Bidirectional Optical Ring Network Having Enhanced Load Balancing and Protection

Dzmitry Kliazovich and Fabrizio Granelli
DIT - University of Trento
Via Sommarive 14, I-38050 Trento, Italy
E-mail: [klezovic,granelli]@dit.unitn.it

Hagen Woesner
CREATE-NET
Via Solteri 38, I-38100 Trento, Italy
E-mail: woesner@create-net.it

***Abstract*— Massive growth of the Internet traffic in last decades motivated the design of high-speed optical network for traffic aggregation from different access technologies. The network architecture proposed in this paper is a low-cost flexible solution consisting of two dual buses located over a physical bidirectional ring network topology. OTDM technology is used for statistical traffic multiplexing while reservation-based, token-rotation, and CSMA/CA with a backpressure control techniques can be used for access to the shared medium at the link layer. The presented distributed resilience algorithm is able to automatically restore network functionality in case of single link break or node malfunction.**

Keywords- Bidirectional Optical Ring, Traffic Aggregation.

I. Introduction

Growing capacity demands of the last-mile access networks require the development and enhancement of a high-speed networking infrastructure capable of metropolitan and wide-area effective transportation of massive amounts of data traffic [1, 2]. In the backbone networks of today, optical fiber and wavelength-routed networks provide total capacities of Tbit/s per fiber – which means that pure bandwidth delivery is generally not considered a problem anymore.

Over the last years, FTTx (fibre to the curb/building/home) solutions have become economically feasible in densely populated areas of Asia, North America and Europe. Only recently massive fibre layout started in the US, with some years of delay compared to Japan and South Korea. These technologies provide today 50 or 100 Mbit/s per user, and usually provide an Ethernet interface towards the end user.

Currently, it is widely considered an open question which of the technologies in access networks will be the winner. Among the available alternatives are point-to-point Ethernet (sometimes referred to as *active Ethernet*) and Passive Optical Networks (PON). The main reason for the introduction of PONs is the supposedly decreased operational cost and the reduced port numbers that arise from multiplexing the traffic from Optical Networking Units (ONU) onto a single fibre served by an optical Line terminator (OLT). Depending on the type of PON (A/B/E/GPON), the total bit rates can be between 155 Mbit/s and 2.5 Gbit/s, which will not be sufficient for enlarged user populations and the accommodation of new services like VoD (video on demand) or HDTV distribution. For this reason, upgrades are being developed (named SuperPON) which will lead to an uplink bandwidth of 10 or 40 Gbit/s in the next step. The same upgrade to 10 Gbit/s is to be expected for the active Ethernet scenario.

While these data rates require optical transmission, the switching inside OLT or Ethernet can easily be done electronically with today's technology. The number of ONUs per OLT varies between 16 and 128, which means that there can be around one OLT per block, easily reaching hundreds of OLTs for a medium sized city. The average traffic that can be expected from such an OLT is rather low (typically between 1 and 10% of the nominal line rate).

This low average load means that, for a network provider, a high-speed transceiver (10 or 40 Gbit/s) in the backbone is much more profitable than in the access network. These considerations set the scene for a network that has to aggregate traffic from hundreds of nodes with a line rate of 10 Gbit/s.

The term *access core network* usually describes a second level in the hierarchy of networks that aggregates traffic from the Access and delivers this into the Metro or core networks. Fig. 1 shows an example of such a network aggregating traffic from several PONs.

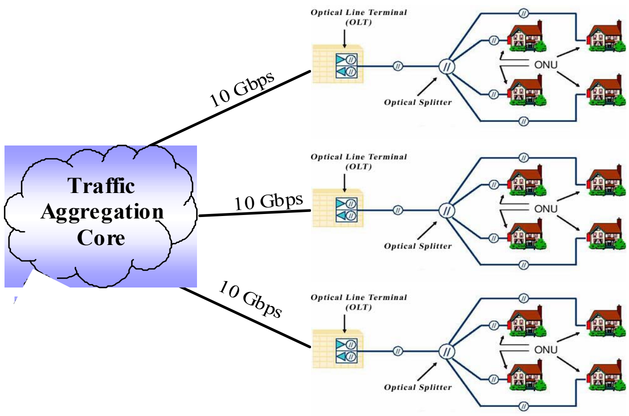

Figure 1. Example of traffic aggregation from several Passive Optical Networks (PONs).

In this example the traffic aggregation has to be performed at a speed equal to 10 Gbps * 3 = 30 Gbps. As mentioned before, the real number of nodes that have an upstream traffic to transmit will be orders of magnitude higher. For that reason, traffic switching and routing becomes a communication and computing bottlenecks for high-speed data communications in the aggregation network.

The purpose of this paper is to propose an optical network architecture able to provide traffic aggregation to a large number of various existing and upcoming network access technologies. The proposed architecture satisfies such requirements like scalability, flexibility, resilience to link break or node failures, while being a low-cost solution operating at high utilization level.

The rest of the paper is organized as follows: Section II describes the proposed solution first by presenting the design of high-speed network architecture and then defining basic architectural components such as client and hub nodes. The description of channel assignment and possible MAC protocols precede the specification of a resilience strategy which provides the robustness to a single link failure or a node malfunction. The comparison with related works is presented in Section III. Finally, Section IV concludes the paper with final remarks.

II. TRAFFIC AGGREGATION CORE

The design of the network architecture for traffic aggregation is based on the idea of a shared medium that performs switching distributed over the network. It can be as well considered an instantiation of the Light-trail architecture presented in [6] and its bidirectional extension [7] designed for IP-centric communication at the optical layer in WDM networks. The main concept behind the light-trails is to perform communication through an optical channel which is shared between nodes included in a particular optical connection. The main advantage of light-trail communications is the avoidance of optical switching as well as multiple optical-electronic conversions of the signal on the data path. As a result, light-trails provide a single optical channel shared between nodes spatially distributed over the network.

The proposed aggregation access network follows hub-and-spoke architecture operating on two dual buses arranged over a physical bidirectional ring topology. Next paragraphs provide the detailed description of the proposed architecture and its components.

A. Network Architecture

Fig. 2 presents the core of the proposed optical network. It is composed of one hub node (HUB) and multiple client nodes CN (six in this example). The hub node and the client nodes are physically connected by the optical fiber forming a bidirectional ring topology. In each direction, an optical signal being inserted into the ring propagates at light speed until being terminated. Light termination is performed by the hub node as well as by several client nodes configured for the termination.

As a result, a single channel is shared between the hub node and several client nodes. On the physical level, client nodes access the channel using optical add/drop couplers which i) absorbs part of the energy from the aggregate signal dropping it to the local receiver, or ii) inserts locally generated signal into the aggregate one. This principle is often called *drop-and-continue*.

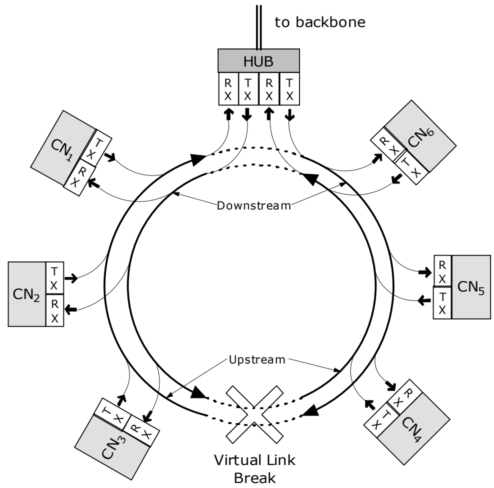

Figure 2. Traffic aggregation core network architecture.

Each client node can be configured either in "pass through" or "loop-back" modes. Such a capability is used for the creation of a virtual link break between any pair of client nodes. The initial configuration of the presented architecture assumes a virtual link break which divides an aggregation network into two parts (buses) with the same number of client nodes. In Fig. 2 the client node CN_3 terminates the optical signal on the inner ring while the client node CN_4 terminates it on the outer ring. Such a configuration is equivalent to a case when the link between client nodes CN_3 and CN_4 is broken.

Such virtual link break creates two dual buses with the main purpose of network capacity increase - due to spatially separated communications. This technique is often referred to as *spatial reuse*.

In Fig. 2 the dual bus which is located to the right of the hub node is called *eastern* bus, while the bus located to the left is *western*. The section of each bus where signal propagates out of the hub node is called *downstream*, while the section where signal propagates towards the hub node is called *upstream*.

Client nodes receive data on the downstream and transmit on the upstream. This makes the hub node a central point, through which all the communications are performed.

As mentioned earlier, we assume the case when dynamic channel sharing is based on OTDM technology. An alternative way of the channel sharing is in the WDM domain. However, it requires fast wavelength tunable transmitters and receivers which are still costly [11, 12]. Moreover, a dynamic channel sharing in WDM means to tune to an available wavelength which requires gain clamped amplifiers, burst mode receivers, and preambles to train them.

Changing channels in OTDM simply involves waiting until the desired timeslot, which can be implemented by using several optical delay line components.

In this scenario, the OTDM clock is generated by the hub node transmitters in the downstream for both buses. The number of timeslots in an OTDM superframe is not fixed to the number of the client nodes connected to the bus. This implies several client nodes can share the same timeslot channel.

For practical implementation we assume that each time slot represents one tributary channel with the speed of the order of 10 Gbit/s. This enables the use of relatively low-cost electronics at the client nodes. The total number of channels then depends on the overall bus data rate, leading us to assume 10 or 16 channels per wavelength.

B. Client Node Architecture

The cost of the hardware used in the client nodes is the main factor which determines the overall network price due to a large number of client nodes supported by the network. A possible client node architecture is presented in Fig. 3.

Optical amplifiers placed into the upstream and the downstream tracts are designed to compensate signal attenuation in the optical fiber between client nodes - whose length is typically of the order of ten kilometers in metropolitan environment as well as due to passive optical components used in node's architecture. In this scenario, Linear Optical Amplifiers (LOAs) represent a feasible and cost-effective solution [13].

No data frame is dropped once transmitted on the shared channel following drop-and-continue principle. This requires a collision-free contention resolution between the nodes as well as an appropriate design of the MAC protocol. An optical component which performs medium sensing combined with the optical delay line helps to ensure the medium is free before packet transmission. Medium sensing can be implemented using low-bit-rate photodiodes, which simply measure the power level of the incoming signal. The optical delay line delays an upstream signal for a time slightly larger than the maximum size of a data frame. This allows to ensure the medium is idle for the duration of at least one data frame.

The transmitter operating in the upstream and the receiver inserted into the downstream are capable of tuning to a single timeslot of the OTDM superframe. Such tuning can be implemented using a short-pulse laser and a parallel or serial delay line as it was demonstrated in [14, 15]. Note that the speed the client node can receive or transit is equal to the bus speed divided by the number of timeslots, i.e. the order of 10 Gb/s.

The optical line terminator and on/off switch of the clock recovery unit are designed to support client node's operation in loop-back mode when it terminates the signal propagation in the downstream as well as provides an upstream with the OTDM clock signal recovered from the downstream bus.

The client node can be a part of the eastern as well as the western bus depending on the virtual link location which defines the length of each bus. This requires a direction of the upstream to the transmitting tract while the downstream is to be directed to the reception tract of the client node architecture which is accomplished by two 2x2 optical switches OS_1 and OS_2.

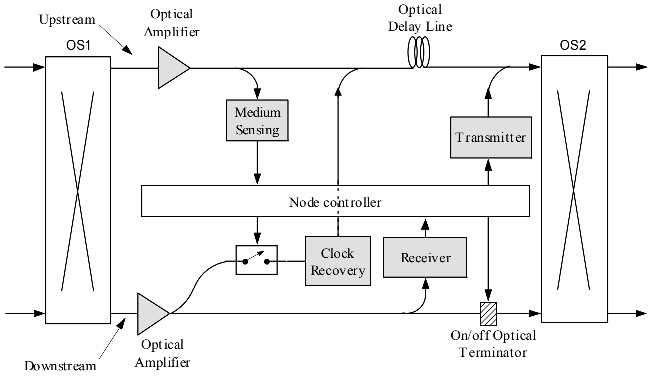

Figure 3. Client node low-cost architecture.

C. Hub Node Architecture

The generic architecture of the hub node is presented in Fig. 4. It consists of two transmitters and receivers: one transceiver unit per each dual bus.

As opposed to the client node, the hub node supports communication at full speed of the bus, receiving all timeslots of the OTDM superframe. For that reason, it is equipped with high-speed (100 Gb/s or 160Gb/s) transceivers which can be implemented using the idea of OTDM multiplexing.

Short pulses (5 – 10 ps) generated by laser delayed for a certain fraction of time (using a parallel delay line) serve as a clock signal for the number of modulators. Each modulator inputs the information destined to a particular timeslot. The receiver follows a similar implementation with the difference that the modulators receive the bus signal as an input, extracting a particular timeslot at the output.

Full bus-rate transceivers are several times more expensive than single timeslot transceivers used in client nodes. However, the architecture of the hub node does not necessarily requires a low-cost design. It does not influence greatly the overall network cost since only a single hub node is required for the entire network.

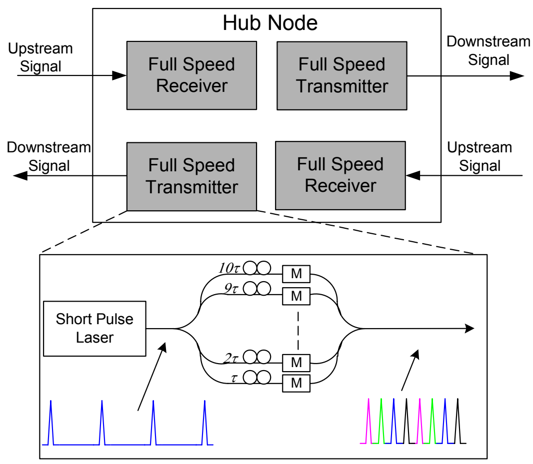

Figure 4. Hub node architecture.

D. Network Initialization

After the network architecture is physically assembled and before any data communications can take place, the hub node performs network setup. This procedure mainly consists of the following steps: topology discovery, virtual link break location, and "home" channel assignment.

Topology discovery. Consider the network architecture presented in Fig. 2. Initially, all client nodes are configured in loop-back mode terminating the optical signal in the downstream. They have their transmitters and receivers tuned to the first timeslot channel in both the upstream and the downstream.

The hub node starts configuring nodes into path-through operation mode in the counterclockwise direction by transmitting a control packet destined to the broadcast address. However, initially only client node CN_1 can hear the hub node, since it terminates the downstream signal not allowing it to reach the node CN_2. Before switching to path-through mode, the node CN_1 transmits on the upstream an acknowledgement using OTDM clock recovered from the downstream.

Upon the reception of the switching acknowledgement from the node CN_1, the hub node updates the client node sequence table with the address of node CN_1. Then, it continues configuring nodes in path-through mode sending the broadcast control frame to the same counterclockwise direction.

At this time the signal reaches nodes CN_1 and CN_2. The client node CN_1 being already configured to the path-through mode does not respond to the request, while the client node CN_2 follows the switching procedure previously performed by the node CN_1.

As soon as the client node CN_6 is in the path-through mode, the next broadcast switching request reaches the hub node's opposite receiver which serves as an indication of the end of the topology discovery phase.

Virtual link break. The hub node initially locates a virtual link break dividing the network topology into two dual buses with the same number of nodes. As mentioned earlier, the virtual link break increases the overall capacity allowing spatial reuse, as well as minimizes maximum propagation delay in the network.

The client node which operates in the loop-back node and terminates a bus is called *end node*. In Fig. 2 the node CN_3 serves as end node for the western bus while the client node CN_4 is the end node for the eastern bus.

Home channels. The receivers and transmitters used in client nodes are components capable of communication using a single OTDM timeslot channel. For that reason, the hub node specifies each client node to listen to a certain OTDM channel in the downstream which is called *home channel*.

The hub node distributes the available OTDM channels in the downstream between the nodes by following the sequence of nodes (determined during the topology discovery phase) sequentially.

In case the number of available timeslots *m* is less than the number of nodes in the bus, the hub nodes begins to reassign timeslot channels starting from the node CN_{m+1}. In this scenario, several client nodes share the same channel, which requires the nodes to perform data filtering through the comparison of the link layer addresses.

In the upstream, the client nodes are not obliged by the hub node to use a certain timeslot for the transmission. However, initially it is recommended for each client node to tune its transmitter in the uplink to the same channel number as in the downstream. The main idea behind such a recommendation is to provide a relatively equal load distribution at the beginning of communications assuming a uniform traffic distribution.

E. Network Communications and MAC Protocol Candidates

The downstream part of the bus is exclusively reserved for data reception. Hence, the only node transmitting onto the downstream is the hub node. On the opposite, in the upstream, transmissions can be initiated by multiple client nodes. Therefore, the downstream corresponds to point-to-multipoint, while the upstream is a multipoint-to-point medium.

As a result, traffic control mechanisms are required to resolve contention on the upstream bus in order to ensure collision-free data communications.

The availability of the medium sensing module allows client nodes to ensure the inserted data do not collide with the traffic already present on the bus. This technique corresponds to the well-known Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. However, pure CSMA/CA implemented in the upstream leads to unfairness in the medium access, studied in [7] in the case of a Light trail bus, since it always favors the nodes located closer to the beginning of the upstream bus. A possible way of fixing unfairness of CSMA/CA medium access is the implementation of a bidirectional signaling involving the downstream bus into the medium access on the upstream.

In order to specify the MAC protocol that can perform well on the proposed architecture, we overviewed existing contention resolution and medium access techniques for fixed and wireless networks present in literature [8]. As a result, we observe three techniques which are the most successive candidates for the MAC protocol.

1) Reservation-based medium access.

The fact that all transmissions are performed between the client nodes and the hub node creates a good environment for the implementation of a reservation-based MAC protocol. Each client node can request a portion of the bandwidth on the upstream. Then, the transmission opportunities computed by the scheduler implemented in the hub node are granted via the downstream bus.

This scheme leads to a perfect fairness which fully depends on the scheduler implementation. However, the main drawback of the reservation-based medium access is a large delay in medium access which can not be less than the time required for the reservation request propagation to the hub node plus the time for the bandwidth grant propagation back to the client node. This makes access delay highly dependant on the distance of the client node from the hub node, which can exceed 100 km in the metropolitan environment.

Nevertheless, the reservation-based protocol can perform well in the scenarios when channel access delay can be avoided. A good example of such scenario is when the network operator constantly provides dedicated bandwidth channels to different access network providers.

2) Token-rotation medium access.

Another technique which can be used for the upstream medium access is a token-rotation MAC. In this scenario, the hub node generates token frames one per each OTDM timeslot channel. The generated tokens propagate in the downstream to the end node which forwards them to the appropriate upstream channels.

For the purpose of token detection the functionality of the medium sensing module implemented in the client node (see Fig. 3) is extended with optical correlator [16]. The task of optical correlator is to detect a predefined sequence of bits which corresponds to a token frame passing on the bus. Note that such detection does not require ultra-fast speeds since it is produced on a channel rate rather than on the bus rate.

In case a token frame is detected and the node has data in the outgoing buffer, it "extracts" the detected token from the bus. Actually, as mentioned earlier, no signal can be dropped after being transmitted on the bus. For that reason, the client node just overwrites several bits in the detected token after it passes the delay line such that optical correlators of other nodes will not detect it as a valid token. However, in order to restore the token-rotation contention, the client nodes finish each data transmission with a valid token frame.

Token rotation medium access techniques have a well-known tradeoff extensively studied in the literature between the medium access delay, the round-trip propagation delay on the bus, token rotation and token holding times. For that reason, the performance and utilization levels of token-based protocols are highly dependant on the network size.

3) Backpressure control

The main disadvantage of two previously described MAC schemes is in the insertion of the propagation delay component into the medium access delay.

In order to minimize the time required for medium access, the CSMA/CA scheme extended with a backpressure flow control is considered as a third MAC candidate. In this scenario, each client node can access the uplink after it is sensed to be idle. Furthermore, in regular intervals of time client nodes report the length of their output queue to the hub node.

Taking into account the fact that all data flows pass through the hub node, it observes the level of fairness in bandwidth allocation. In case some of client nodes grab more bandwidth than the computed fair share the hub node transmits a backpressure signal in the downlink forcing these nodes to reduce their outgoing data rate to the computer share.

Basically, the time required for the backpressure feedback is equal to the time required for signal propagation from the hub node to the node exceeding the computed rate, while the medium - in case it is free of pending transmissions - can be immediately accessed.

F. Resilience Strategy

The proposed network architecture is robust to a single link failure or a single node malfunction. The way to recover the network functionality in case of limited connectivity is to shift the virtual link break to the physically broken link.

In order to do so, we propose a completely distributed algorithm which does not require any coordination from the hub node.

The basic set of rules used by the client node to restore the network functionality is the following:

1. in case the OTDM clock is detected on the downstream but no clock is present on the upstream the node turns into the loop-back mode starting to generate the clock recovered from the downstream bus to the upstream;
2. in case no clock signal is detected on the downstream the node tries to join another bus flipping its optical switches, switches to the path-through mode, and then transmits a "pilot" signal for the duration of a least one OTDM superframe;
3. any node operating in the loop-back mode sensing an incoming upstream signal switches its operation to the path-through mode.

In the network presented in Fig. 2, we assume a link failure happened between the client nodes CN_1 and CN_2 while the virtual link break is still located between CN_3 and CN_4.

The node CN_1 hearing the clock on the downstream and no clock on the upstream becomes the end of the western bus switching to the loop-back mode. The nodes CN_2 and CN_3, being isolated from the clock signal from both sides, try to join eastern bus by flipping their optical switches and sending "pilot" signals in the upstream. Then, after sensing an incoming signal on the upstream, node CN_4 switches to the path-through mode according to rule no. 3, bringing the downstream bus to the nodes CN_2 and CN_3. This places the nodes CN_2 and CN_3 into the situation described by rule no. 1. Suppose node CN_3 was first to switch to the loop-back mode beginning to generate an upstream clock. However, after it hears an incoming from the node CN_2 signal on the upstream, it follows rule no. 3.

Finally, when node CN_2 switches into the loop-back mode (becoming the termination of the eastern bus), the network communications are resolved.

In case of a node failure which considers complete shut down of its optical functionality, the resilience algorithm isolates the malfunctioned node from both buses.

The case of hub malfunction reduces the proposed architecture to Wonder architecture discussed in the following section, which fault-recovery strategy is extensively presented in [17].

III. Related Works and Comparison

There is a number of research works on metropolitan traffic aggregation networks present in the literature. The most related and recent solutions in the area are RingO and its evolution to Wonder architectures developed by Politecnico di Torino [10] as well as Dual Bus Optical Ring Networks (DBORN) architecture released by the Research and Innovation center of Alcatel [9].

RingO network architecture is based on the unidirectional fiber ring where packets transmitted in the time-slotted manner are delivered to the destination using WDM technology. For that reason, in order to transmit a packet, a node is required to tune its transmitter to the wavelength listened by the receiver, to wait for the channel to become idle, and then to produce pending transmission.

The simplicity of RingO design does not require link layer addressing as well as optical active routing components. However, it requires all the nodes equipped with fast WDM-tunable transmitters which operate at the bus rate.

Wonder architecture - an evolution of the RingO network – specifies the way for multiple nodes to share a single wavelength channel. A bidirectional ring interconnecting the nodes of the network is transformed into a folded bus. One part of the bus is exclusively reserved for transmission while the other one serves for reception purposes.

Such a topology overcomes the limitation of the RingO network where the number of nodes can not be greater than the number of wavelength channels. However, the price to pay for the desired feature is that capacity is halved.

DBORN architecture is organized on the fiber ring split into the downstream and the upstream buses, or a dual bus. Similar to the proposed architecture, communications are always performed between the hub and client nodes, which can be slotted or with a variable data unit size. For medium access, DBORN considers CSMA/CA protocol or TCARD protocol which operation is based on the notion of the bucket of anti-tokens – the requests to leave the medium free for a fraction of time.

Table I summarizes the characteristics of the discussed architectures.

TABLE I. Network Architecture Comparison.

Feature/ Architecture	**RingO**	**Wonder**	**DBORN**	**Proposed**
Physical Medium	Unidirectional Ring	Bidirectional Ring	Ring Fiber Split	Bidirectional Ring
Topology	Ring	Folded Bus	Dual Bus	Two Dual Buses
Multiplexing	WDM	WDM	WDM	WDM/ OTDM
Hub node	×	×	√	√
Frame length	fixed	fixed	variable	variable
Protection	Protection fiber	Single failure	Protection fiber	Single failure

The level of physical medium utilization depends on the network topology. Such that, if compared with a folded bus implemented by the Wonder project, DBORN increases the capacity by the factor of two while the network proposed in this paper results in capacity increase by the factor of 4 due to spatial reuse between dual buses as well as between the parts of each dual bus.

Furthermore, the proposed architecture provides resilience to a single link failure or a node malfunction similar to the Wonder architecture, while RingO and DBORN require availability of an additional protection fiber.

IV. Conclusions and Future Work

This paper proposes optical network architecture designed for traffic aggregation in the metropolitan area. It is implemented on two dual buses defined on a bidirectional fiber ring. Statistical traffic multiplexing is performed using OTDM technology, resulting in the low-cost architecture of client nodes.

We identified three possible candidates for the MAC protocol. They are reservation-based, token-rotation, and CSMA/CA with a backpressure flow control medium access techniques.

The presented resilience strategy is able to resolve network functionality in case of single link break or node malfunction.

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