Ultra-Dense Wavelength Switched Network: A Special EON Paradigm for Metro Optical Networks

Gangxiang Shen, Ya Zhang, Xu Zhou, Yang Sheng, Ning Deng, Yiran Ma, and Andrew Lord

Abstract

Intensive video and cloud computing services are putting much pressure on metro networks to meet stringent requirements such as low latency, low power consumption, and high spectral efficiency, where the system cost is sensitive. To address this challenge, we introduce a special elastic optical network paradigm called the ultra-dense wavelength switched network (UD-WSN) for metro optical networks. The architecture supports a spectrum granularity (e.g., 6.25 GHz or even 5 GHz) finer than the current smallest standardized 12.5 GHz, which enables more efficient spectrum utilization when provisioning metro low-speed service connections (e.g., sub-1G/1G/10G services). The performance of UD-WSN is evaluated from the techno-economic perspective in comparison with the conventional OTN over DWDM network. Case studies demonstrate the merits of the proposed architecture. Considering the promising potential of UD-WSN, we also suggest several open research issues for it.

Introduction

The Internet traffic keeps on increasing due to the popularity of bandwidth-intensive video, fourth/fifth generation (4G/5G) mobile, and cloud services. Cisco predicted that annual global IP traffic will surpass the zettabyte (1000 EB) threshold in 2016, and overall IP traffic will grow at a compound annual growth rate (CAGR) of 22 percent from 2015 to 2020 [1]. Similarly, the forecasting from Bell Labs indicated that metro traffic would grow about two times faster than traffic going into the backbone by 2017, and overall there would be a 560 percent increase in traffic in the metro by last year [2]. On the other hand, in contrast to the backbone network, where high-speed optical channels prevail, in the metro network sub-1G/1G/10G service connections occupy a dominant percentage among all the client ports, and it was predicted that in the foreseeable future this will not change [3]. With the popularity of 4G/5G mobile and cloud services, more stringent quality of service (QoS) requirements are imposed on these service connections in the metro network. These include low latency (e.g., 1 ms latency according to the Next Generation Mobile Networks Alliance), low power consumption, high spectral efficiency, and so on.

The pure optical transport network (OTN) and the OTN over dense wavelength-division multiplexing (DWDM) network, also referred to as the OTN/DWDM network [4], are two typical metro network architectures today. However, the pure OTN architecture would experience extensive optical-electronic-optical (OEO) conversions, which leads to high cost, high power consumption, long connection latency, and so on. Although the OTN/DWDM network introduces intelligence in the optical layer by deploying reconfigurable optical add/drop multiplexers (ROADMs) to reduce OEO conversions, it is still a type of OTN-based network, in which OEO conversions are still common. Too many OEO conversions would create challenges for the OTN/DWDM network to meet the aforementioned stringent QoS requirements. Thus, it is vital to find new architectures and technologies for the metro network that can minimize OEO conversions. This motivated us to seek a new solution for the metro network.

Jointly inspired by the techniques of the elastic optical network (EON) [5] in the backbone network and ultra-dense WDM passive optical network (UDWDM-PON) [6] in the access network, in this article, we introduce the ultra-dense wavelength switched network (UD-WSN) for the metro network. We position UD-WSN as a special EON paradigm that combines the merits of EON and UDWDM-PON. It is novel, aiming to resolve the difficulties and challenges faced by today's OTN-based metro optical networks. First, considering the dominance of sub-1G/1G/10G services in the metro network, UD-WSN splits frequency slots (FSs) to even finer granularities (e.g., 5 GHz or 6.25 GHz) than those in today's EON. This would improve the spectrum utilization when using an FS to accommodate a sub-1G/1G/10G service. Second, a smaller FS granularity enables a larger number of optical channels in the fiber C-band. Considering the reality that sub-1G/1G/10G service connections occupy a dominant percentage among all the client ports in today's and foreseen future optical metro networks [3], it is beneficial to make UD-WSN inherit the "wavelength-to-the-user" operational mode from UDWDM-PON [6]

Intensive video and cloud computing services are putting much pressure on metro networks to meet stringent requirements such as low latency, low power consumption, and high spectral efficiency, where the system cost is sensitive. To address this challenge, the authors introduce a special elastic optical network paradigm called the ultra-dense wavelength switched network (UD-WSN) for metro optical networks.

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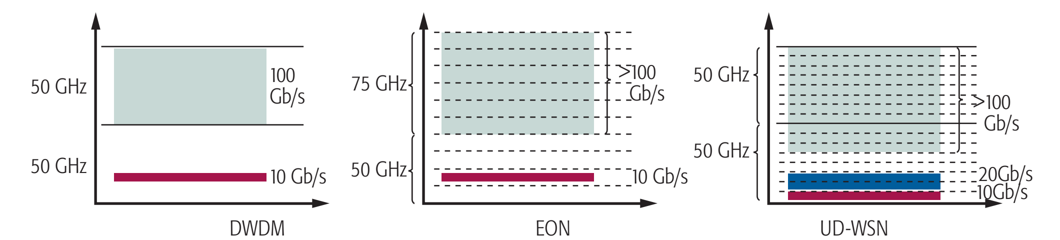
Digital Object Identifier: 10.1109/MCOM.2018.1700025

UD-WSN can be considered as a special EON, particularly targeted at the metro network where many sub-1G/1G/10G services are provisioned. With a common modulation format (e.g., QPSK without polarization division multiplexing (PDM)), a 2-bit/s/Hz spectral efficiency can be achieved, which approximately corresponds to 0.5-GHz and 5-GHz bandwidth for a 1G and 10G service, respectively.



# of channels in C-band	DWDM	EON	UD-WSN	UD-WSN
	50 GHz	12.5 GHz	6.25 GHz	5 GHz
	80	320	640	800

Figure 1. Spectrum usage in the DWDM network, today's EON, and UD-WSN [8].

to establish direct lightpaths for each user, which avoids OEO conversions required in the OTN/DWDM network, and therefore can eliminate many intermediate OTN switches for lower hardware cost, and help reduce connection latency and system power consumption. It should be noted that different from UDWDM-PON, where a user can be a residential one, users in UD-WSN can be enterprises, central offices, optical line terminals (OLTs), and so on, whose required bandwidth is generally higher than a residential user. Third, as a special case of EON, UD-WSN inherits the merit of *elastic channel capacity* from EON, which can combine multiple neighboring FSs to form a larger optical channel. As a result, UD-WSN is also capable of provisioning lightpaths with different data rates, ranging from sub-1G/1G/10G to 40G and 100G.

In [7], we proposed the concept of UD-WSN and validated it through hardware implementation for the first time. In this article, we aim to introduce UD-WSN to a broader audience and demonstrate its advantages from the techno-economic perspective in comparison with other conventional metro network architectures. Particularly, the performance in terms of cost, spectral efficiency, power consumption, and connection latency are evaluated and compared. Also, considering the promising potential of UD-WSN, we discuss other open issues.

Ultra-Dense Wavelength Switched Network

Spectrum Usage

Figure 1 compares the spectrum usage for the three different types of networks, including the DWDM network, today's EON, and UD-WSN [8]. In the DWDM network, the fiber spectrum is sliced into coarse granularities, each of which is fixed to be 50 GHz. Each optical channel that uses a DWDM wavelength exclusively occupies the 50 GHz bandwidth regardless of the actual carried data rate on the channel. Although it is spectrally efficient for a 50 GHz grid to carry a 100 Gb/s channel, the spectrum utilization would be fairly low when it is used to carry a 10 Gb/s channel.

To improve the spectrum utilization, EON was proposed to shrink the FS granularity from 50 GHz (for the DWDM system) to 12.5 GHz [9]. Multiple neighboring FSs are allowed to be combined to provide a broader bandwidth for a high-speed channel (e.g., 400 Gb/s). As such, EON is promising in spectrum utilization and has been widely implemented in the form of super-channels in the backbone network.

UD-WSN can be considered as a special EON, particularly aimed at the metro network where many sub-1G/1G/10G services are provisioned. With a common modulation format (e.g., quadrature phase shift keying, QPSK, without polarization-division multiplexing, PDM), a 2 b/s/Hz spectral efficiency can be achieved, which approximately corresponds to 0.5 GHz and 5 GHz bandwidth for 1G and 10G service, respectively. Using a 12.5 GHz FS to carry a 1G or 10G service is obviously spectrally wasteful. To improve the spectral efficiency, UD-WSN further shrinks the FS granularity to smaller ones (e.g., 6.25 GHz or 5 GHz), which can better match the bandwidth requirement of these low-speed services. Note that although it would be more efficient to shrink the FS to just fit the spectrum required by a 1G service, the physical limitation on optical components (e.g., the spectrum resolution of a wavelength selective switch, WSS) and the cost of the system prevent us from doing so. Shrinking FS granularity signifcantly increases the number of optical channels establishable in the fiber C-band. UD-WSN with a 5 GHz FS can provide a maximum number, up to 800, of channels for end-to-end lightpath establishment, in comparison with 80 and 320 channels in the DWDM network and today's EON, respectively (Fig. 1). A larger number of FSs greatly increases the flexibility of user capacity provisioning, thereby leading to better spectral efficiency for UD-WSN.

Network Architecture

Figure 2 shows the architecture of UD-WSN, which follows the conventional multi-level metro network architecture to include core and *aggregation* segments. The core segment is the backbone of the metro network, while the aggregation segment is an access part to aggregate traffic demands from various distributed access nodes, which are connected to users, for example, a wireless base station (BS). The switch nodes in the core segment are called metro core (MC) nodes, and those in the aggregation segment are called metro aggregation (MA) nodes.

Because the core and aggregation segments in UD-WSN have different traffic demand distributions, two different subnetwork architectures are proposed. For the core segment as shown in Fig. 2, a symmetric architecture is adopted to match the symmetric traffic characteristics between MC nodes. Specifically, multi-flow coherent transceivers [7] with 50 GHz optical bandwidth are

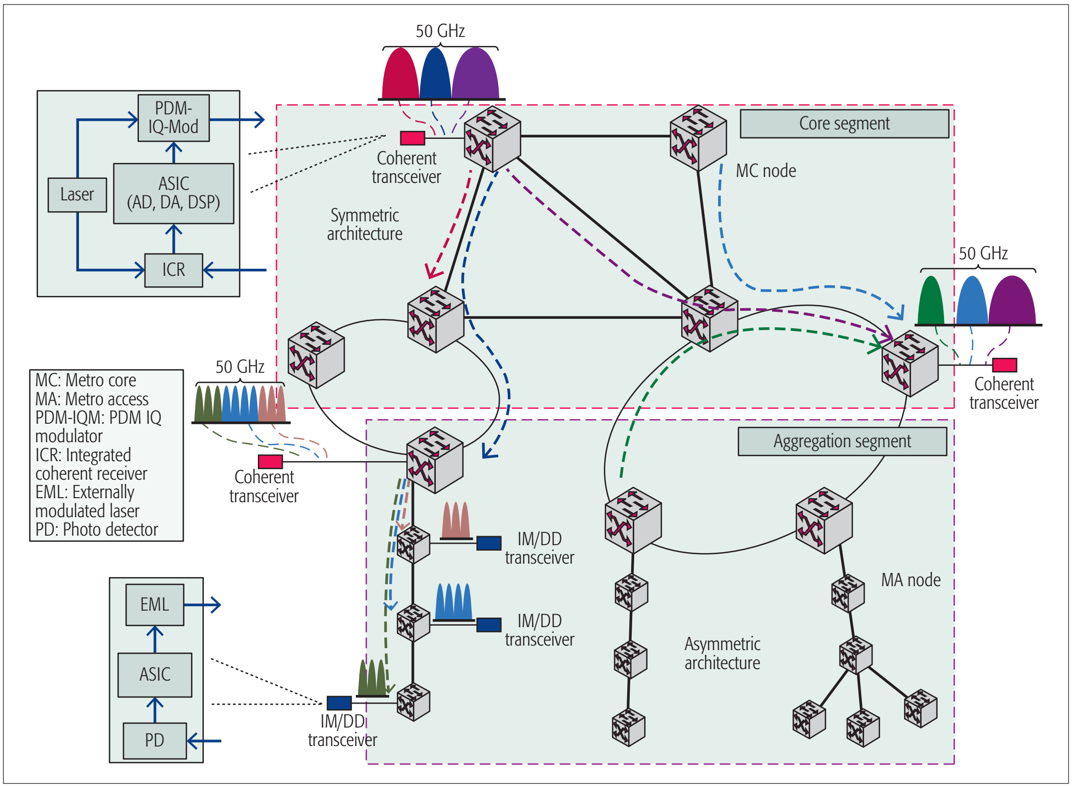


Figure 2. UD-WSN metro network.

The core segment is the backbone of the metro network, while the aggregation segment is an access part to aggregate traffic demands from various distributed access nodes, which are connected to users, for example, a wireless base station. The switch nodes in the core segment are called metro core nodes, and those in the aggregation segment are called metro aggregation nodes.

employed for optical channel establishment between MC nodes. This bandwidth is limited by the 3 dB modulation bandwidth of a commercial transceiver and is sliced into multiple subcarriers or FSs with a certain granularity (e.g., 5 GHz). The traffic flows to different destination MC nodes are mapped onto different optical subcarriers. These subcarriers can be optically switched by WSSs and flexibly added/dropped at different MC nodes with one or multiple FSs. In the opposite direction, a coherent transceiver receives multiple optical subcarriers from different MC nodes subject to the condition that no spectrum collision would happen among these subcarriers.

For the aggregation segment (Fig. 2), because the traffic demands mainly exist between the MC nodes and the MA nodes, an asymmetric architecture is implemented. Specifically, at the MC node, multiple optical subcarriers are generated by a single coherent transceiver within a 50 GHz range, which can be split and switched by WSSs in the optical domain and further dropped to different MA-node chains. At each MA node on the chain, no WSS and coherent detection are required to drop and receive sub-channels; rather, low-cost intensity-modulated and directly detected (IM-DD) transceivers are used to receive the corresponding subcarriers, which are filtered by the pairs of UD-blockers and UD-array waveguide gratings (AWGs). In the opposite direction, multiple optical subcarriers generated from different MA nodes are optically multiplexed and forwarded to a common coherent transceiver at the MC node. The combined spectrum from the different MA nodes is required to be within a 50 GHz range.

The key challenges for realizing UD-WSN include the WSS technique supporting ultra-fine FS granularity (e.g., 6.25 or 5 GHz granularity) and the wavelength stability of a laser source in an optical transponder. Today, WSS with 10 GHz smallest channel bandwidth and 1 GHz resolution is commercially available (e.g., Finisar's WaveShaper Series), of which the crosstalk is typically as low as –30 dB. A WSS supporting 5 GHz smallest channel bandwidth, 1 GHz resolution, and 50 MHz spectral addressability was recently reported in [10] using a waveguide grating router with permanent phase trimming, which demonstrated a high isolation of each channel passband at a very low crosstalk level. In addition, our simulation studies based on a UD-WSS (4K LCoS) with 12.5 GHz 6 dB bandwidth show that the crosstalk from the adjacent channels (12.5 GHz) is no higher than –50 dB. If considering the non-ideality of the device, we are confident that the crosstalk will not be higher than –30 dB. All these techniques convince us of the possibility of fabricating a WSS to support an ultra-fine FS granularity. Also, a laser source with frequency stability of 0.5 GHz is technically mature. As an example, wavelength stability of 5 pm (i.e., 0.3125 GHz) over a lifespan was verified by Furukawa in 2003 [11]. The maturity of these key technologies enables UD-WSN to minimize the usage of bandwidth for the guardband between neighboring UD FSs (as small as 10 percent of the channel bandwidth), thereby ensuring the efficiency of spectrum utilization.

Techno-Economic Analyses for UD-WSN

To evaluate the benefits of applying UD-WSN in the metro network, we perform a techno-economic analysis in comparison with its counterparts, that is, the pure OTN and the OTN/DWDM

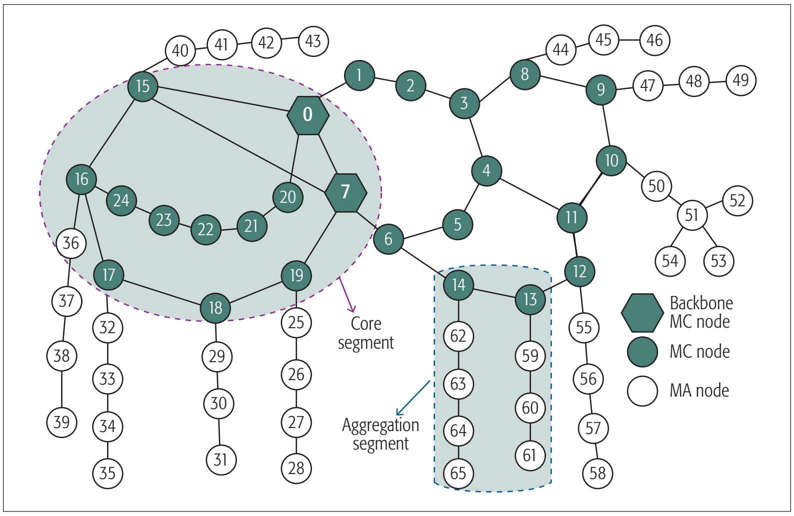


Figure 3. Test network.

Network device	Cost (unit)	Power consumption (unit)
100G coherent TRx	60	36
10G IM-DD TRx	6	5
25G IM-DD TRx	9	7.5
WSS (50 GHz)	47	4.5
WSS (12.5 GHz)	54	4.5
EDFA	8	3.2
UD-blocker	0.2	0
UD-AWG	1.6	0
OTN switchboard	120	72

Table 1. Relative costs and power consumptions of network devices.

network, from the perspectives of cost, spectrum usage, power consumption, and service connection latency.

Test Condition

We use a metro network topology shown in Fig. 3 as our test network. Note that this network topology is an adapted version from a real industrial network, and therefore the practicality of the subsequent simulation study is convincing. The symmetric and asymmetric architectures are implemented for the core and aggregation segments, respectively, which are highlighted as a ring and a chain. Among all the MC nodes, there are two backbone MC nodes, which aggregate the traffic demands from the other nodes and function as gateways to the backbone network. In the aggregation segment, traffic flows are aggregated from dispersed MA nodes to their associated MC nodes and the latter further forward the aggregated traffic flows (together with other local traffic demand) to the two backbone MC nodes. There is an OTN switch deployed at each intersecting node between the core network and the aggregation network (e.g., node 18 in Fig. 3). The OTN switch functions to groom the traffic demand incident to the node. In the aggregation segment, the ratio of the service connections of 1G, 10G, and 40G is 3:6:1, and in the core segment, the ratio of the service connections of 10G, 40G, and 100G is 8:1:1. Such ratios are set based on the industrial statistical data as in [3], where small bandwidth services occupy dominant percentages. For performance analysis, we also assume the relative costs and power consumptions of network devices in Table 1. These parameters are real, from industry products, but relative as their absolute values are industrially confidential.

We consider three network cases. UD-WSN-x corresponds to UD-WSN, where x means the FS granularity used. OTN corresponds to the pure OTN case, where only an OTN switch is deployed at each node (without a ROADM). OTN/DWDM corresponds to the case that consists of two network layers (i.e., the OTN and optical layers). In the optical layer, ROADMs are deployed at each node, which enable lightpath optical bypass and establish optical channels for the OTN layer. For the pure OTN case, the shortest path algorithm is employed to find the route between each node pair, and electronic traffic grooming is carried out at each node. For the OTN/DWDM case, lightpath bypass is always used in the optical layer if possible, and electronic traffic grooming is performed only at the ending nodes of lightpaths. An efficient scheme called *multihop traffic grooming* [12] used in the IP-over-DWDM network was employed for OTN-over-DWDM traffic grooming.

Techno-Economic Analyses

We perform techno-economic analyses for UD-WSN in comparison with the other two architectures, that is, the pure OTN and OTN/DWDM networks, from the perspectives of capital expenditure (CapEx), power consumption, spectral efficiency, and average service connection latency.

CapEx: Figure 4 shows the network CapEx per 1 Gb/s and power consumption with increasing traffic demand. Because almost no OEO conversions are required at intermediate nodes in UD-WSN, we observe that UD-WSN can significantly reduce CapEx per 1 Gb/s compared to the pure OTN and OTN/DWDM networks by 53.5 and 35.3 percent, respectively. Moreover, UD-WSN with the smallest spectrum granularity (i.e., 5 GHz) shows the lowest CapEx per 1 Gb/s. This is because in the aggregation segment, the asymmetric architecture of UD-WSN significantly reduces the number of coherent transceivers used given that a single coherent transceiver can support many subcarriers transmitted to different MA nodes, and moreover, the direct modulation scheme is employed at each MA node. Compared to the 12.5 GHz case, the 5 GHz granularity is shown to improve CapEx per 1 Gb/s up to 14.2 percent. This is significant in demonstrating the benefit of employing a finer spectrum granularity for UD-WSN. Also, it is interesting to observe a saturation trend, that is, with increasing traffic demand, the network CapEx per 1 Gb/s decreases significantly at the beginning and slows down when the traffic demand reaches a certain threshold level.

Power Consumption: We also compare the

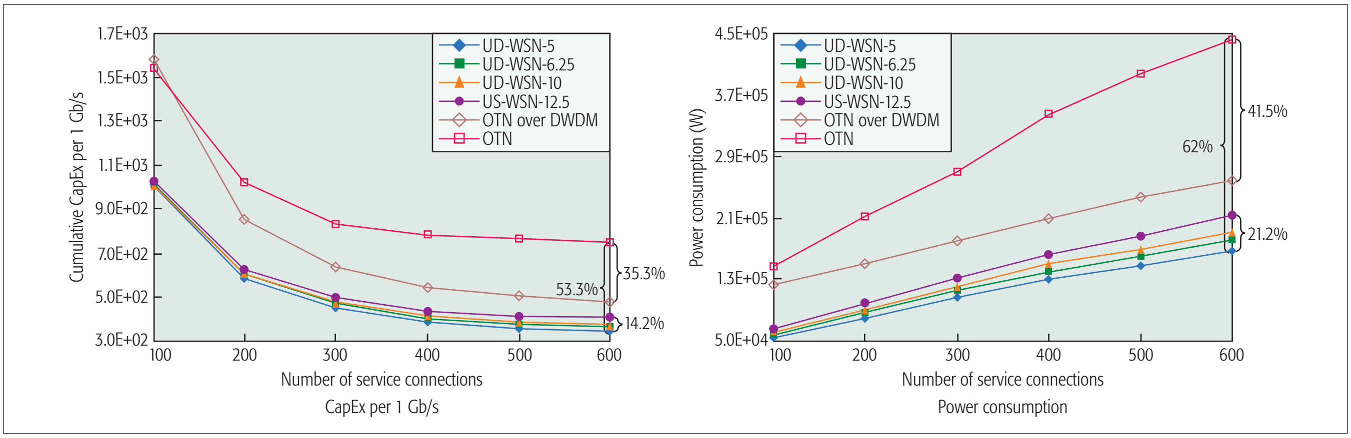


Figure 4. CapEx per 1 Gb/s and power consumption.

power consumption of the three types of networks (Fig. 4). UD-WSN can significantly reduce the power consumption by up to 62.0 and 41.5 percent compared to the other two network architectures, that is, OTN and OTN/DWDM, respectively. This is because UD-WSN has almost no intermediate OEO conversions when establishing end-to-end connections between node pairs, while the other two networks experience many more OEO conversions at intermediate nodes. Specifically, the OTN network needs to experience an OEO conversion every hop when the traffic demand traverses a node, and although fewer, the OTN/DWDM network with multihop traffic grooming still needs to go through many OEO conversions at the ending nodes of each lightpath hop. In contrast, for UD-WSN, OEO conversions only happen at the intersecting nodes of the core and aggregation segments. As a result, each service connection will experience *at most* one OEO conversion if the traffic flow is aggregated from an MA node to a backbone MC node. Because OEO conversion consumes more power than all-optical bypass, fewer OEO conversions mean lower power consumption. In addition, compared to the 12.5 GHz case, the 5 GHz granularity is shown to reduce power consumption by up to 21.2 percent. This is also significant in demonstrating the benefit of employing a finer spectrum granularity for UD-WSN.

Spectral Efficiency: We also evaluate the spectral efficiency of UD-WSN under dynamic traffic load where the service arrival between each node pair follows a Poisson process and the holding time of each established connection takes a negative exponential distribution. A total of 10^6 service arrival events are simulated. A bandwidth blocking probability (BBP), defined as the ratio of total blocked traffic bandwidth to the total bandwidth of arrived traffic requests, was evaluated. Figure 5 shows BBPs of the different network architectures under variable Erlang traffic loads per node pair. We see that UD-WSN with 5 GHz FS granularity is spectrally efficient to achieve BBPs close to the OTN/DWDM network, although the latter has the network-wide traffic grooming capability. Moreover, with the decrease of FS granularity, UD-WSN tends to demonstrate a better BBP performance; for example, comparing the cases of 5 GHz vs. 12.5 GHz, the BBP improvement is more than 10 times. This is because a finer FS granularity can provide more optical channels in the fiber C-band as shown in Fig. 1, which allows more lightpaths to be established.

Latency: With the assumptions that each OEO conversion (i.e., OTN switching) would suffer a 50 μs delay and that an optical signal would take 5 μs to traverse a 1 km fiber distance, we also compare the average connection latency of the different network architectures in Fig. 5. We see that UD-WSN can achieve the lowest average latency, while the OTN network shows the highest latency, and the OTN/DWDM network falls in the middle. The reason for this is similar to that for the power consumption in the previous subsection. In UD-WSN, service connections experience the fewest OEO conversions, thereby demonstrating the lowest average connection latency.

Other Research Issues

Based on the above techno-economic analyses, we can see that UD-WSN is promising for the metro network. This motivates us to consider other research issues so as to exploit its greater advantages. We discuss these issues as follows.

Multi-Flow Transponder

In the reference architecture (Fig. 2), the multi-flow coherent transponder generates ten 5 GHz FSs from a single-laser multi-wavelength (MW) source. These FSs are required to be spectrally neighboring, which adds a restriction on spectrum assignment when establishing lightpaths. To relax this constraint, a multi-flow transponder that is designed from an array of *N* lasers [13] can be employed, where each of the lasers can generate an independent 5 GHz flow. This type of transponder allows FSs assigned to different lightpaths not necessarily to be neighboring, but scattered in a wider spectrum as long as the FS indices will not collide when they are combined back to a common 50 GHz bandwidth. This type of transponder provides flexibility in lightpath spectrum assignment at the cost of a more expensive subsystem.

Filterless Node Architecture

For the access segment in Fig. 2, it is cost effective to employ the direct modulation subsystem to add/drop user traffic at each MA node. To further reduce the system cost, we may remove the ROADM by using a filterless architecture, that is, through an optical splitter at the node, to tap a

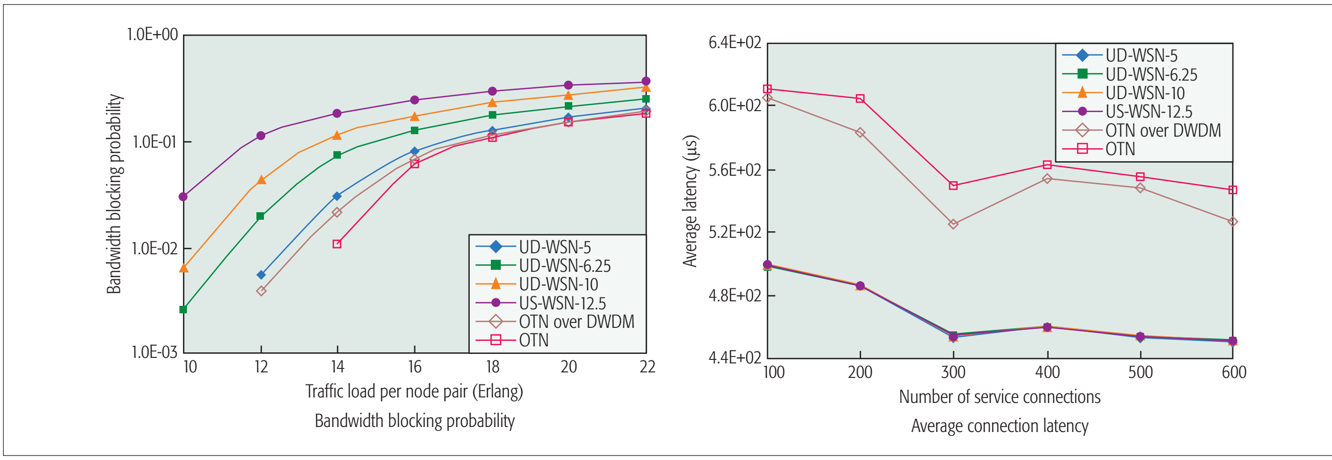


Figure 5. Bandwidth blocking probability and average connection latency.

part of the optical signal and then employ a simplified low-complexity coherent transceiver to filter the optical sub-channel that is aimed at the node. Such a *drop-and-continue* architecture is similar to the one proposed for the filterless optical network in [14]. By doing this, we can reduce the system cost at each MA node and the overall network cost since there are a large number of MA nodes in the whole network. However, without stopping the dropped sub-channels from the fiber, we need to pay special attention to their interference when assigning spectra for the sub-channels to other MA nodes in the downstream. Appropriate spectrum assignment approaches have been developed in [14] to tackle this, which can be reused for UD-WSN.

Mixed Configuration with OTN Switches

In the current UD-WSN architecture, only the intersection node between the core and access segments is deployed with an OTN switch, which performs OEO conversion and traffic grooming for better capacity utilization. A more general scenario is to consider a mixed configuration where multiple nodes can be deployed as the combinations of OTN switches and ROADMs. In this context, a fully occupied lightpath can directly bypass an OTN-ROADM node without electronically going through the OTN switch, while for an underutilized lightpath, an OEO conversion can be performed by the OTN switch to interrupt the lightpath, and more client-layer traffic can be aggregated onto it. For this type of mixed configuration, open issues can include where to place OTN switches and when to interrupt an optical channel by an OTN switch to fill up its capacity.

Impact of Traffic Time-Spatial Variation

For the metro network, traffic demand demonstrates a strong time-spatial variation. For example, in a city there can be an industrial park or business section in the downtown area, together with multiple living places in suburban areas. In the daytime, there can be high traffic volume in the downtown area and low traffic volume in each of the suburban areas. However, in the evening, when all the people in the downtown area return to their homes, the traffic volume in the downtown area can significantly shrink, while that in the suburban areas can surge. Such a traffic time-spatial variation has posed a significant challenge for the metro network. In the context of UD-WSN, it is interesting to evaluate whether a much larger number of FSs in each fiber can help alleviate the capacity wastage due to the time-spatial variation. A similar evaluation can also be made for multi-stage planning of a metro network. We wish to find whether UD-WSN can still show its advantage in various aspects due to its larger number of optical channels in the C-band.

Spectrum Defragmentation

Similar to EON, UD-WSN also faces the issue of spectrum defragmentation. Given a metro network that contains multiple rings and/or chains, it is interesting to evaluate how the FS granularity can impact the performance of spectrum defragmentation. Although there have been extensive studies on spectrum defragmentation for EON, spectrum defragmentation for UD-WSN in the context of the multi-layer scenario is an interesting open issue to be considered. Recently, we have performed a preliminary study on the benefit of spectrum defragmentation in UD-WSN [15]. It is interesting to observe that spectrum defragmentation is promising to further improve spectrum utilization in a spectrum granularity finer than 12.5 GHz.

Spectrum Leasing

Fiber leasing is an important business model today for the carriers of different tiers. A single leased fiber can carry up to 80 channels with the DWDM technique. In UD-WSN, since up to 800 channels can be provided in each fiber if a 5 GHz FS is employed, a new business model, *spectrum leasing*, can be considered. We may divide the fiber C-band into 10 bands with each supporting 80 channels. As a result, 10 customers can be supported by a single fiber. The benefit of spectrum leasing is apparent. From the customer's perspective, they can still get 80 channels as in the case of fiber leasing, but they need to pay much less compared to fiber leasing. From the carrier's perspective, they can use a single fiber to support 10 customers and therefore overall make more from a single fiber. Spectrum leasing may be implemented in two modes. The first is called *hard leasing*, which strictly splits and assigns the C-band to each customer, not permitting spectrum trading between customers. For better capacity utilization, it can also be implemented as *soft leasing*, which allows customers who share a common fiber to trade their spectrum resources in different time slots. For this, game theory may be required to ensure trading fairness between different customers.

Conclusions

Metro networks are facing the challenge of efficiently provisioning network bandwidth subject to the stringent requirements of latency, power consumption, spectral efficiency, and so on. For this, a special EON paradigm, UD-WSN, is proposed for the metro network that supports finer spectrum granularities (e.g., 6.25 GHz or even 5 GHz) when allocating spectrum resources to lightpaths. The finer spectrum granularities can achieve a nice match in bandwidth with the sub-1G/1G/10G services whose percentages are dominant in the metro network, thereby improving spectrum utilization. Moreover, UD-WSN can also support more optical channels in the fiber C-band, thereby allowing more direct lightpaths to be established, which can significantly shorten the connection latency and reduce the power consumption of the whole system. From the techno-economic perspective, we evaluate UD-WSN in comparison with the other two metro network architectures, OTN and OTN/DWDM. Results verified the merits of UD-WSN from the perspectives of CapEx per 1 Gb/s, power consumption, spectral efficiency, and average connection latency. Finally, considering the promising potential of UD-WSN, we also discuss its several open issues. We hope this article will spark new research interest in this topic.

Acknowledgment

This work was jointly supported by the Collaborative Industrial Project from Huawei Technologies Co., Ltd, China (YBN2016050116), the National Natural Science Foundation of China (NSFC) (61671313), and the Science and Technology Achievement Transformation Project of Jiangsu Province, PR China (BA2016123).

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Fiber leasing is an important business model today for the carriers of different tiers. A single leased fiber can carry up to 80 channels with the DWDM technique. In UD-WSN, since up to 800 channels can be provided in each fiber if a 5-GHz FS is employed, a new business model, that is, spectrum leasing, can be considered.