A Cost-effective and Energy-efficient All-Optical Access Metro-Ring Integrated Network Architecture

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Abstract—**All-optical access-metro networks avoid costly OEO conversions which results in subsequent reduction of infrastructure costs and improvement in energy-efficiency of the network. However, avoiding OEO conversions imply that OLTs are unable to route packets to the ONUs due to unavailability of processing provisions, which necessitates setting up of lightpaths between ONUs. Setting up lightpaths, require a control mechanism, which considers requests from all ONUs in the metro-ring and informs them about the lightpath to be set up. Owing to high data rate of optical networks, the lifetime of a lightpath may be minuscule (few microseconds), which enforces the control mechanism to perform these operations frequently, which incurs large control overhead and processing complexity. This turns out to be a major bottleneck in all existing proposals, which can be alleviated if lightpaths are set up between OLTs instead of ONUs. However, in this case, facilitating data transmission between source and destination ONUs becomes a challenge, due to inability of OLT to process and buffer data packets. In this paper, we resolve this issue by proposing a novel architecture which supports a plausible MAC protocol. The proposed architecture demonstrates significant reduction in cost and power-consumption figures with a slight improvement in reach when compared to traditional architectures.**

Index Terms—**all-optical, access-metro integration, metro-ring network**

I. Introduction

Passive Optical Network (PON) has emerged to be a widely accepted mature access technology that promises support for wide range of emerging bandwidth-hungry Internet services and applications. A PON typically comprises of a centrally located Optical Line Terminal (OLT), connected to several Optical Network Units (ONUs) located at customer's premises and one or more Remote Nodes (RNs) realized using passive power splitters (PS) or arrayed waveguides (AWGs) [1]. While access networks employ packet switching due to bursty nature of traffic from users, they are often connected to backbone networks through circuit-switched metro network. This results in inefficient handling of bursty data leading to a bandwidth bottleneck termed as metro gap. Moreover, circuit-switched metro, and packet-switched access network necessitates expensive Optical-Electrical-Optical (OEO) conversions at the OLT which account for major infrastructure costs [2]. Several packet-switched metro-network architectures and protocols have been studied to alleviate metro gap [3]–[6]. Packet-switched optical access and metro networks provide an opportunity of avoiding OEO conversions which develops into the notion of all-optical access-metro networks.

Several all-optical access-metro network architectures have been proposed in the literature [2]–[5], [7]. The authors of [3], [5] employ Optical Burst Switching (OBS) to facilitate an all-optical network, which adds significantly to cost and power consumption [2]. Another architecture, STARGATE, proposes infusion of a star network along with the existing metro-ring topology [4]. The OLTs supported by a metro-ring are connected both by the metro-ring network and the star network. Introduction of a star network requires laying of additional cables within the ring, thereby increasing infrastructure costs. These proposals avoid OEO conversions between a source-destination pair, which indicates unavailability of routing provisions at any intermediate node. Thus, they set up optical lightpaths (a wavelength channel without any OEO conversion) between a source ONU and a destination ONU. Since ONUs are equipped with a single transceiver, only one lightpath can be set up for a source-destination pair at any given time to avoid collisions. This calls for a control mechanism which maintains essential network information and performs related processing for setting up new lightpaths. Then, the information about the new lightpath has to be passed over to source, destination and the intermediate nodes, which is achieved through control messages. Therefore, architectures proposed in [3]–[5] separates data and control planes, wherein the control packets undergo OEO conversions. The data packets are sent over the established lightpaths without any OEO conversion.

As discussed above, the aforementioned architectures set up lightpaths by sending control messages among ONUs. We illustrate that such a scheme suffers from large overhead due to control messages and processing complexity. Consider a metro-ring network that supports N OLTs. Suppose a lightpath exists between ONUs of OLT_i and OLT_j. This lightpath may pass through some intermediate nodes in the ring. The same lightpath (wavelength channel) cannot be used for these intermediate nodes unless the lightpath expires. Once the lightpath expires, the corresponding wavelength is released and a new lightpath can be set up. Hence, the control mechanism has to consider all ONUs connected to OLT_i, OLT_j and those connected to the intermediate nodes as well for setting up the new lightpath. In the worst case, the control mechanism considers all ONUs supported by the ring. Thereafter, in order to avoid collisions, the information regarding the new lightpath has to be passed to all ONUs in the metro-ring, which incurs large control overhead. Since the lifetime of a lightpath may be minuscule (few microseconds), the control mechanism has to perform these operations (processing and message passing) very frequently.

Another approach in this regard (all-optical access-metro integration) is to replace a metro-ring network by few metro-

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core (MC) nodes which serve both access and core network [7]. This eradicates the overhead involved in message passing as discussed above. However, this scheme suffers from the following drawbacks. Since access fibers are directly linked to MC nodes, the reach of PON is extended (termed as long reach PON or LR-PON). Thus, metro-core nodes serve several PONs (large number of ONUs) employing more power splitters which impairs the power-budget. Further, packets undergo OEO conversions only at ONUs and MC nodes. Since the MC nodes replace the metro-ring, they support as many ONUs as the ring used to support which leads to a manyfold increase in the scheduling complexity. The power-budget and complexity issues would restrict the scalability of such networks.

The above discussions demonstrate that, while replacing metro-ring by metro-core nodes suffers from scalability and processing issues, the other approaches incur large control overhead and processing complexity. Thus, in order to realize a cost-effective all-optical access-metro network, it is essential to reduce the number of control messages involved in setting up of lightpaths without replacing the metro-ring by few centralized nodes. This can be achieved if lightpaths are set up between OLTs instead of ONUs, which reduces the control complexity and overhead drastically (as many times as the number of ONUs connected to an OLT). Further, all-optical network avoids OEO conversions at OLT which indicates that the OLT is devoid of electrical buffering and processing provisions. This leads to the following challenges:

- During the lifetime of a lightpath between two OLTs (say OLT_i and OLT_j), OLT_i can only transmit data intended for OLT_j. Thus, OLT_i must be able to segregate data packets for OLT_j from its ONUs in the upstream (US). Since an OLT is unable to process packets, this segregation poses a challenge.
- The OLT, being unable to process packets, is unaware of its destination address (ONU). Thererfore, routing packets to a destination ONU from the OLT appears to be a challenging task.

In this paper, in order to address these issues, first, we propose a plausible MAC protocol for a metro-ring network. Then we present a cost-effective, energy-efficient All-optical Access Metro Ring Integrated Network (AMRIN) architecture which supports the proposed MAC protocol. AMRIN avoids OEO conversions for the data packets while two control channels are maintained for scheduling in upstream and downstream, wherein the control packets undergo OEO conversions. AMRIN exhibits significant reduction in cost and power-consumption with a slight improvement in reach when compared to broadcast and select (BS) and wavelength split (WS) architectures [1].

The rest of the paper is organized as follows. Section II describes the mentioned issues in detail followed by solution proposals which result in the proposed AMRIN architecture. We evaluate the performance of AMRIN with respect to traditional ones in Section III. Section IV concludes the paper with remarks on the advantages and applicability of AMRIN.

II. Proposed Solutions

As discussed above, we aspire to set up lightpaths between OLTs which reduces the control complexity. We clarify that the lightpaths are set up between OLTs if they belong to the same metro-ring network. Otherwise, lightpath is set up between OLT of a metro ring and the gateway edge router of the same metro-ring. In this section, we develop the intuition behind our proposed architecture which aims at mitigating the issues presented in Section I. First, we look into the challenges in the MAC layer which serves as a motivation for the proposed architecture. Thereafter, we propose architectures for supporting the downstream (DS) and upstream (US) data transmissions respectively.

A. MAC Design

Here, we discuss the issues in the Medium Access Control (MAC) layer and propose solutions for realizing all-optical access-metro networks. First, we describe a process of setting up a lightpath by an OLT. In order to do so, we consider that each metro node is equipped with a reconfigurable optical add-drop multiplexer (ROADM) [8]. The ROADM of metro nodes associated to the source and destination OLTs of a lightpath, adds (for source) or drops (for destination) the wavelength corresponding to the lightpath during its lifetime. All intermediate nodes bypass this wavelength during the lifetime of the lightpath. Thus, ROADMs need to be configured, which requires knowledge of the lightpath to be set up. One of the simplest possible approach to set up lightpaths is by dividing all wavelengths into fixed time slots where each slot is statically assigned to a certain source-destination pair (metro-nodes) similar to slotted rings without channel inspection protocol [8]. Since metro-nodes are aware of the static allocation, the ROADM can be easily configured to add or drop wavelengths during their slots (lightpaths). Variable-sized time slots and their dynamic allocation can also be managed by sending a control message (token). This requires designing an efficient metro-ring MAC protocol which is beyond the scope of this paper.

The protocol discussed above facilitates setting up of lightpaths in the metro-ring. We now describe how the US data from ONUs reach an intended OLT through the set up lightpaths. Traditionally, an OLT schedules the US data without considering the metro-ring MAC protocol. This US data is then processed and buffered at the OLT which allows US data to be sent to an intended OLT in its corresponding slot. The OLT then processes and sends the received data to the destination ONU. However, all-optical networks are devoid of buffering and processing provisions at the OLT. A reasonable approach would then be to segregate packets according to the intended OLTs (or a gateway edge-router), at an ONU. This can be achieved if each ONU maintains separate buffers for all OLTs in the metro-ring. When a packet arrives at an ONU, it discerns the address of the intended OLT, and stores the packet in the corresponding buffer. During the slot between two OLTs (say OLT_j and OLT_k), OLT_j polls its ONUs, to upstream data from the buffers corresponding to OLT_k with help of control messages sent through separate control channels (for US and DS). The OLT schedules multiple ONUs such that the upstream (US) data from these ONUs occupy the respective lightpath (slot) by avoiding collisions. The US data requires a propagation delay to reach an OLT which has to be considered while polling.

The above process enables US data transmission from an ONU to an intended OLT in an all-optical network. However, the inability to process packets at OLT, implies that the OLT is unaware of the destination address (ONUs) of any packet. This suggests that a packet may not be able to reach the destination ONU directly. Thus, in our proposed approach, an OLT bypasses a DS packet, which reaches an arbitrary ONU. This ONU then routes the packet to the destination ONU without sending the packet again to the OLT, which solves the routing issue. Next, we propose an architecture which facilitates the US and DS solutions.

B. Proposed Architecture

Traditionally, access architectures employ two stages of remote nodes for the optical distribution network [9]. As discussed above, the DS routing issue is addressed if all ONUs served by an OLT can share data among themselves (local sharing). Fortunately, we have already proposed an architecture which supports content sharing (CS-OAN) among ONUs [9] by modifying the remote nodes and the ONUs as shown in Fig. 1 and Fig. 2. CS-OAN maintains the passive nature of the remote nodes which is a desirable feature for any PON architecture. The content sharing feature and its operation is briefly discussed as follows:

The downstream (DS) and upstream (US) of CS-OAN operate on non-overlapping sets of wavelengths denoted by $\lambda'_1, \lambda'_2, \ldots, \lambda'_N$ and $\lambda_1, \lambda_2, \ldots, \lambda_N$ respectively. In Fig. 1, the US and DS AWGs (AWG_{US} and AWG_{DS}) ensure that each ONU under a second stage remote node (say $ONU_{x_l,i}$ under RN_{2,x_l}) operates on a unique US and DS wavelength (say λ_i and λ'_i respectively). $ONU_{x_l,i}$ upstreams data to OLT only on λ_i and thus the other free US wavelengths $(\lambda_1, \ldots, \lambda_{i-1}, \lambda_{i+1}, \ldots, \lambda_N)$ can be used to reach the rest of the ONUs under same remote node $(ONU_{x_l,1}, \ldots, ONU_{x_l,i-1}, ONU_{x_l,i+1}, \ldots, ONU_{x_l,N})$. This is achieved by employing a $N \times N$ AWG (AWG_{CS} in Fig. 1) which acts as a routing device. If λ_i is incident on j^{th} input port of AWG_{CS}, λ_i appears at $((N - j + i)\ mod\ N)^{th}$ output port of the AWG_{CS} (symmetric routing property of AWG [9]). Thus, a wavelength and input port pair uniquely maps an output port of AWG_{CS}. Connecting each output port to an ONU of the same remote node allows an ONU to access all other ONUs by selecting suitable input port and wavelength pair. For example, in Fig. 1, if $ONU_{x_l,k}$ connected to the k^{th} input port of AWG_{CS}, has to share data to $ONU_{x_l,j}$, $ONU_{x_l,k}$ can transmit the data on wavelength $\lambda_{((N-j+k)\ mod\ N)}$ which appears at the j^{th} output port of AWG_{CS}. The j^{th} output port then is fed to a 3:1 combiner at the DS of $ONU_{x_l,j}$ which now caries both DS and content shared (CS) data. Since the CS data is carried by an US wavelength, there is no collision in the fiber with the DS data of $ONU_{x_l,j}$. Fiber Bragg Grating, filters the US data from the CS data where the US data is forwarded to the OLT through AWG_{US} while CS data is forwarded to the destination ONU through AWG_{CS} and a 3:1 combiner as shown in Fig. 1.

At the ONU, the tunable transmitter transmits the US data as well as data for content sharing. The DS data (now combined with CS data) is passed through a band splitter which segregates the DS and US wavelengths. The DS data is then received by a fixed receiver tuned at corresponding DS wavelength while the CS data is received by a broadband photo detector which tunes into US wavelengths as shown in Fig 2. However, ONUs are usually equipped with a single line card which cannot process both CS and DS data at the same time (receiver collision). This calls for proper scheduling of CS data which may be performed by a control message. Since the OLT can detect DS data only on its arrival, control message cannot be sent before the arrival of the data. Thus, DS data has to be delayed such that the control message informs the ONUs on the same DS wavelength to suspend their reception of CS data. This can be achieved by employing delay lines (DL) at the OLT for each wavelength as shown in Fig. 1.

It is important to note that content sharing is limited within the ONUs of a second stage remote node. Thus, our problem is only partially solved. It is not guaranteed that the packets will reach an ONU which is under the same remote node as the destination ONU (as explained in the example above with RN_{2,x_l}). This problem can be dealt with, if we ensure that packets reach at least one of the ONUs under all second stage remote nodes. It is then easy to conceive that one possible way to achieve this is by realizing the first remote node (RN_1) as a power splitter (PS) which broadcasts a packet to all remote nodes. Since the OLT bypasses any DS packet, the DS architecture operates on all wavelengths supported by the metro-ring network. Thus, each packet reaches one of the ONUs of each second-stage remote node. If the packet has already reached the destination ONU, content sharing will not be necessary. Otherwise, the packet is locally shared (under same remote node) to the destination ONU.

In our proposed AMRIN architecture, we consider that the DS utilizes all wavelengths used for setting up lightpaths in the metro-ring. The ONUs of AMRIN operate on single wavelengths for upstreaming their data to the OLT. However, the lightpaths between two OLTs can be of any DS wavelengths $(\lambda'_1, \lambda'_2, \ldots, \lambda'_N)$. This necessitates an OLT to convert US wavelengths to the lightpath wavelength. Since wavelength conversions are not required in the DS, the US data is segregated from the DS at OLT by using a circulator as shown in Fig. 1. First, the US data passes through an AWG which de-multiplexes the wavelengths. Separate wavelength converters (WCs) are employed for each wavelength which ensures full flexibility. Since wavelengths can be converted to any arbitrary DS wavelength, connecting the WC outputs to ROADM ports at the metro ring will require proper switching. However, this switching can be avoided by using a power combiner and AWG combination as shown in Fig. 1 which

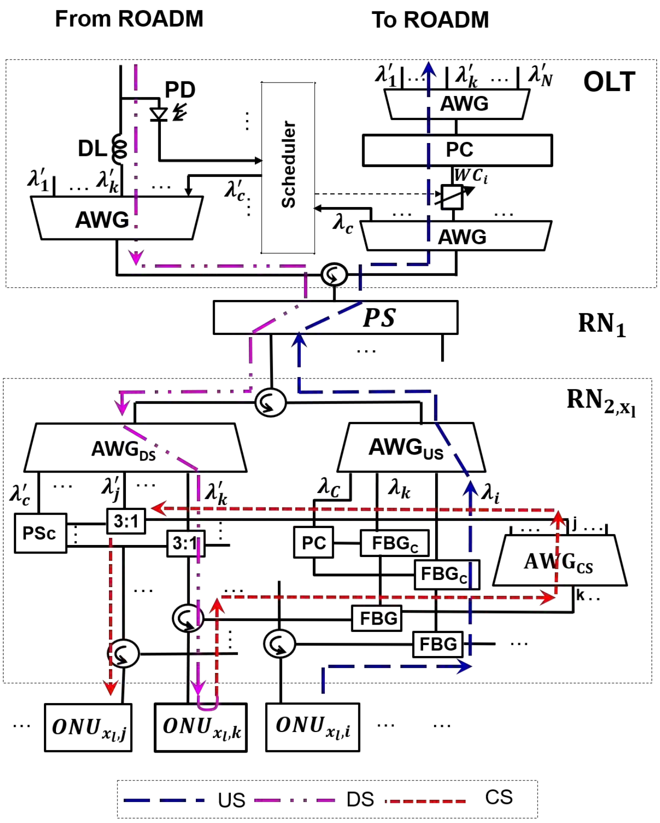

Fig. 1. Proposed Architecture for OLT and Remote Nodes. PC- Power Combiner, 3:1- 3:1 PC, DL- Delay Line, PD- Photo Detector

outputs fixed DS wavelengths for the metro node ROADM.

The above discussions demonstrate the operation of AMRIN for US, DS and CS data. As discussed before, scheduling of CS and US data requires sending control message in the DS direction as shown in Fig 1. In AMRIN, this control message is sent through the control channel λ'_c, which is shared among the ONUs. Following the DS path as described above, the control message reaches the power splitter, PS_C (refer Fig. 1). Each output of PS_C is connected to a 3:1 combiner for each ONU and thus the control packets reach ONU through the DS path. In order to schedule the ONUs, the OLT requires buffer reports from ONUs, which is sent after US data through the control channel λ_c. In order to facilitate this, the US data is passed through a fiber bragg grating (FBG_C) which separates the control wavelength from the US wavelengths. This control wavelength (λ_c) of all ONUs is combined by a power combiner, and is connected to AWG_{US}. The US control packets then reach OLT by following the US path (refer Fig. 1). Since same control channel (both λ'_c and λ_c) is shared by all ONUs, the OLT has to avoid collisions in control messages.

C. Data transmission in AMRIN

We illustrate the working of AMRIN with help of an example. Consider a scenario where a lightpath has been set up between OLT_1 and OLT_2 at wavelength λ'_k. We describe

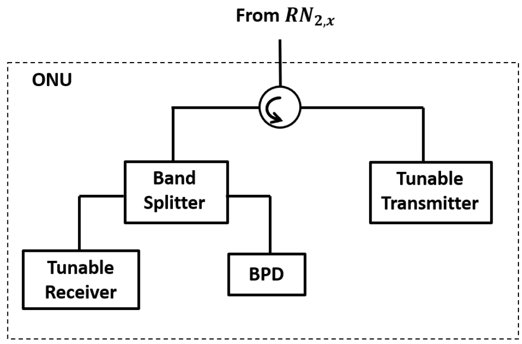

Fig. 2. Architecture for ONUs

the process by which an ONU (say $ONU_{x_l,i}$) under OLT_1 can facilitate data transmission to any ONU (say $ONU_{x_m,j}$) under OLT_2. Let λ_i, λ_j and λ'_i, λ'_j be the corresponding US and DS wavelengths respectively for ONUs $ONU_{x_l,i}$ and $ONU_{x_m,j}$. For sake of illustration, in Fig. 1, we have shown the path for US from $ONU_{x_l,i}$ to its corresponding metro-node. OLT_1 being aware of the start and end times of the lightpath, sends a control message through the DS path to poll $ONU_{x_l,i}$. In addition, it configures the wavelength converter associated to λ_i (WC_i) such that it converts λ_i to the DS wavelength of the lightpath (λ'_k). The control message informs the address of the OLT associated with the lightpath (in this case OLT_2) to $ONU_{x_l,i}$. This enables $ONU_{x_l,i}$ to upstream (at λ_i) its data from the buffer maintained for OLT_2 at the ONU after receiving the control message. The US data passes through the FBG at RN_{2,x_l} which forwards λ_i to AWG_{US} and reaches OLT_1 through RN_1. The pre-configured WC_i then converts the US wavelength to λ'_k which reaches to the metro node.

The metro node adds λ'_k with help of a pre-configured ROADM to the metro-ring as discussed in Section II-A. The US data from $ONU_{x_l,i}$ is now carried from the metro-node by the lightpath on λ'_k as DS data for OLT_2. Since OLT_2 also implements similar architecture as OLT_1, the path for DS of OLT_2 is shown in Fig. 1 as well. Further, in Fig. 1, we illustrate the data transmission from $ONU_{x_l,i}$ of OLT_1 to $ONU_{x_m,j}$ of OLT_2 for $m = l$. The DS data, received by OLT_2 is bypassed via RN_1 and reaches the k^{th} ONU of all second stage remote nodes. Then $ONU_{x_m,k}$ has to locally share the data to $ONU_{x_m,j}$ shown in Fig. 1. OLT_2 sends a control message to $ONU_{x_m,k}$ for scheduling the local sharing to $ONU_{x_m,j}$. On arrival of this control message, $ONU_{x_m,k}$ upstreams the data on $\lambda_{(N-j+k) mod N}$. The data comes out of the j^{th} port of the AWG and finally reaches $ONU_{x_m,j}$ where it will be detected by the broadband photo detector (BPD) as shown in Fig 2. In the case when source and destination ONUs are under same OLT but different remote nodes, the data is routed through ROADM.

III. Results and Discussion

In this section, we compare the proposed AMRIN architecture with two popular TWDM access network architectures:

TABLE I
COST, POWER-BUDGET AND POWER-CONSUMPTION FIGURES OF COMPONENTS

Component	Cost (€)	Power Budget (dB)	Power Consumption (W)	Component	Cost (€)	Power Budget (dB)	Power Consumption (W)
OLT Transceiver	140	NA	6	PS (2X2)	40	-3	0
OLT Line Card	4000	NA	7	Fiber Braggg Grating	30	-1	0
OLT Rack	82800	NA	100	EDFA	8000	30	8
Wavelength Converter	100	NA	0.5	Street Cabinet	150	NA	0
Circulator	30	-1	0	ONU Transceiver	140	NA	2.3
AWG (32X32)	500	-3	0	ONU Line Card	260	NA	4
AWG (4X4)	60	-3	0	Tunable Filter	60	0	0
PS (32X32)	132	-15	0	Band Splitter	60	-2	0

TABLE II
COMPARISON OF PERFORMANCE MEASURES FOR DIFFERENT ARCHITECTURES

	Cost Per User (€)				Power Consumption (W)				Reach (km)				Flexibility	Supports Local Sharing
Architecture \ BW/ONU (Mbps)	320	160	80	40	320	160	80	40	320	160	80	40		
AMRIN	839	776	744	728	6.58	6.44	6.37	6.34	150	135	120	105	HIGH	YES
BS	2368	1434	967	732	10.8	8.55	7.43	6.86	130	115	100	85	HIGH	NO
WS	2308	1374	907	673	10.8	8.55	7.43	6.86	145	130	115	100	MODERATE	NO
WS-LS	2556	1623	1155	922	10.8	8.55	7.43	6.86	145	130	115	100	MODERATE	YES

Broadcast and Select (BS) and Wavelength Split (WS) [1]. We consider overall cost per user, power-budget (reach) and power-consumption as metrics for the comparison. The effects of increasing the number of OLTs supported by the metro-ring and technology up-gradation from existing Coarse Wavelength Division Multiplexing (CWDM) to Dense Wavelength Division Multiplexing (DWDM) have also been demonstrated.

Table I enlists the metric values for various components used in the architectures [1]. We consider a metro-ring network supporting 8 OLTs and 32 wavelengths (10 Gbps each) with a total data-rate support of 320 Gbps in the ring, unless mentioned otherwise. For conventional architectures (BS and WS) 32 transceivers and wavelengths will be required at the OLT to support the 32 wavelengths in the metro-ring. In addition, we assume that the total data rate is uniformly distributed between the OLTs which implies that access network would require four 10 Gbps transceivers and line cards (at OLT) since each PON supports an average data rate of 40 Gbps. In AMRIN, as the OLT does not perform any OEO conversions for data packets, only one line card is sufficient for processing the control packets. Since the metro-network is not modified by AMRIN, its components would add to a fixed cost and power consumption figure for all architectures which is ignored in the calculations. The reach is calculated for the access network considering 0 dBm power at the OLT. Further, we consider a receiver sensitivity, system margin and fiber attenuation loss of -25 dBm, 6dBm and 0.2 dB/Km respectively.

A. Comparison of AMRIN with various access technologies

As discussed above, we calculate the performance metrics (cost per user, reach and power-consumption) for AMRIN, BS and WS using Table I. We consider the metro-ring network to support 8 OLTs and 32 wavelengths (10 Gbps each) as mentioned above. In Table II, the performance figures have been tabulated for the architectures by varying the average bandwidth per ONU (BW/ONU) which is equivalent to varying the number of ONUs connected to each OLT. For example, a BW/ONU of 320 Mbps $\implies$ (40 Gbps)/320 Mbp = 128 ONUs are being served by an OLT. We observe (from Table II) that AMRIN costs almost a third as much compared to BS and WS for BW/ONU = 320 Mbps (128 users). Also, the power consumption figure for AMRIN is lower than BS and WS architectures by 4.22 W. Increasing the number of users, leads to a reduction in gain for both cost and power consumption figures. This is due to the following reason. AMRIN requires a single transceiver and line card at the OLT whereas a WS or BS OLT require 36 transceivers and line cards. The cost of these components are shared among the ONUs and thus the gain reduces by increasing the number of ONUs. For 1024 ONUs (BW/ONU = 40 Mbps), AMRIN incurs a higher cost compared to WS architecture. However, AMRIN supports a technically advanced feature of content sharing which serves the purpose of enhancing user bandwidth [9]. Thus, for comparison, we consider a modified WS architecture that supports local sharing (WS-LS) which emerges to be costlier than AMRIN. The PON reach has been evaluated for varying number of users as well. In addition, AMRIN provides better reach compared WS, WS-LS and BS.

B. Effect of Number of OLTs in Metro-ring

Increasing the number of OLTs in the metro-ring manifests scaling of metro-network to support larger number of users. Table III compares the effect on performance measures (cost per user, power-consumption and reach) on increasing the number of OLTs (from 8 to 16) for the architectures discussed above. Table III shows that an increment in the number of

TABLE III
EFFECT OF THE NUMBER OF OLTS IN METRO RING

	Cost Per User (€)				Power Consumption (W)				Reach (km)			
BW/ONU (Mbps)	80		40		80		40		80		40	
Architecture \ No. of OLTs	8	16	8	16	8	16	8	16	8	16	8	16
AMRIN	744	776	728	744	6.37	6.44	6.34	6.37	120	135	105	120
BS	967	1402	732	951	7.43	8.45	6.86	7.37	100	115	85	100
WS	907	1342	673	891	7.43	8.45	6.86	7.37	115	115	100	100
WS-LS	1155	1591	922	1139	7.43	8.45	6.86	7.37	115	115	100	100

TABLE IV
EFFECT OF NUMBER OF WAVELENGTHS IN METRO RING

	Cost Per User (€)				Power Consumption (W)				Reach (km)			
No. of ONUs/OLT	512		1024		512		1024		512		1024	
Architecture \ No. of Wavelengths	32	64	32	64	32	64	32	64	32	64	32	64
AMRIN	744	751	728	731	6.37	6.40	6.34	6.35	120	135	105	120
BS	967	1256	732	877	7.43	8.34	6.86	7.32	100	100	85	85
WS	907	1196	673	818	7.43	8.34	6.86	7.32	115	130	100	115
WS-LS	1155	1438	922	1060	7.43	8.34	6.86	7.32	115	130	100	115

OLTs, increases the cost for all architectures. However, the rate of increment for AMRIN is much lower compared to others. For example, in case of BW/ONU = 80 or 512 ONUs/OLT, AMRIN reduces this rate by three times compared to others. This benefit improves further for larger number of users (1024 ONUs/OLT or BW/ONU = 40). Further, power consumption in AMRIN increases by 0.07 W compared to 1.02 W for others, while reach improves by 20 Km.

C. *Effect of Technology Up-gradation*

Technology Up-gradation refers to increase in the overall average data rate supported by the metro-ring. This may be achieved by increasing the number of wavelengths supported by the ring from 32 wavelengths to 64 wavelengths using Dense Wavelength Division Multiplexing (DWDM). Table IV shows that the rate at which cost increases in AMRIN is almost 40 and 50 times lower than other architectures (BS and WS) for 512 and 1024 ONUs respectively. While AMRIN consumes an additional power of 0.03 W and 0.01 W, BS and WS consumes an additional power of 0.91 W and 0.46 W for 512 ONUs and 1024 ONUs respectively. Thus, tables III and IV demonstrate that AMRIN is quite insensitive to scaling and up-gradation of the metro-ring network compared to other architectures which is highly desirable.

IV. CONCLUSION

In this paper, we proposed an access-metro integrated architecture, AMRIN, which facilitates data transmission among ONUs just by setting up lightpaths between OLTs, instead of ONUs, without undergoing OEO conversions at OLT. In the process, the computational complexity and costs, involved in setting up lightpaths, is reduced drastically when compared to existing all-optical access-metro architectures. AMRIN reaps a significant benefit in infrastructure cost (CAP-EX) and overall access-network energy consumption (300% and 64% respectively for 8 OLTs, 32 wavelengths, and 128 ONUs) over traditional TWDM architectures even though it supports a technically advanced feature of content sharing. AMRIN exhibits low sensitivity towards scaling and technology up-gradation compared to the conventional architectures, which is a desirable feature for any future optical network architecture. Also, an AMRIN OLT does not require back plane switch which suggests significant cost benefit. Further extensions of the present work would involve design of efficient protocols both for orchestrating local sharing operation and setting up dynamic lightpaths. In AMRIN, since DS data is routed through ONUs, these ONUs may not forward the data. An efficient mechanism design is required which enforces the local sharing of DS data.

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