

SUCCESS: A Next-Generation Hybrid WDM/TDM Optical Access Network Architecture

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Abstract—In this paper, the authors propose a next-generation hybrid WDM/TDM optical access network architecture called Stanford University aCESS or SUCCESS. This architecture provides practical migration steps from current-generation time-division multiplexing (TDM)-passive optical network (PONs) to future WDM optical access networks. The architecture is backward compatible for users on existing TDM-PONs, while simultaneously capable of providing upgraded high-bandwidth services to new users on DWDM-PONs through advanced WDM techniques. The SUCCESS architecture is based on a collector ring and several distribution stars connecting the CO and the users. A semipassive configuration of the Remote Nodes (RNs) enables protection and restoration, making the network resilient to power failures. A novel design of the OLT and DWDM-PON ONUs minimizes the system cost considerably: 1) tunable lasers and receivers at the OLT are shared by all ONUs on the network to reduce the transceiver count and 2) the fast tunable lasers not only generate downstream data traffic but also provide DWDM-PON ONUs with optical CW bursts for their upstream data transmission. Results from an experimental system testbed support the feasibility of the proposed SUCCESS architecture. Also, simulation results of the first SUCCESS DWDM-PON MAC protocol verify that it can efficiently provide bidirectional transmission between the OLT and ONUs over multiple wavelengths with a small number of tunable transmitters and receivers.

Index Terms—Access networks, bidirectional transmission, media access control protocol, passive optical networks, time-division multiplexing (TDM), wavelength division multiplexing (WDM).

I. INTRODUCTION

EMERGING applications, such as video-on-demand, High Definition TV (HDTV), digital cinema, tele-presence, and high-quality audio transmission demand high-throughput optical access networks with stringent Quality of Service (QoS) requirements. Nevertheless, the infrastructure of current access networks suffers from limited bandwidth and high network management cost, which obstructs the network from delivering integrated services to end users. Thanks to the maturity of optical components and electronic circuits, optical fiber links

have become practical for access networks. Passive optical network (PON) is one of the most promising solutions for fiber-to-the-home (FTTH), fiber-to-the-business (FTTB), and fiber-to-the-curb (FTTC), since it breaks through the economic barrier of traditional point-to-point solutions [1]–[3]. PON has been standardized for FTTH solutions and is currently being deployed in the field by network service providers worldwide [4], [5]. It employs dynamic bandwidth allocation (DBA) algorithm in media access control (MAC) protocol [6]–[8] to ensure network efficiency.

Once PONs with tree topology are deployed, upgrading the time-division multiplexing (TDM)-based optical access networks will be a challenge when user demand eventually outgrows the existing network capacity. Though TDM PONs have many advantages over other optical access network architectures, its bandwidth-sharing nature posts a serious challenge for future network upgrade. Installing new fibers in the field is still the most straightforward way to expand PON coverage, but the virtually infinite bandwidth of a single strand of fiber is mostly wasted. Moreover, the tree-topology of TDM PON restricts versatility of the network, such as protection, restoration, and point-to-point link on wavelength domain features.

Wavelength division multiplexing (WDM) has been considered as an ideal solution to extend the capacity of optical networks without drastically changing the fiber infrastructure. Many architectures that incorporate WDM into access networks have been proposed by from both academia and industry [9]–[13]. However, integrating WDM and TDM to ensure the flexibility and a smooth transition still requires substantial investigation.

In this paper, a next-generation hybrid WDM/TDM optical access network architecture—SUCCESS, which stands for Stanford University aCESS—is proposed with a focus on a pragmatic migration scenario from current TDM-PONs to future DWDM-PONs. The proposed SUCCESS architecture is based on a collector ring and distribution star networks and can support both existing TDM-PONs and new DWDM-PONs. It guarantees backward compatibility for users on existing TDM-PONs with only minimal upgrades on feeder networks while providing higher bandwidth to users on new DWDM-PONs. The SUCCESS architecture provides users with better protection and restoration capabilities than traditional PONs through the collector ring. This means that with the SUCCESS architecture, business and home users can coexist harmoniously on the same network.

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Under the SUCCESS architecture, several mechanisms are provided to minimize the total system cost:

- 1) ONUs employ uncooled components;
- 2) $N \times N$ array waveguide gratings (AWGs) are used to double the number of ONUs supported by the network;
- 3) the optical line terminal (OLT) uses tunable lasers and receivers to decrease total transceiver count and to generate optical carriers onto which ONUs can modulate their upstream traffic.

The rest of the paper is organized as follows: Section II describes the proposed SUCCESS architecture; Section III demonstrates the feasibility of the SUCCESS architecture through experimental results on a testbed; Section IV describes the design of SUCCESS DWDM-PON MAC protocol and provides the initial results of its performance analysis through simulations; Section V concludes our work in this paper.

II. SUCCESS ARCHITECTURE

By the time next generation optical access networks become pervasive, it is very likely that conventional TDM-based PON with tree-like fiber topology will dominate in the field. Since it is desirable for the network to support the existing users on PON without upgrading their customer premises equipments (CPEs), the new access architecture shall provide a smooth migration path while providing capacity upgrade and backward compatibility. In the current scenario for TDM-PONs, if more users are to be added, an entirely new PON with the capability of serving up to 32 users has to be deployed on the field, and a new set of transceivers at OLT side is added inside central office (CO) to serve a few additional users. This implies over provisioning and complicated cabling, so it may not be an economical solution. A more flexible design is required to solve this problem. Also, the outside plant is desired to be passive, but, at the same time, protection and restoration capabilities, at least for the feeder fibers, are necessary. Since cost is always a major concern, both hardware and software shall be efficient to serve as many users as possible given the available resources. Note that some of the features may not coexist on the same network; for example, having protection and restoration means that some electrical power is needed.

Based on the design philosophy discussed above, we propose SUCCESS, a novel architecture for optical access networks. This architecture provides an efficient and economical solution for the next generation access networks, a smooth migration path and flexibility so that a network designer can adopt part of its architecture to fit the need of a specific network topology and migration scenario.

A. Overall Architecture

The overall architecture of SUCCESS is shown in Fig. 1. The basic topology consists of a single-fiber collector ring with stars attached to it. The collector ring strings up remote nodes (RNs), which are the centers of the stars. The ONUs attached to the RN on west side of the ring talk and listen to the transceiver on the west side of OLT, and likewise for the ONU attached to the RN on the east side of the ring. At a logical level, there is a point-to-point connection between each RN and OLT. No

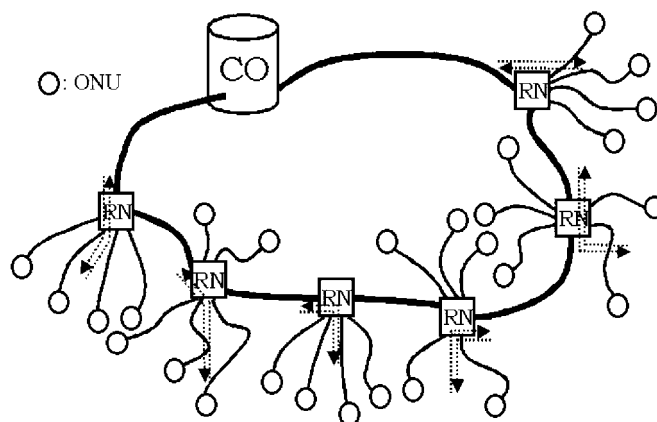


Fig. 1. Architecture and topology of SUCCESS.

wavelength is reused on the collector ring. When there is a fiber cut, all affected RNs will sense the signal loss and flip their orientation.

A RN has either a passive power splitter (coupler) or an AWG inside. If a RN contains a passive splitter, one dedicated wavelength on DWDM grid is used to broadcast the downstream data for the ONUs attached to the RN. Correspondingly, the ONUs have transmitters that consist of Fabry-Perot (FP) lasers send upstream data on CWDM grids. On the other hand, if a RN possesses an AWG, each ONU has its own dedicated wavelength on a DWDM grid to communicate with OLT. Since the insertion loss of AWG is roughly 6 dB regardless of the number of ports, an AWG with more than eight ports will likely need to be employed to enjoy the better power budget compared to a passive splitter. Each RN generally links 16 to 64 ONUs. Detailed design of an RN is described in the latter section. The downstream traffic and upstream traffic belonging to the same ONU may use the same wavelength, but different direction on the same fiber.

One of the benefits of having both CWDM TDM-based stars and DWDM WDM-based stars is traffic balancing. The WDM stars tend to serve corporations, while TDM stars tend to serve residential areas. Due to the nature of different traffic patterns, the overall network traffic tends to smooth out [12].

Tunable components are employed to reduce transceiver counts in the OLT. Tunable lasers generate both downstream frames and continuous wave (CW) bursts to be modulated by the ONUs. No extra set of laser sources is required. This configuration results in a half duplex communication between each ONU and the OLT. Compared with other architectures that have a two-fiber ring, two sets of light sources, and two sets of multiplexing/demultiplexing devices to perform full-duplex communication, our design dramatically lower deployment cost. By careful design of the bandwidth allocation algorithm in the MAC protocol, we can still provide efficient bidirectional transmissions between OLT and ONUs.

B. Remote Node Design

The basic structure is shown in Fig. 2(a). All but two output ports of an $N \times N$ AWG are connected to the distribution fibers that link to the ONUs associated with this RN. Unlike the conventional configuration of AWG that serves as a $1 \times N$ multiplexer/demultiplexer, where one side connects to OLT and the

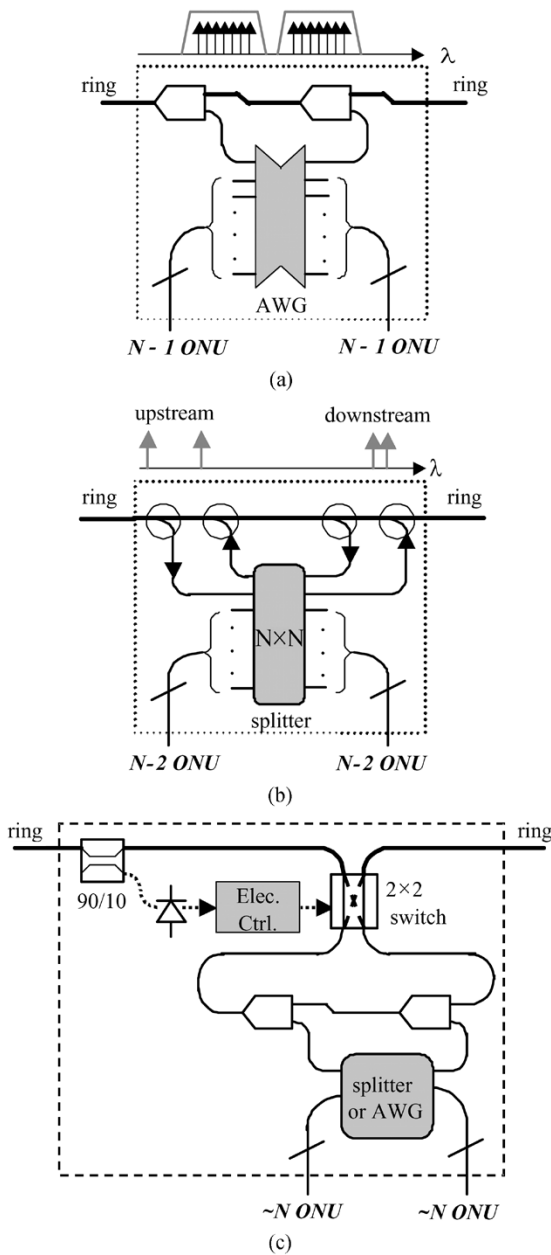


Fig. 2. Design schematics of remote node. (a) RN contains an AWG that supports DWDM. Each thin-film filter drops a different wavelength band. (b) RN contains a passive optical splitter that supports PON-like CWDM transmission. Cascading thin-film filters that pass a DWDM wavelength and a CWDM wavelength may be needed for downstream and upstream data transmission. (c) RN that has the capability of protection and restoration. The 2×2 optical switch is a bistable device that will latch into current state during power failure.

other connects to ONUs, this AWG is arranged in a “spider” way. Since the difference in terms of fabrication process of $1 \times N$ and $N \times N$ AWG is minuscule, and so is the difference in terms of cost, this “spider” configuration serves almost two times the users with the same cost. Since reconfigurability of wavelength assignment is not the top priority in the design of access networks, network architects can predetermine the wavelength assigned for the ONUs attached to the RN by applying proper band splitters. Avoiding reconfigurability keeps the RNs passive. A band splitter is a three-port passive device made of a thin-film filter that performs add/drop functionality. The first band splitter

on the left-hand side (LHS) of AWG performs add/drop for the ONU on the right-hand side (RHS), and vice versa for the second band splitter. Note that the groups of wavelengths being added/dropped by the two-band splitters in the RN must be different. Due to the cyclic property of AWG, each ONU will obtain its own unique wavelength.

If we desire full-duplex transmission with upstream and downstream on different wavelengths, we can use band splitters that add/drop $2N-1$ wavelengths instead of $N-1$. The upstream and downstream traffic will be separated apart by $N \times \Delta\lambda$, where $\Delta\lambda$ is the channel spacing of the AWG device.

Fig. 2(b) shows the variation of the RN for full-duplex transmission. First, the AWG is replaced with an $N \times N$ passive power splitter (coupler). The band splitter in this case is a cascade of a CWDM add/drop thin-film filter and a channel add/drop thin-film filter in either a 1490- or 1550-nm band; a specially designed thin-film filter that performs the same functionality can be used instead. Downstream wavelengths reside on DWDM grids either on a 1490- or 1550-nm band and are broadcasted to all ONUs, while upstream wavelengths reside on CWDM grids and are collected by the power splitter. In this case, the existing ONUs do not see any difference between this configuration and conventional TDM-PON.

The structures presented in Fig. 2(a) and (b) are both passive. They are attractive from the network maintenance’s point of view, but they lack protection and restoration capability. If provided with electrical power, a RN can be configured as shown in Fig. 2(c) to enable these. A simple circuit consists of photo diode and integrator that detect the optical power on one side of the ring, east bound in this case. If optical power ceases, the node assumes there is a broken fiber link and triggers the 2×2 optical switch to swap from the “bar” state to the “cross” state such that the RN listens to the traffic on the other side. When the RN experiences power failure, the power sensing circuit will stop functioning. However, it will not affect the light path and normal operation can proceed as usual. This property makes the node semipassive.

C. ONU Design

Since there are optical filters and AWGs on the light path, a relatively stringent specification of the stability of the upstream wavelength is required. The most straightforward way of implementing the ONU transmitter is using a stabilized laser source. However, stabilizing the emitting wavelength of a laser requires bulky optics and power-hungry electronics. Using a laser source at the ONUs therefore has a considerable impact on the cost of network deployment and management. There are several alternatives to do this. First, employ a tunable laser (without wavelength stabilization) at the ONU but have wavelength monitoring functionality in the OLT. In this case, however, an expensive tunable laser is still needed in each ONU. Second, use a broadband light source such as light emitting diode (LED) and let the AWGs perform spectral slicing [13], [14]. The benefit of this approach is its low system cost. However, the transmitting power after spectral slicing is significantly low, and thus link reach can be seriously limited. A third option is to provide the ONUs with external lightwave generated by OLT [11]. No wavelength stabilization is required in ONU. If a semiconductor

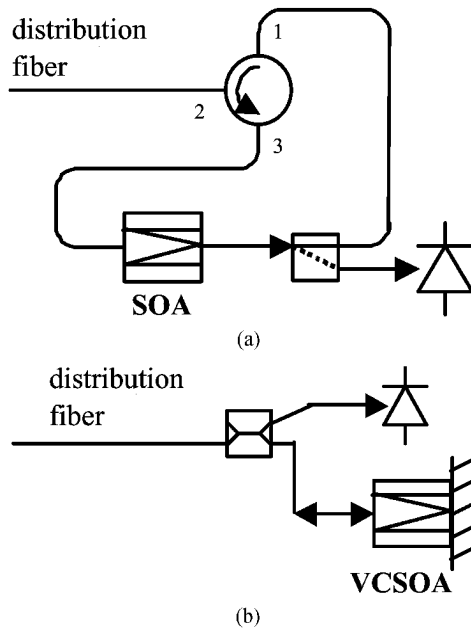


Fig. 3. Possible designs of ONU with optical carrier provided externally by OLT. (a) An SOA can be used as both modulator and preamplifier. (b) Polarization-insensitive VCSOA is used for its better coupling to fiber and higher degree of system integration.

optical amplifier (SOA) is used as a modulator at the ONU, the signal can be amplified to increase transmission quality.

Fig. 3 shows possible configurations of the optical front end of the ONUs. In Fig. 3(a), a SOA can be used as both a modulator and a preamplifier for the receiver during half-duplex operation. Fig. 3(b) demonstrates the possibility of using vertical cavity semiconductor optical amplifiers (VCSOAs) in the ONUs of optical access networks. VCSOA has the advantage of easy on-wafer testing and lower polarization dependence [15], [16] with a gain of more than 10 dB. This last configuration suggests possible integration of the whole optical front-end of the ONU.

D. OLT Design

Fig. 4(a) shows the basic structure of the optical front-end of OLT. A WDM coupler separates the upstream O band to S band CWDM channels from the C band and L band DWDM channels. A CWDM demultiplexer made by thin-film filters is used to demultiplex the upstream traffic. Tunable components, such as fast tunable lasers and tunable filters are employed for the DWDM channels. Given the fact that the average load of the network, in practical situations, is generally low [17], tunable components can be used to minimize transceiver counts, thus minimizing total system cost. Another benefit of using tunable components is to allow multiple ISPs to coexist on the same network. With tunable optical components, ISPs will be able to bundle and unbundle packets in the optical domain. Each ISP may use different MAC protocols if necessary and security of the network is strengthened.

The outputs of transmitters (downstream traffic) in DWDM channels are boosted by optical amplifiers and injected into port 1 of the circulator. The downstream data then pass through port 2 of the circulator and WDM coupler to enter the network. Upstream traffic in DWDM channels passes through the WDM

coupler, into port 2 of the circulator, and out of port 3 of the circulator. An optical preamplifier may be used to increase receiver sensitivity.

In general, there are three options to implement the receiver structure for DWDM upstream traffic at OLT, as follows:

- 1) $1 \times N$ demux followed by a receiver array;
- 2) fast-tunable single-channel add/drop filters;
- 3) multiple-channel add/drop filters.

The first option may be desirable only if the receivers are cheap; however, unbundling in optical domain is not possible with the first option. In the second option, the tuning speed of the filters has to be fast enough to minimize the overhead. Also, the tuning range has to be wide enough to cover C and L bands. According to [18], liquid crystal Fabry-Pérot filter (LCFP) and electrooptic tunable filter (EOTF) are possible candidates. Acoustooptic tunable filter (AOTF) is the only device so far that can achieve simultaneous multiple-channel add/drop by applying associated RF tones. It has a tuning speed in the range of micrometers and a tuning range of more than 60 nm. Fig. 4(b) shows the possible configuration of the DWDM receiver with AOTFs. The characteristic of having two input ports and two output ports makes it possible for AOTFs to cascade one another. For example, in a cross-connected AOTF, if both λ_1 of the four east bound upstream channels and λ_7 of the four west-bound upstream channels need to be dropped by AOTF-1, the RF tones associated with $\lambda_1, \lambda_5, \lambda_6, \lambda_8$ will be used to modulate AOTF-1.

E. Network Scalability

This section analyzes the scalability of the network in terms of the number of users and link reach. There are two main constraints: the link's power budget and available wavelengths. Exact numbers depend on components' characteristics, such as maximal transmission power, receiver sensitivity, and insertion loss. However, we can reasonably estimate the numbers according to common specifications, as summarized in Table I.

First, assume the network supports only DWDM users, which means every RN has an AWG. Without loss of generality, we assume each RN supports up to 32 ONUs. Let W_t be the total number of ONUs. Then, the number of RNs on the ring to support W_t ONUs, X , is given by

$$X = \left\lceil \frac{W_t}{32} \right\rceil. \quad (1)$$

Let L be the maximal fiber length between the OLT and any ONU. The power splitting ratio between receiver branch and modulation branch inside ONU is 6 to 1.3 dB.

The downstream traffic power budget must satisfy the following condition in order for signals to be successfully received

$$P_T - IL_{AD} \cdot X - IL_F \cdot L - IL_{AWG} - 6 - IL_{SA} \geq R_{sen} \\ \Rightarrow \left\lceil \frac{W_t}{32} \right\rceil + 0.3 \cdot L \leq 26 \text{ (dB)}. \quad (2)$$

As for the power budget of upstream traffic, it is more accurate to include the spontaneous emission noise of the SOA in estimating links' power budget. For binary transmission, the

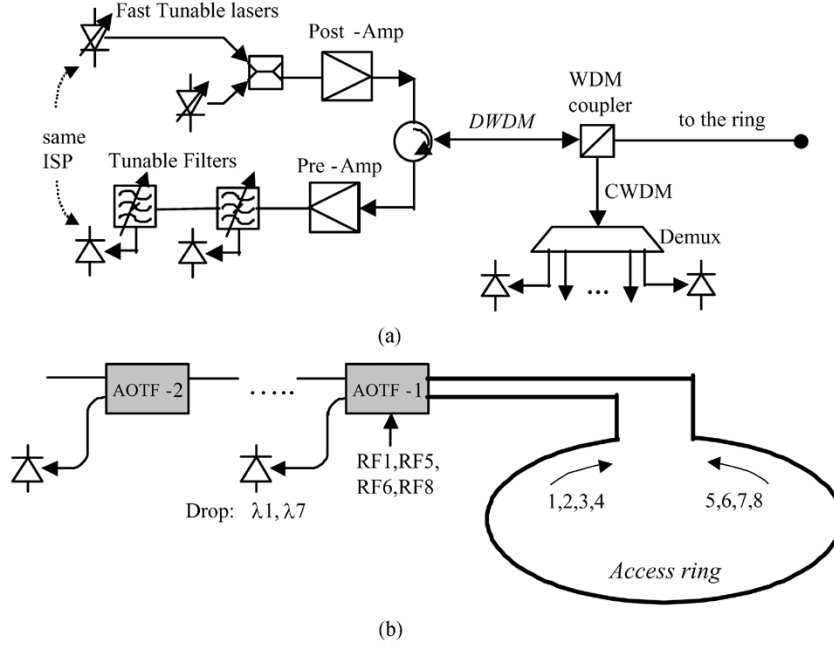


Fig. 4. Design of transceivers at OLT. (a) WDM filter separates DWDM traffic and CWDM upstream traffic. Tunable lasers and filters are used to decrease the transceiver count. Each ISP may have a laser/filter pair to perform traffic bundling/unbundling in optical domain. (b) Demonstration of the use of an AOTF as demultiplexer at OLT.

TABLE I
SPECIFICATION OF OPTICAL COMPONENTS

Symbol	Description	Value	Unit
P_T	Transmission power	+5	dBm
P_{TFP}	Output power of FP laser	-5	dBm
R_{sen}	Receiver sensitivity	-35	dBm
IL_{AD}	Insertion loss: thin-film add/drop	1	dB
IL_F	Propagation loss: fiber	0.3	dB/km
IL_{AWG}	Insertion loss: AWG	6	dB
IL_{SA}	Loss: splicing and aging on the link	2	dB
G_{SOA}	Gain of SOA	10~25	dB
S	Passive splitter's splitting ratio	4~32	none
NF	Noise figure of SOA	7	dB

digital SNR, Q , has to be greater than 6 in order for the bit error rate (BER) to be less than 10^{-9} (see (3) at the bottom of the page). In the previous equation, σ_{th}^2 , σ_{sh}^2 , σ_{sig-sp}^2 , and σ_{sp-sp}^2 are the power of thermal noise, shot noise, signal-spontaneous noise, and spontaneous-spontaneous noise, respectively. The i_{sig} term is the postdetection signal current. We further assume the responsivity, R , to be 0.7, the postdetection electrical bandwidth to be 1 GHz, and the predetection optical bandwidth to be 100 GHz. The noise power of thermal and shot noise can be estimated from receiver sensitivity. Following the equations in [24, ch. 4 and 8], we can estimate the power budget

of DWDM upstream traffic. Note that the upstream traffic has a tighter bound of power budget than that of the downstream traffic.

Similarly, we can derive a bound for the number of users and link reach assuming the network only serves CWDM users. Since the output power of a FP laser in an ONU is small, we only need to consider the upstream traffic's power budget as shown in (4).

$$P_{TFP} - \log_2(S) \cdot 3 - IL_{AD} \cdot X - IL_F \cdot L - IL_{SA} \geq R_{sen} \\ \Rightarrow \left[\frac{W_t}{S} \right] + 0.3L \leq 28 - 3 \log_2(S) \text{ (dB)}. \quad (4)$$

Fig. 5 shows the bound for different values of G_{SOA} and S . Although in a real world situation, the network serves both CWDM and DWDM users, (2)–(4) can be effective guidelines for network design. This analysis assumes that Rayleigh back scattering is not a limiting factor for the network power budget. It also assumes the worst-case scenario where the network experiences fiber break and all ONUs are served by the transceiver on one side of OLT.

Wavelength is another scarce resource that limits the total number of users that can be supported by the network. Assuming the water-peak on the attenuation spectrum of fiber is removed, a total 18 CWDM wavelengths with 20-nm spacing are available. However, some channels (in C and L bands) will be reserved for DWDM. To analyze the network scalability, we make the following assumptions:

$$Q = \frac{i_{sig}}{\sqrt{\sigma_{th}^2 + \sigma_{sh}^2 + \sigma_{sig-sp}^2 + \sigma_{sp-sp}^2} + \sqrt{\sigma_{th}^2 + \sigma_{sh}^2 | P_s=0 + \sigma_{sp-sp}^2}} \geq 6. \quad (3)$$

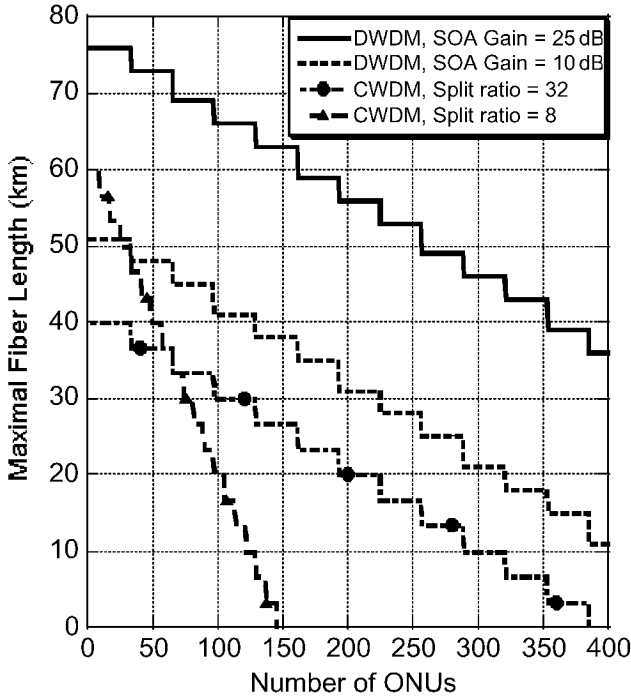


Fig. 5. Link reach and number of ONUs bound given the gain of SOA and the splitting ratio of the optical splitters as parameters. The power budget for CWDM transmission is tighter.

- 1) λ_C channels for CWDM TDM-based upstream traffic;
- 2) λ_D channels for DWDM ONUs;
- 3) each nanometer corresponds to roughly 125 GHz;
- 4) AWGs channel spacing is $\Delta\lambda$ GHz;
- 5) each of λ_C channels supports up to 32 CWDM ONUs, while λ_D means there are λ_D DWDM ONUs.

The following equation gives the relationship of λ_C and λ_D :

$$\lambda_D = \frac{20 \cdot (18 - \lambda_C) \cdot 125}{\Delta\lambda} - \lambda_C. \quad (5)$$

Fig. 6 depicts the relationship of λ_C and λ_D . Athermal AWG usually has a channel spacing of 100 GHz. The maximal tuning range of tunable components can be 60 nm. This criterion gives the network 15 CWDM channels (480 CWDM ONUs) and 60 DWDM channels (60 DWDM ONUs).

F. Network Migration Scenario

Fig. 7 demonstrates the network migration scenario for optical access networks based on the SUCCESS architecture. Fig. 7(a) shows the existing PON dangling from the same CO. Each PON has its own cabling and OLT inside CO. Fig. 7(b) shows the first migration step of the existing network infrastructure. The passive couplers of the PONs are replaced with RNs that consist of passive couplers and thin film add/drop filters as depicted in Fig. 2(b). The feeder fibers of PON are replaced with a single fiber ring that strings the RN served by this CO. Note that distribution fibers are untouched during this migration. From the point of view of the ONU, the functionality of the optical access network is exactly the same; only a short downtime for upgrade is needed. Therefore, existing ONUs can virtually work the same as before without major upgrade.

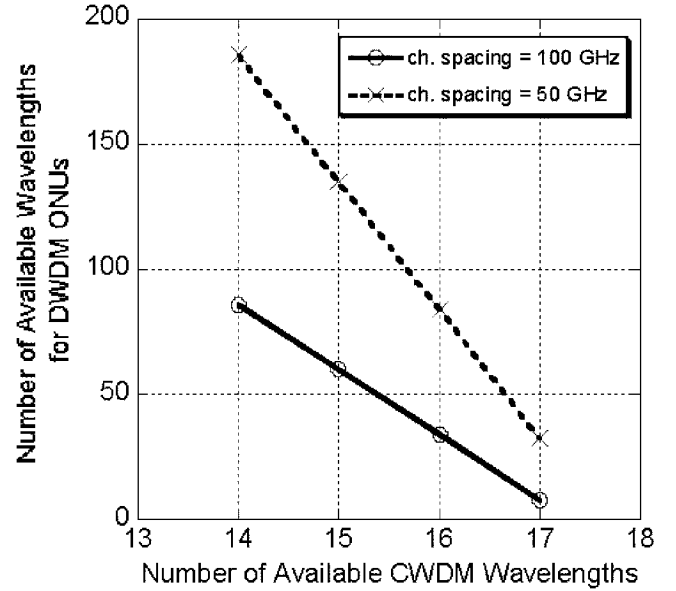


Fig. 6. Trade-off between the number of CWDM wavelengths and the number of DWDM wavelengths. Each CWDM wavelength can potentially support 8 to 32 ONUs.

Fig. 7(c) illustrates the second phase of migration. As more users demand high-bandwidth for future broadband applications, network engineers can insert RNs with AWGs as described in Fig. 2(a). In this case, there is a dedicated DWDM channel between each ONU and the CO. If protection and restoration functionality is implemented in the existing RNs, inserting a new RN in the network will not disturb the network operation in general.

Fig. 7(d) shows the possible extension of the network. Since there is a dedicated wavelength at the output of the AWG, it is possible to use the collector ring as a backhaul for the PON with tree topology. The two feeder fibers of the PON can connect to different RNs to form a protection path. Detailed implementation of the PON with tree topology served by the collector ring is currently under investigation.

To upgrade the capacity of the network even further, the SOA-based modulator can be replaced by a stabilized laser source to perform full-duplex operation. In general, the proposed SUCCESS architecture guarantees smooth upgrades of optical access networks from pure TDM-based PONs to CWDM-based PONs and finally to DWDM-based PONs in an economical manner.

III. TESTBED AND EXPERIMENTAL RESULTS

Constructing a SUCCESS testbed serves two purposes. First, to demonstrate the feasibility of bidirectional transmission of upstream and downstream traffic on the same wavelength with reasonable transmission quality. Second, to demonstrate the functionality of the MAC protocol.

A. Testbed Setup

Fig. 8 shows the testbed configuration. The collector ring is composed of standard single-mode fiber (SMF) sections of 2.2, 15, 15, and 2.2 km. The line rate is 1.25 Gb/s. There are two tunable laser sources in the OLT. Downstream data and CW

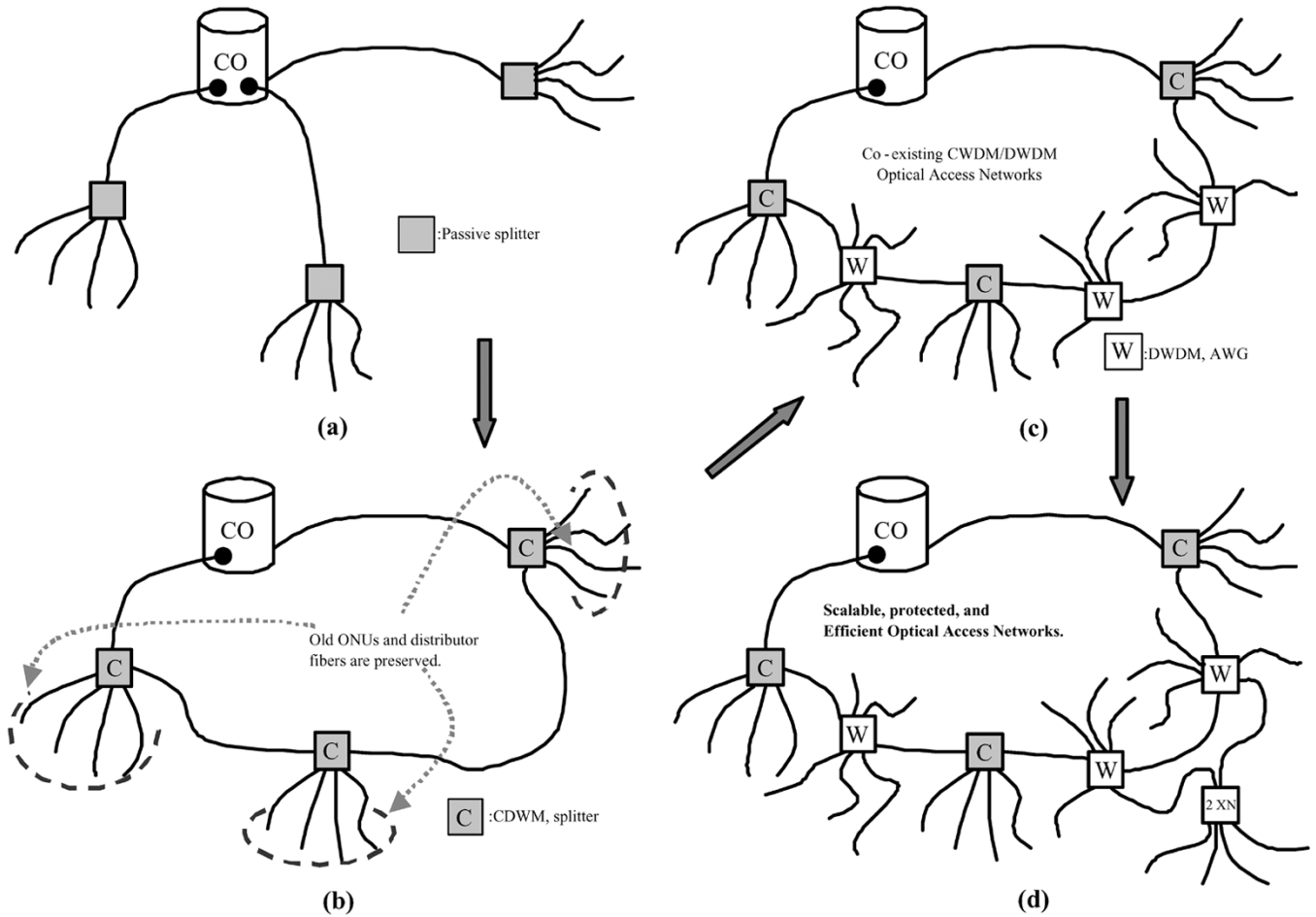


Fig. 7. Network migration scenario from existing TDM-PONs to future WDM-enabled optical access networks under SUCCESS architecture.

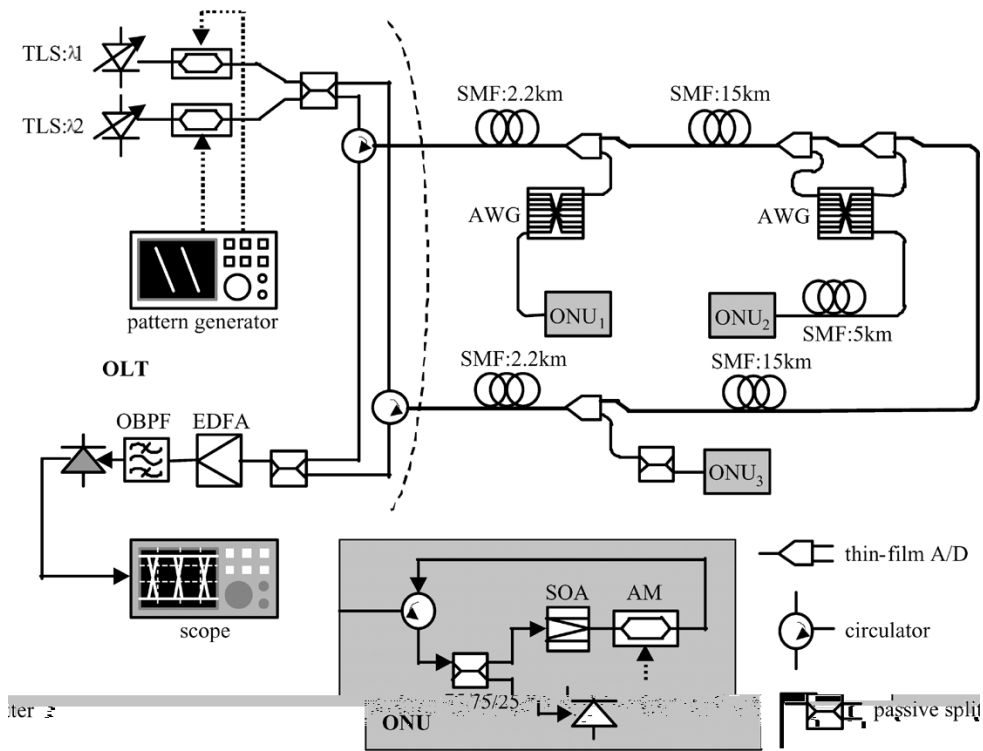


Fig. 8. Experiment setup.

bursts are generated by a pattern generator and modulated externally with Mach-Zehnder modulators. The downstream traffic

and CW bursts pass through the port 1, and then port 2 of the circulators to enter the ring. Upstream traffic enters the receiver

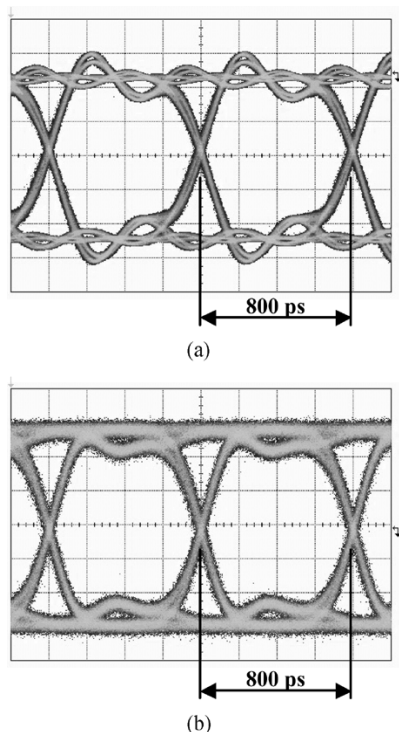


Fig. 9. Eye diagrams of continuous transmission between OLT and ONU2. (a) Downstream traffic. (b) Upstream traffic.

at OLT through port 2 and port 3 of the circulator. Each remote node has at least one thin-film add/drop filter. The channel spacing of AWG is 100 GHz. The receiver at OLT side has an erbium-doped fiber amplifier (EDFA) as preamplifier. The length of the distribution fiber between the RN and ONU₂ is 5 km. The total distances from the OLT to the ONUs are 2.2, 22.2, and 2.2 km, respectively.

ONU connects to the distribution fiber through port 2 of the circulator. Twenty-five percent of the optical power goes to the receiver, and 75% goes to the SOA for better power budget. Since driver circuitry to modulate the SOA is currently unavailable, we convert the CW bursts into the upstream packets with an external modulator that has 6 dB loss. The feasibility of using SOA of modulator has been demonstrated in [11]. When the ONU is receiving downstream data, the modulator is turned off to prevent interference caused by data fed through.

B. Experimental Results

1) *Bidirectional Transmission Over the Same Wavelength on a Single Fiber:* Fig. 9(a) shows the continuous downstream eye diagram monitored at ONU₂. The signal traverses 22.5-km SMF. Pseudorandom bit sequence (PRBS) of $2^{23} - 1$ word length is used to modulate the modulator at the OLT at a data rate of 1.25 Gb/s. Fig. 9(b) shows the eye diagram for upstream data. In this case, the transmitter at OLT keeps generating CW optical carriers for the modulator at ONU₂ to modulate onto. The SOA provides 20-dB gain. The PRBS sequence used here is again $2^{23} - 1$. As can be seen, both the figures show clear eye diagrams. The eye diagram in Fig. 9(a) is clearer than that in

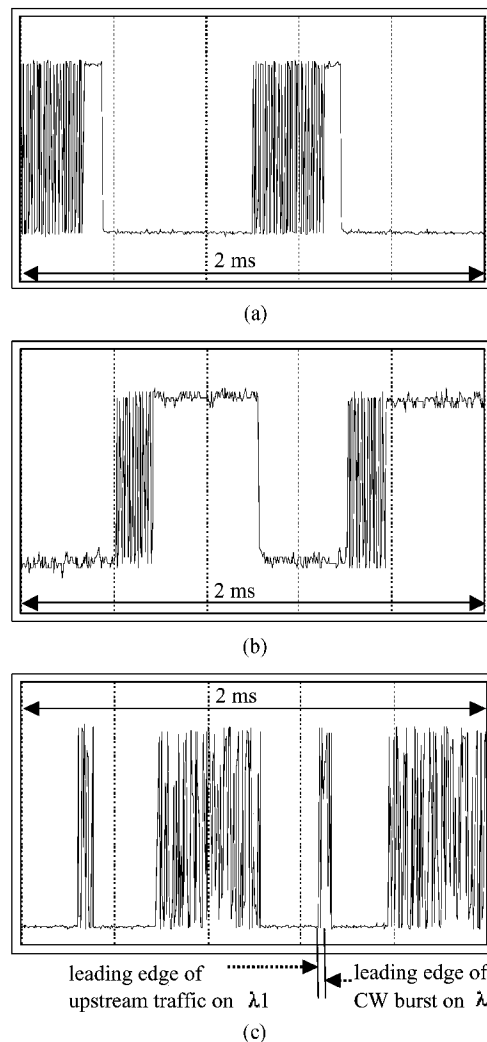


Fig. 10. Timing diagram of packetized transmission based on SUCCESS MAC. (a) Downstream packets and CW bursts on λ_1 . (b) Downstream packets and CW bursts on λ_2 . (c) Upstream traffic monitored at OLT. There is a forward time shift of the upstream traffic belonging to ONU₁ relative to that belonging to ONU₂, since the RTT of ONU₁ is shorter.

Fig. 9(b) because the higher noise figure of the SOA degrades the quality of the eye diagram.

2) *Modulating Packets Onto CW Bursts at the ONU:* The two lasers at OLT emit at the 1550.92 nm (λ_1) and 1550.12 nm (λ_2) wavelengths. They repetitively generate downstream traffic and CW bursts piggybacked together within an 1 ms frame, as shown in Fig. 10(a) and (b). λ_1 and λ_2 are the assigned wavelengths for ONU₁ and ONU₂, respectively. The modulators in ONUs are instructed to operate by the MAC protocol. They are modulated with PRBS $2^{23} - 1$ during the presence of CW bursts at ONU, and are turned off when ONU is listening to downstream traffic or idle. The receiver at the OLT detects the upstream traffic on both λ_1 and λ_2 . Fig. 10(c) shows the upstream traffic pattern retrieved by the oscilloscope at the OLT side. Note that the timing of downstream and upstream traffic on λ_2 are aligned; however, there is a forward time shift of the upstream traffic on λ_1 compared with the downstream data on λ_1 . The reason is that the distance between OLT and ONU₁ is shorter, so is the corresponding round-trip time (RTT). This factor is taken into account by the MAC protocol design.

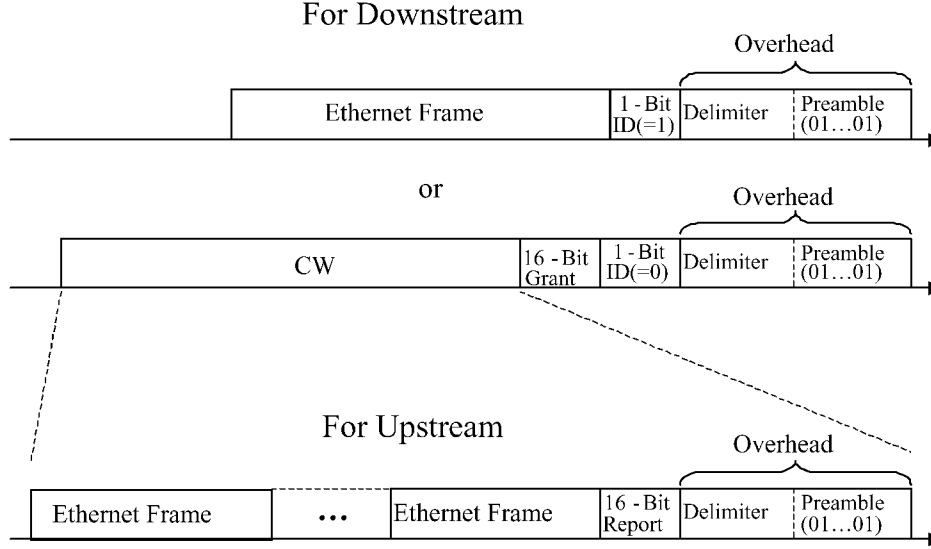


Fig. 11. Frame formats for SUCCESS DWDM-PON MAC protocol.

IV. MEDIA ACCESS CONTROL PROTOCOL FOR SUCCESS DWDM-PON

In the SUCCESS DWDM-PON architecture, the downstream bandwidth on a given wavelength is to be shared by both downstream (i.e., real data) and upstream (i.e., CW bursts) traffic for the ONU as previously discussed. Also, the tunable lasers and receivers in the OLT are to be dynamically shared by all the ONUs. Therefore, MAC protocols for SUCCESS DWDM-PON should be able to control all the resources available, such as tunable lasers, tunable receivers, and wavelengths, in order to avoid any conflicts among them and to provide efficient bidirectional transmissions between OLT and ONUs.

Here we report the results of the initial design of the SUCCESS DWDM-PON MAC protocol. This design is based on intelligent scheduling for harmonization of the use of tunable components over multiple wavelengths as in [20]. Like current APON and EPON systems [6], the OLT polls the ONUs to check the amount of upstream traffic stored inside them and sends grants, along with the corresponding CW bursts to allow ONUs to transmit their upstream traffic. The SUCCESS DWDM-PON MAC protocol, however, is distinctive in the following ways:

- it uses time compression multiplexing (TCM) technique [19] (also known as “Ping-Pong”) to provide half-duplex bidirectional transmission between the OLT and the ONUs;
- there is no separate control channel or frames;
- there is no embedding of control messages with escape sequences as in [20].

Considering that fairness guarantee and QoS issues can be better handled at upper layers, we focus on providing efficient bidirectional transmission in the design of this MAC protocol.

A. Global Status Information and Frame Formats

We consider a DWDM-PON system with W wavelengths (and ONUs), M tunable lasers, and N tunable receivers. The guard band between successive frames is G ns and this takes

into account the effect of unstable local ONU clock frequencies and tuning time of lasers and receivers at OLT. Each ONU _{i} has a round-trip time RTT_i . Since we do not equalize end-to-end delays among ONUs, the round trip times are usually different from one another. Note that because the tunable lasers are shared by both upstream and downstream traffic while tunable receivers are not, generally $W \geq M \geq N$.

There are several global status variables that the MAC protocol stores and manages at the OLT.

- CAT: Array of channel available times. $CAT[i] = t$ means that the wavelength λ_i will be available for transmission after time t , for $i = 1, 2, \dots, W$;
- TAT: Array of Transmitter Available Times. $TAT[j] = t$ means that the tunable laser TX_j will be available for transmission after time t , for $j = 1, 2, \dots, M$;
- RAT: Array of Receiver Available Times. $RAT[k] = t$, means that the tunable receiver RX_k will be available for reception after time t , for $k = 1, 2, \dots, N$.

The following are parameters to control the operation of the MAC protocol.

- *ONU timers*: These timers reset at system initialization and thereafter whenever a grant (CW burst) is sent downstream to an ONU or whenever a report message is received. On expiration, the OLT sends a new empty grant to poll that ONU. This timer keeps duration of the polling cycle within a given maximum value.
- *Maximum grant size*: Maximum size of a grant (i.e., the length of CW burst) to the ONUs for upstream traffic.

The frame formats for the SUCCESS DWDM-PON MAC protocols are shown in Fig. 11. Note that there are two different downstream frame formats, one for downstream data traffic and the other one for CW bursts for upstream transmission. The 1-bit ID field is used to indicate whether this frame is for downstream data or not. As shown in the figure, the length of a CW burst corresponds to that of all upstream frames, a report message and an overhead.

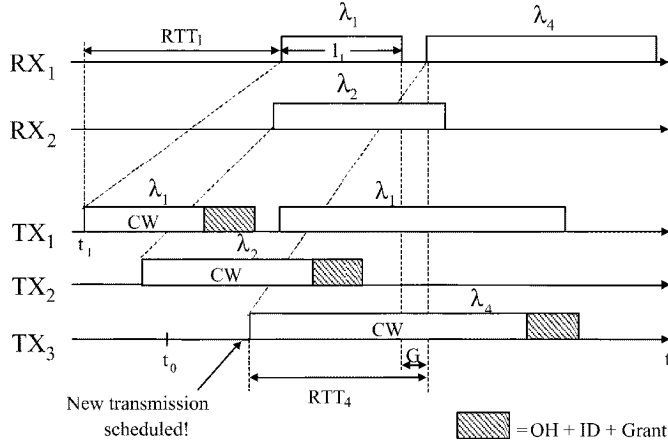


Fig. 12. Sequential scheduling example for a system with $W = 4$, $M = 3$ and $N = 2$.

```

Begin
wait until a packet arrives;
set d = packet.destination, l = packet.length;
select i such that TX[i] <= TX[m] for all m = 1,...,M and m < i;
if packet is for upstream
  select j such that RX[j] <= RX[n] for all n = 1,...,N and n < j;
  set t = max(RX[j] + G - RTT[d], TX[i] + G, CH[d]);
  set RX[j] = t + l + RTT[d]; /* update status variables */
  schedule reception at time = t + RTT[d] with RX[j] via CH[d];
else /* packet is for downstream */
  set t = max(TX[i] + G, CH[d]);
/* Common processing for both up- & downstream packet */
set CH[d] = t + l, TX[i] = t + l; /* update status variables */
schedule transmission at time = t with TX[i] via CH[d];
End

```

Fig. 13. Pseudocode for sequential scheduling algorithm.

B. Scheduling Frame Transmission and Reception

We describe a simple sequential scheduling algorithm that processes one frame at a time. This algorithm is not optimal in that only one frame is considered in scheduling at a time without any information on future or past frames. However, it serves as a reference protocol for other MAC protocols that will be designed for SUCCESS DWDM-PON in the future.

Fig. 12 illustrates an example of the sequential scheduling algorithm, showing timing relations among tunable lasers, tunable receivers, and frames over channels. In the figure, we can see that actual downstream data frames have no impact on the OLT receiver status. At $t = t_0$ a new report for upstream traffic from ONU₄ arrives. First, the OLT checks the laser availability and finds that TX₃ is available now. Then, it checks the receiver availability and finds that RX₁ will be available after $t = t_1 + RTT_1 + l_1 + G$. Then, the OLT checks the channel availability and finds that λ_4 is available now. The OLT, based on all these information, determines the earliest possible time to schedule the frame to be $t = t_1 + RTT_1 + l_1 + G - RTT_4$ through TX₃ on λ_4 . C-style pseudocode description of the sequential scheduling algorithm is given in Fig. 13.

C. Simulation Results and Discussions

We have developed a simulation model for the performance evaluation of the MAC protocol based on *Objective Modular*

TABLE II
CONFIGURATIONS FOR SIMULATION OF SUCCESS
DWDM-PON MAC PROTOCOL

NUMBER OF TRANSMITTERS	NUMBER OF RECEIVERS	AGGREGATE ARRIVAL RATES [GBPS]
1	1	1, 2, ..., 10
2	1	1, 2, ..., 20
2	2	1, 2, ..., 20
4	2	1, 2, ..., 40
4	4	1, 2, ..., 40
8	4	1, 2, ..., 80
8	8	1, 2, ..., 80

Network Testbed in C++ (OMNeT++) [21]. For this SUCCESS DWDM-PON model, we use 16 ONUs and wavelengths. The ONUs are divided into four different groups and placed from the OLT at 5, 10, 15, and 20 km, respectively. The line speed for both upstream and downstream transmissions is set to 10 Gb/s. The maximum grant size, the ONU timer, and the guard band are set to 2 Mb, 2 ms, and 50 ns, respectively.

IP packets are generated based on a Poisson process with a packet size distribution matching that of a measurement trace from one of MCIs backbone OC-3 links [22] and uniform destination distribution for downstream packets. Each generated IP packet is encapsulated into an Ethernet frame, put into a FIFO queue and then encapsulated, possibly with other Ethernet frames, in a SUCCESS frame. The size of the queue is set to 10 MB for both the ONUs and the OLT. At the OLT we assume that polling and CW burst downstream SUCCESS frames are stored in separate queues after their transmissions have been scheduled. We limit the number of these special frames stored in the queues by discarding frames with scheduling delay of more than 2 ms.

We ran simulations for seven different configurations of transmitters and receivers as summarized in Table II. The aggregate arrival rate is the sum of arrival rates for both downstream and upstream traffic, where the ratio of the former to the latter is 2:1. For example, if the aggregate arrival rate is 30 Gb/s, the downstream rate from the OLT is 20 Gb/s and the upstream rate from each ONU is 10 Gb/s/16 ONUs = 0.625 Gb/s. The maximum aggregate arrival rate for each configuration is set to slightly overload the system.

The throughputs and average end-to-end packet delays for total, downstream, and upstream traffic are shown in Figs. 14 and 15, respectively. From the figures, we can see the increase in the number of transmitters greatly improves the overall performance of the MAC protocol, while the number of receivers in the given configurations has minimal impact. This is because under the current SUCCESS architecture, the main bottleneck is the transmitter capacity that is shared by both upstream and downstream traffic. From these results, a 2:1 ratio for the number of transmitters and that of receivers would be an ideal choice for the SUCCESS architecture.

From Fig. 14, we observe that the deviation from the linear behavior in total throughput is mainly due to severe performance degradation in upstream traffic. Delay results in Fig. 15 show

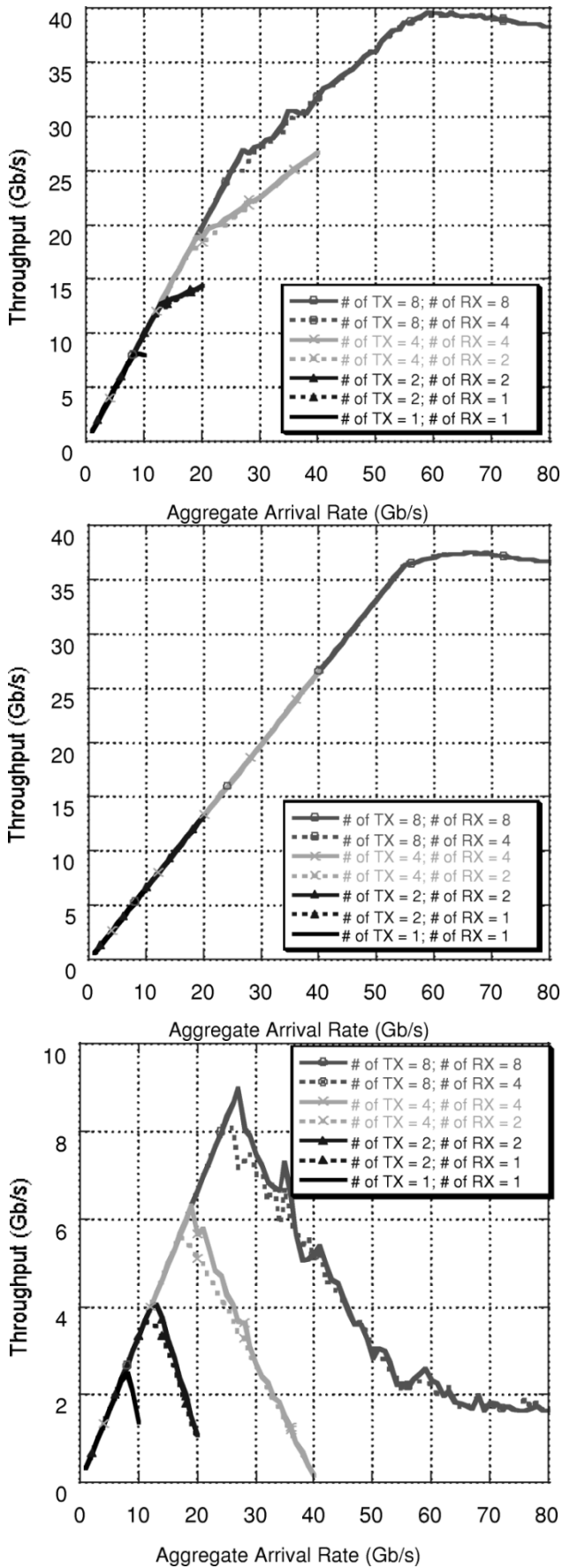


Fig. 14. Throughput with downstream and upstream traffic ratio of 2:1. (a) For aggregate traffic. (b) For downstream traffic. (c) For upstream traffic.

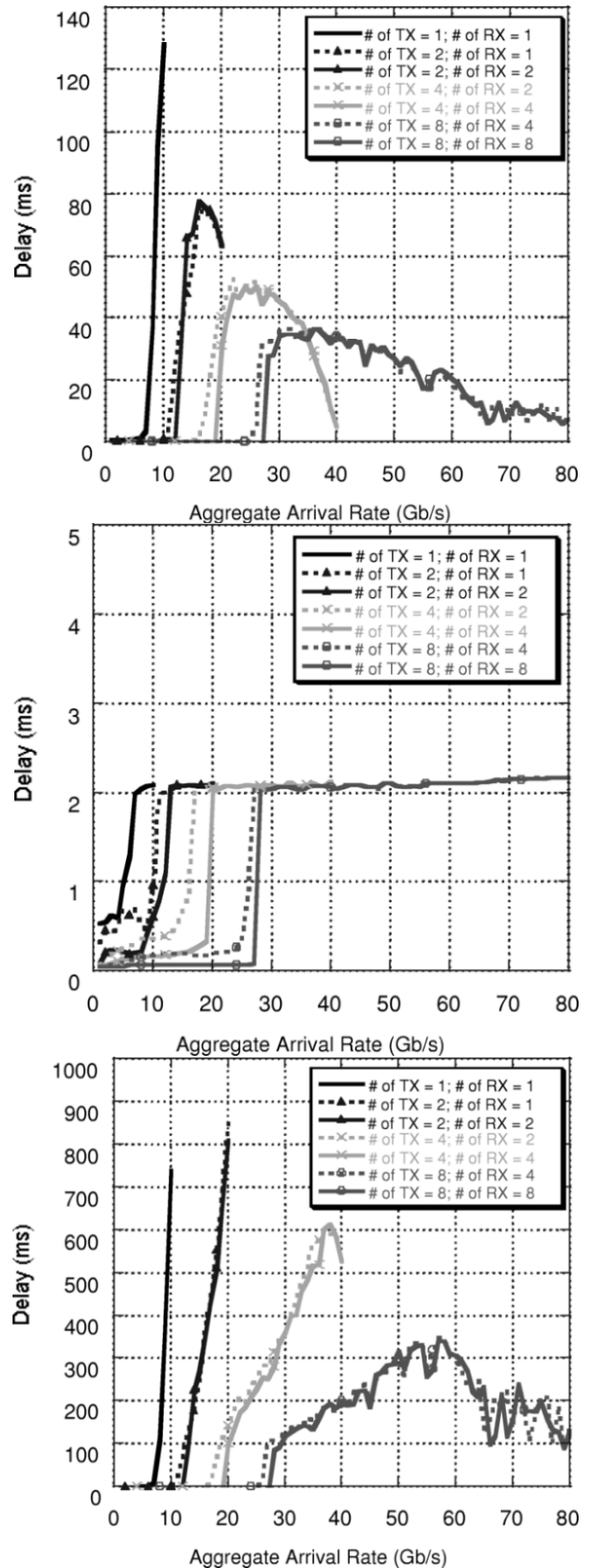


Fig. 15. Average end-to-end packet delay with downstream/upstream traffic ratio of 2:1. (a) Aggregate traffic. (b) Downstream traffic. (c) Upstream traffic.

similar behaviors as well. On the other hand, the downstream throughput results show nearly perfect linear behavior until the aggregate arrival rate reaches the maximum capacity that can be supported by a given configuration. The reason for the relatively poor performance of upstream traffic is that since there is no priority given for polling messages in the scheduling at the OLT, when the downstream link gets overloaded, the polling messages will likely get lost due to longer scheduling delays. In this case, the ONUs have few or no chances to report the size of upstream traffic queue. Therefore, downstream traffic dominates the whole bandwidth available as a result.

This point of change in throughput and delay performance provides us insight on the proper operational range for the aggregate arrival rates. For example, with two transmitters and one receiver, it would be safer to operate the system with an aggregate arrival rate of less than 11 Gb/s. Note that this aggregate arrival rate is only for payload of Ethernet frame, i.e., IP packets, and considering all the overheads related with Ethernet and SUCCESS frames and the guard band, the actual load on the system is larger than that.

The efficiency of the system is indicated by the ratio of aggregate arrival rate showing the start of performance degradation to the transmitter capacity. In general, as the number of transmitters and receivers increases, the corresponding efficiency decreases. This is mainly due to the nonoptimality of the current sequential scheduling as discussed earlier.

Based on these observations from the simulation results, we are currently designing the second version of the SUCCESS MAC protocol based on batch scheduling and priority queuing for polling messages. The basic idea of the batch scheduling is to schedule over multiple frames arrived during a certain time period, called a batch period, in order to minimize scheduled transmission time for higher throughput and shorter delay. Scheduling over multiple frames rather than just one can provide a room for some optimization to minimize unused bandwidth. The batch scheduling provides a tradeoff between sequential and global optimized scheduling. Detailed simulation results for both sequential and batch scheduling algorithms are reported in [23].

V. CONCLUSION

We have proposed the SUCCESS architecture based on a topology of a collector ring and distribution stars. This architecture provides a practical and scalable migration path for current-generation optical access networks from TDM to DWDM. The SUCCESS architecture is capable of providing protection and restoration capability by replacing the existing feeder networks with a new collector ring and semipassive RNs. To the best of our knowledge, the work reported in this paper is the first attempt to bridge the traditional TDM-based PONs with the next-generation WDM-based access, guaranteeing seamless coexistence of old and new ONUs on the same network.

In the SUCCESS architecture, state-of-the-art optical components are used in an efficient way for the economical deployment of the networks. For example, the use of tunable components at OLT can not only decrease total transceiver counts but also provide gradual upgrade path to higher bandwidth by simply

adding more transceivers as user demand increases. Also, the $N \times N$ AWG is configured so that it can serve about two times more ONUs compared to conventional use of $1 \times N$ AWG MUX/DEMUX.

As for the scalability of the SUCCESS architecture, our analysis shows the number of DWDM ONUs is limited by available wavelengths, while the number of CWDM ONUs is limited by power budget. For example, this network can support more than 60 DWDM ONUs as well as more than 100 CWDM ONUs. The experimental results from the testbed also demonstrate the feasibility of the SUCCESS architecture, showing high quality and efficient packetized transmission over 22.5-km-long path with a line rate of 1.25 Gb/s.

We have also designed a simple MAC protocol based on the sequential scheduling algorithm for SUCCESS DWDM-PON to provide efficient bidirectional transmission between the OLT and the ONUs. The initial results of simulations for several different configurations of tunable transmitters and receivers show that the increase in the number of transmitters greatly improves the overall performance while the number of receivers in the given configurations has minimal impact on it due to the nature of SUCCESS architecture where the main bottleneck is the transmitter capacity.

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