecutive LPs with the help of IP router that switch between the LPs. The whole set of LPs formed is represented by a LPs Topology (LT) in which LPs are originated at the source node 'N_s' and terminate at destination node 'N_d' by flexible SBVT. The heuristic used to obtain LT is described in the section IV. The maximum transmission capacity of SBVT is represented by T_{max} = 400 Gb/s, whereas the capacity of the spectrum link is represented by SL_{max} = 4 THz. The EON provides a finer granularity $12.5GHz$ [17] per slot, which enables the spectrum link available to be divided into 320 spectrum slots represented by SS_{max}. The fixed modulation technique of Quadrature Phase-Shift Keying (QPSK) is considered that has the optical reach of 2000 km [18]. The transmission rate R of QPSK is $25Gb/s$. Spectrum slots required for each traffic request T_{sd} between source and destination is calculated as T_{sd}/R. According to capability defined, we have 16 numbers of fixed slots/ SBVT according to the transmission rate of 25 Gb/s per slot defined in [19].

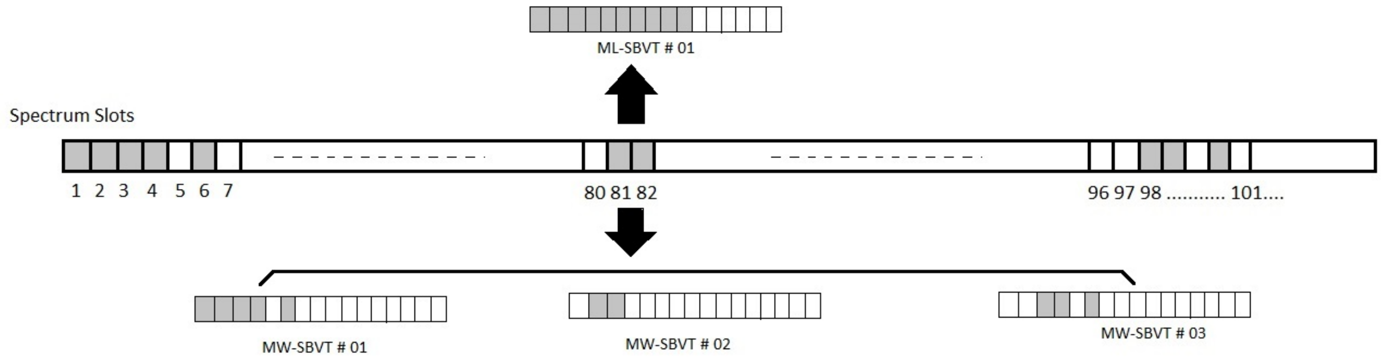

Fig. 2: Mapping of ML & MW SBVT onto Spectrum

III. ML SBVT, Flex-OCSM and MW SBVT Architecture

The new generation of optical transponders named as SBVTs have the ability to virtually *slice* themselves into sub-transponders that enables more effective utilization of the network resources. Typically, SBVTs have two main classes based on optical carrier source. The traditional class of SBVTs has relied on multi-laser as optical carrier source *(ML-SBVTs)*, while the latest class of SBVTs has multi-wavelength as an optical carrier source *(MW-SBVTs)*.

ML-SBVTs have incorporated multiple number of independent tunable lasers sources that can tune themselves at any required frequency within the limits of C-band as shown in Fig. 1. The frequencies f_1, f_2, f_3 and f_4 in the case of ML can be tuned independently and both equal and non-equal carrier spacing can be achieved without applying any constraints. Whereas in case of MW-SBVT, the central frequencies of all the equally spaced carriers of frequency comb (within comb bandwidth) can be easily tuned within C-band as shown in Fig. 1. However, the spacing between the carriers are equal and maximum achievable carrier spacing is limited to $<$50 GHz. It is important to understand the impact of these constraints on the network performance. This gives more flexibility to ML-SBVTs over MW-SBVTs in terms of slots mapping as it can move independently all over the spectrum. In contrast to this, ML-SBVTs inserted a guard band of *(*$\approx$2 GHz*)* between sub-carriers of a *super-channel* to overcome frequency drift issues which may cause inter-carrier interference.

Additionally two constraints of continuity and contiguity are considered on both the transmitting and receiving ends. As ML-SBVT can map anywhere within the provided spectrum, it can accommodate more requests and can effectively utilize the resources in case of lower traffic requests. Whereas MW-SBVT has the intrinsically locked central frequency, it can accommodate the requests that lie within its frequency window as shown in Fig. 1. The mapping of the SBVTs on to the spectrum are shown in Fig. 2. Further to this, MW-SBVTs give benefit in saving a large number of independent laser sources and also carriers generated in MW-SBVTs are intrinsically locked which helps in saving guard-bands between sub-channels which in turns improves spectral efficiency [13]. Considering the constraints offered by both ML-SBVT and MW-SBVT architectures, a novel *centralized Flex-OCSM* architecture is proposed in [13], which has the potentiality to overcome the constraints offered by both ML-SBVT and MW-SBVT. In the centralized Flex-OCSM model, optical carriers to all the deployed transponders in the particular node are provided by centralized Flex-OCSM controller as shown in Fig. 3. The detailed architecture of Flex-OCSM is discussed in [13].

The Flex-OCSM controller is connected to all the SBVTs required at the node and is responsible to provide optical carriers in optimized manner. Both in ML-SBVT and MW-SBVT architectures, carrier source is dedicated to a single SBVT and its unused carriers in case of MW-SBVT can not be shared with other SBVTs on the same node. Centralized Flex-OCSM architecture proposed in [13] tackles this constraint. Both equal and unequal carrier spacing (sometimes required for sliceability) can be achieved without any maximum carrier spacing constraints. It is expected that performance of ML-SBVT and Flex-OCSM will be comparable with additional benefits of spectral efficiency.

IV. Model Orchestration

The model proposed in this work mainly depends on the heuristic named as Lightpath and Spectrum Mapping for SB-VTs (LSM-SBVTs), defined in Algorithm. 1. Input parameters required for the LSM-SBVTs are the physical topology and traffic matrix. Physical routes are calculated based on the *Dijkstra*, shortest path algorithm and all the routes are saved as possible route set in γ_{paths} against every source to destination (s –> d) pair of all nodes τ. Traffic demands are arranged in descending order and stored as demand set in ζ. The maximum capacity of link in the form of Gb/s is represented by Δ. Output is the LT fully mapped onto the given physical topology represented by Γ.

LSM-SBVTs performs its functionality into two main steps. The first step is to define the establishment of Γ considering the network constraints and second step is to map the LP requests onto SBVTs. When establishing an LP, it is important to consider the constraint of optical reach for QPSK and number of spectrum slots required to fulfill the traffic request. When a LP reaches its optical transmission limit of 2000 km [18], the LP is dropped at the node and a new LP is initiated at that intermediate node. While mapping the LPs onto the available spectrum, two major constraints

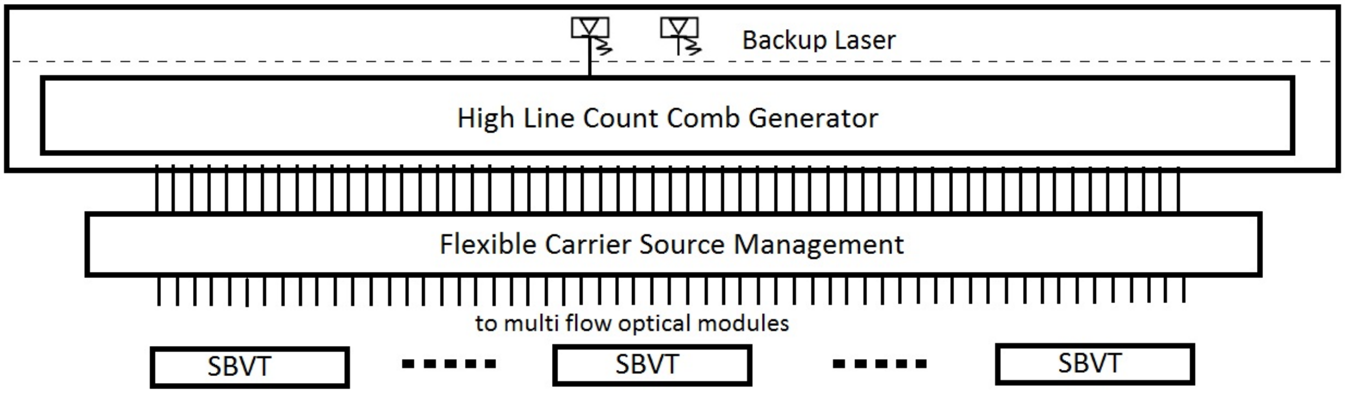

Fig. 3: Flex-OCSM Centralized Laser Source Architecture

Algorithm 1 Lightpath and Spectrum Mapping for SBVTs

Require: $\gamma_{sd}, \forall(s,d) \in \tau$, ζ
Ensure: Γ
for all $\zeta_{sd} \in \zeta$ **do**
  request-satisfied $\leftarrow$ **false**;
  h=shortest-path(γ_{sd});
  while dir-lightpath-allowed(h) is **true** **and** request-satisfied is **false do**
    s=calculate-required-spectrum- slots(ζ_{sd});
    if $s \leq$ available-slots(h) **then**
      generate-lightpath(ζ_{sd},h);
      request-satisfied $<-$ **true**;
    else
      Request is dropped
      ERROR: Exit
    end if
  end while
end for
assign-slots=slot-assignment on respective SBVT considering constraints;
if assign-slots is **true then**
  return Γ;
else
  return Solution NOT possible;
end if

are kept in consideration: *continuity and contiguity*. To fulfill the *continuity constraint*, each LP has assigned consecutive spectrum slots. For *contiguity constraint*, each LP has assigned the same index of spectrum slots while traversing the different intermediate physical paths.

Moreover, during assigning the slots for each SBVT, constraints of *continuity and contiguity* are considered on both the transmitting and receiving side. A single MW-SBVT cannot accommodate the required spectrum slots that are farther apart or lies outside the frequency window available within the SBVT. Whereas, ML-SBVT can accommodate any independent traffic request slot that does not exceed its capacity. In ML-SBVT, due to sub-carrier interference within the super-channel (typically of 1-2 GHz), $\approx$ 2 GHz of guard-band is required as internal guard-band [20]. The spectrum is assigned to the LPs using *first-fit algorithm*, by simply assigning first-available spectrum to first LP. As ML-SBVT can tune itself to any frequency given, it can accommodate any spectrum slot index upto 16 slots as LSM-SBVTs considered fixed modulation format of QPSK for simplicity. QPSK has the data rate of 25 Gb/s [19], which gives 16 slots for a 400G transponder. Whenever these 16 slots are exhausted only then a new ML-SBVT is initiated. On the other hand MW-SBVT can only accommodate the spectrum slots that lie within its frequency range of consecutive 16 slots. If a LP exists outside the range of already spawned MW-SBVT frequency range, a new MW-SBVT is initiated to fulfill that request. In case of Flex-OCSM, as the optical carriers are centralized, the constraint of channel spacing is negligible while providing the flexibility of accommodating spectrum slots as of ML-SBVT.

V. Simulation Scenario and Results Analysis

Simulations are performed on a static network scenario. We are considering German network scenario in our work with 17 nodes and 26 physical links which makes the overall node degree of 3.06 (connectivity 19%) [21], shown in Fig. 4. Another network that we are considering is random network topology of 20 nodes with node degree of 3 (connectivity 15.8%) and 4 (connectivity 21%), shown in Fig. 5, adopted from [22]. The transponders capacity is considered to be 400Gb/s with 16 slots per transponder due to the QPSK modulation with no limitation on the number of transponders allowed per node. The performance of three SBVT architectures (ML-SBVT, Flex-OCSM & MW-SBVT) are compared in terms of the number of SBVTs required per node and spectrum slots used by each SBVT. Two separate traffic profiles are considered; heterogeneous traffic and homogeneous traffic, for comprehensive comparison in different traffic scenarios. In heterogeneous traffic profile, the traffic is randomly distributed on the nodes such that the network has an average traffic of T_r per node [22]. While in homogeneous traffic profile, a uniform traffic of T_h is considered for each (s,d) pair represented in traffic matrix.

A. German Topology

1) Number of SBVTs: Fig. 6 depicts a comparison of the number of ML-SBVT, Flex-OCSM and MW-SBVT for heterogeneous traffic profile. While the Fig. 7 shows the number of SBVTs comparison for homogeneous traffic profile.

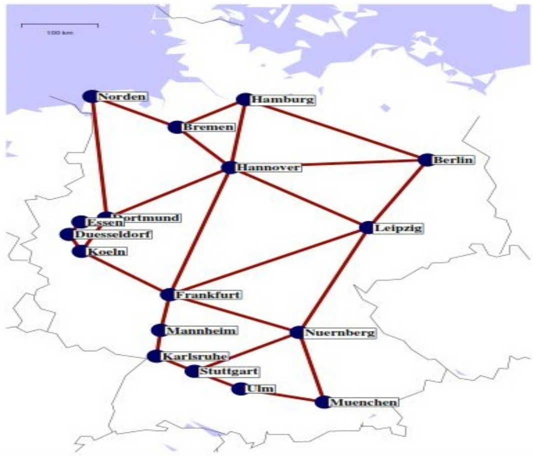

Fig. 4: German Network

Fig 6 shows ML, Flex-OCSM and MW SBVTs trend with the increasing heterogeneous traffic profile. It depicts that

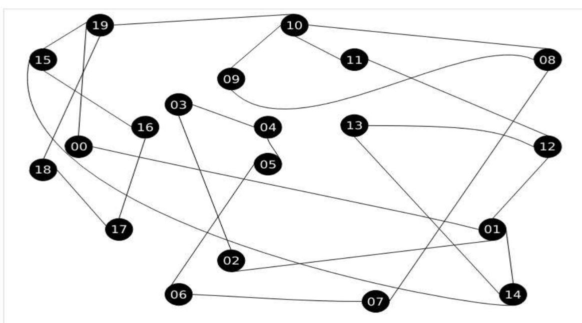

Fig. 5: Random Network

with the increasing heterogeneous traffic, ML-SBVT performs better than MW-SBVT as it can efficiently map onto the spectrum slots due to independent laser sources that can freely tune within the spectrum. The Flex-OCSM performs better than the other two as it does not require 2 GHz guard band between the sub-carrier. Moreover, in comparison to Fig. 7, the performance of ML-SBVT and Flex-OCSM degrades for homogeneous traffic profile because of the higher traffic request. This is due to the characteristic of MW-SBVT that it has the better capability of handling greater traffic that can be accommodated by super-channel as it uses a single laser source and optical carriers are intrinsically locked. For that reason the guard bands between the subcarriers within the super-channel can be reduced significantly and hence it can efficiently utilize the SBVT.

2) ML-SBVT, Flex-OCSM and MW-SBVT in-device utilization: Keeping the same traffic profiles, simulation results are generated for the difference between number of slots used by each of the SBVT are shown in Fig. 8 and Fig. 9. It is interesting to note that the MW-SBVT and Flex-OCSM performs better in the slots utilization as compared to the ML-SBVT for each case as ML-SBVT have to insert guard band of ≈2GHz between each sub-carrier. The difference is increased with the increase in traffic demand as more number

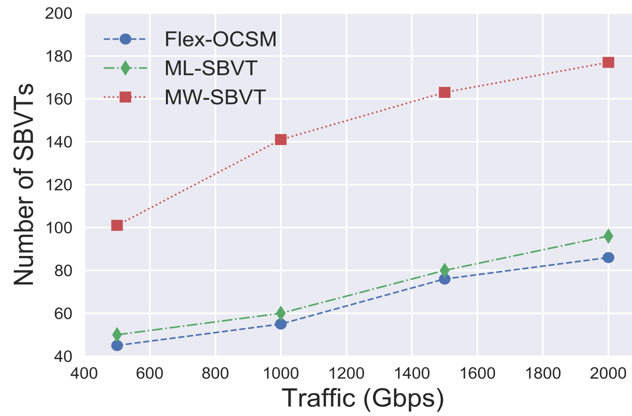

Fig. 6: SBVTs Comparison for Heterogeneous Traffic

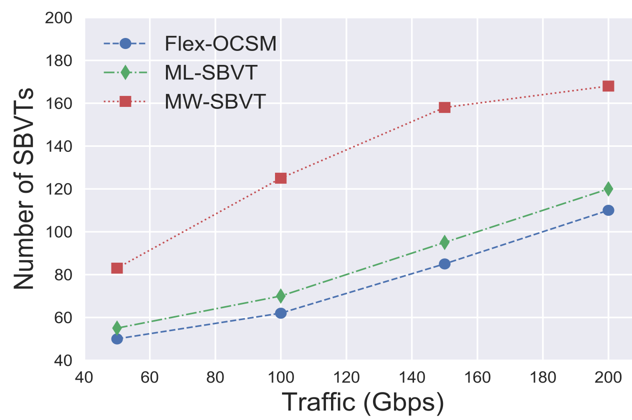

Fig. 7: SBVTs Comparison for Homogeneous Traffic

of guard bands (≈2GHz) will be used. By comparing both traffic profile scenarios, the results show that for homogeneous traffic the difference between SBVTs result is less as compared to heterogeneous traffic profile.

Above results shows that Flex-OCSM performs better both in hardware utilization as well as in-device utilization due to its ability to counter the sub-carrier interference and negating the requirement of guard-band between sub-carriers. Other than Flex-OCSM, result shows that ML-SBVT performs better in terms of number of SBVTs as compared to MW-SBVT, whereas MW-SBVT performs better when device utilization is considered because of the ability to generate intrinsically locked sub carriers which do not require guard band between them unlike ML-SBVT.

B. *Random Topology*

Random topology is selected to compare the performance of various significant network parameters that can not be varied for actual network. Random topology having the same traffic profiles is considered with parameters of link lengths and connectivity between nodes to see its effect on number of SBVTs and device utilization. There are 20 nodes in the network having increasing average physical link lengths

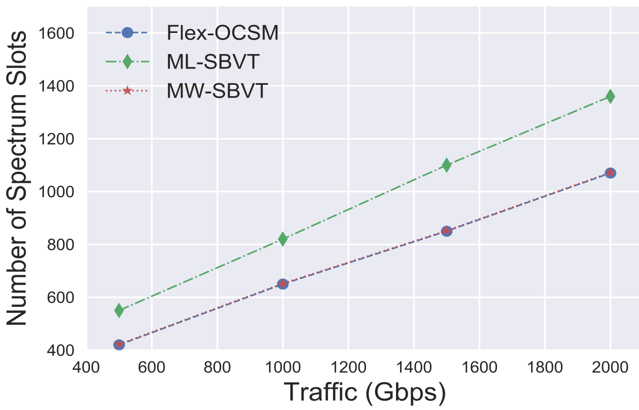

Fig. 8: In-device Utilization of Slots for Heterogeneous Traffic

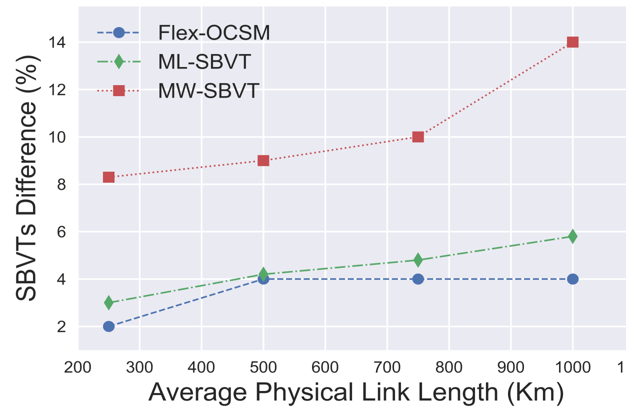

Fig. 10: SBVTs Difference (%) for ND=3 (ND=4 as ref.)

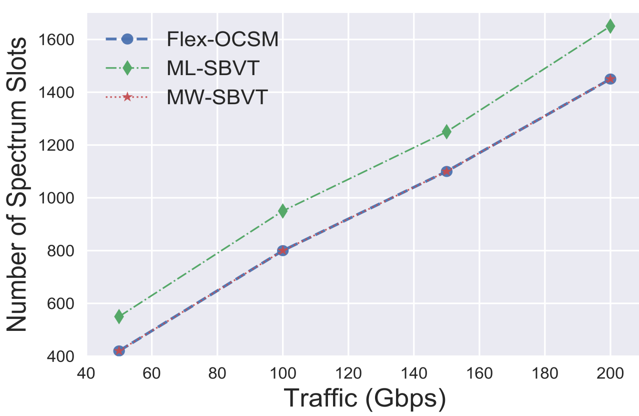

Fig. 9: In-device Utilization of Slots for Homogeneous Traffic

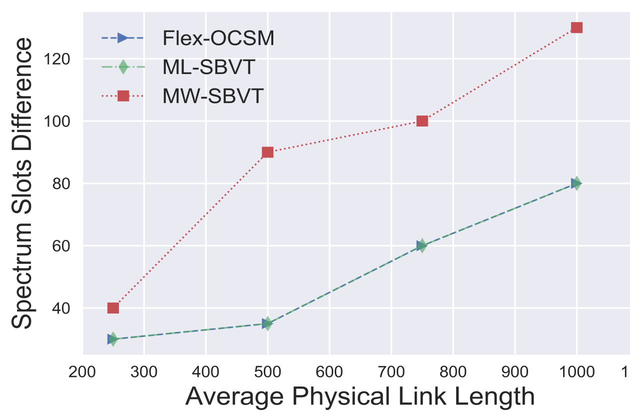

Fig. 11: Spectrum Slots Comparison for ND=3 (ND=4) as ref.)

starting from 250 km up to 1000 km with gap of 250 km. Two different node degrees (ND=3 and ND=4) are considered.

1) Number of SBVTs: Fig. 10 shows the plot of avg. physical link length against the percentage difference between the number of SBVTs required for different network connectivity. The plot shows the difference for ND=3 with ND=4 taken as reference.

From the fig. 10 we can conclude that less number of SBVTs are required to accommodate the requests for more connected network (ND=4) as compared to less node degree (ND=3). The reason for this is that in higher ND network the path for each request is available in less number of hops whereas for less connected network (ND=3) the same request is fulfilled by following a comparatively longer path (more hops). As the avg. physical link length of the network increases, the difference of SBVTs requirement also increases, showing the negative impact of higher physical link length of network.

2) ML-SBVT, Flex-OCSM and MW-SBVT in-device Utilization: In Fig. 11, the graph is plotted of average physical link length against the difference of slots utilization in SBVTs. The difference is plotted between the slots utilization of ND=3 for SBVTs and ND=4 for SBVTs. The difference between the spectrum slots utilization for the SBVTs increase as the link length increases because of the fact that request is fulfilled by passing through longer paths (more hops), which in turn will use more number of slots in the SBVTs traversing through-out the path. The performance of Flex-OCSM and MW-SBVT is better than ML-SBVT in in-device utilization because of the additional guard-band requirement in the ML-SBVT.

From above results, we conclude that MW-SBVT and Flex-OCSM has better utilization of device over ML with lower connectivity and this gap reduces with the graph connectivity.

From above results, we can conclude that Flex-OCSM performs better in terms of hardware utilization because it takes the flexibility of ML-SBVT of tuning the laser sources anywhere within the C-band. On the other hand it benefits from the intrinsically locked frequency slots of MW-SBVT, thus performing equal to MW-SBVT in the in-device utilization.

VI. Conclusions

In this paper we have analyzed the impact of different optical carrier source technologies (ML-SBVT, MW-SBVT and Flex-OCSM) and deployment strategies (dedicated and centralized) on the network performance of SBVTs. We considered the German network of 17 nodes and a random network of 20 nodes and analysed for different parameters like traffic profiles, average link lengths and network connectivity. The results shows the pros and cons of three types of SBVTs under different network conditions and determine the tradeoff between them. The paper presented a comprehensive performance analysis of three types of SBVTs and based on the findings of the analysis proposed selection criteria for suitable SBVT type depending on the specific network requirement. Results show that Flex-OCSM has better utilization in terms of hardware number and as well as in-device resource utilization confirming the additional benefits of centralized Flex-OCSM architecture and further proving its techno-economic viability.

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