A Wavelength-Division-Multiplexed Passive Optical Network With Flexible Optical Network Unit Internetworking Capability

Qiguang Zhao and Chun-Kit Chan, *Senior Member, IEEE*

***Abstract*—We propose and experimentally demonstrate a novel flexible optical network unit (ONU) internetworking architecture over a wavelength-division multiplexed passive optical network (WDM-PON). By employing our designated wavelength assignment and remodulating the downstream differential phase-shift keying signal as the ONU internetworking carrier, one ONU can broadcast its own message to all other ONUs, with negligible signal interference. Moreover, the inter-ONU communication can further be partitioned into arbitrary virtual private groups of ONUs by employing designated RF tones for identification and control. It was experimentally demonstrated that the performance degradation due to the introduction of RF tones is negligible compared with the full broadcast case. Our proposed scheme can provide high flexibility and practical implementation for WDM-PONs.**

***Index Terms*—Optical networks, passive optical networks (PONs), wavelength-division multiplexing.**

I. INTRODUCTION

THE WAVELENGTH-division multiplexed passive optical network (WDM-PON) [1] is emerging as a promising broadband access technique that will meet the ever-increasing bandwidth requirement for the end users. Recently, peer-to-peer Internet applications, such as sharing of data or video among peers, as well as virtual private connections among branch sites in the enterprise arena, are getting more popular. Therefore, it is anticipated that the amount of traffic among the subscribers in a passive optical network (PON) will get significantly large. Nevertheless, conventional WDM-PON architectures only support both the downstream and the upstream transmission with a dedicated set of wavelength channels for communications between the optical line terminal (OLT) and each optical network unit (ONU). The ONUs cannot directly communicate with each other. The inter-ONU traffic must first be transmitted, via the upstream carrier, back to the OLT, where it is electronically routed [2] and modulated on the respective downstream carriers that are destined to other ONUs. This consumes the bandwidth on both the downstream and upstream carriers. Besides, the additional round-trip propagation time between the ONU and the OLT, as well as the increased loading to the OLT for electronic scheduling and routing of the inter-ONU traffic, imposes extra latency to the inter-ONU traffic. Therefore, it is desirable to provide direct connections for internetworking of ONUs in WDM-PONs.

Several schemes have been reported to support inter-ONU communications in PONs. In [3] and [4], the cyclic property of array waveguide gratings (AWGs) was utilized to construct a virtual ring network. However, the reconfiguration of the inter-ONU connections required the tuning of the laser wavelength or the optical filter's passband. In [5] and [6], a fiber Bragg grating (FBG) was placed before the star coupler at the remote node (RN) to redirect the designated wavelength for the inter-ONU traffic in a tree-shaped time-division multiplexed (TDM) PON. However, the double pass of the $1 \times N$ power splitter at the RN imposed high loss budget for the inter-ONU traffic. Besides, the outgoing inter-ONU signal and the reflected signal from the FBG were simultaneously transmitted over the same distribution fiber. This might lead to power penalty due to Rayleigh backscattering-induced interference. In [7] and [8], an $(N+1) \times (N+1)$ star coupler with loop-back connections was employed at the RN to broadcast the inter-ONU traffic. However, this was applicable to TDM-PONs only. In [9], a waveband selective mechanism was proposed to facilitate internetworking among the designated ONU groups. However, the reconfiguration of the ONU groups required the modification of the waveband reflector at the OLT and the waveband filter at the ONU. In general, these previous schemes suffered from limitations in terms of flexibility, reconfigurability, and data rate.

In this paper, a novel ONU internetworking architecture is proposed and experimentally demonstrated. Remodulation [10] of the downstream carrier is employed at the ONU to save the dedicated optical transmitter for the inter-ONU traffic at the ONU. The inter-ONU broadcasting functionality (ONU broadcast) is realized by a designated connection pattern between the AWG and the star coupler at the RN. Therefore, the inter-ONU traffic from an ONU can be broadcast to all other ONUs, except itself, as illustrated in the example in Fig. 1(a) and, thus, could alleviate the problem of backscattering-induced crosstalk on the distribution fiber. On the other hand, in some practical situations, inter-ONU communication is needed among a few ONUs only in the WDM-PON; therefore, it is desirable to have a number of ONUs that are grouped together to form a virtual private group (ONU-virtual private group, ONU-VPG), such that the inter-ONU traffic that is sent from one ONU

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The authors are with the Department of Information Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong (e-mail: ckchan@ie.cuhk.edu.hk).

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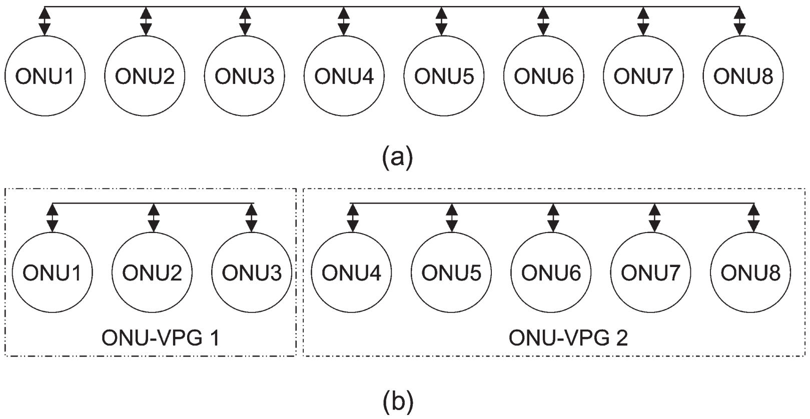

Fig. 1. (a) ONU-broadcast scenario in which each ONU can communicate with all other ONUs in the network. (b) Example of having two ONU-VPGs in the network in which each ONU can only communicate with those ONUs in its own ONU-VPG.

would be broadcasted to the ONUs that belong to its virtual private group only, while ONUs belonging to other virtual private groups could not access that traffic, as illustrated in the example in Fig. 1(b). The formation of such virtual private groups of ONUs is arbitrary and flexible, and a WDM-PON can support several ONU-VPGs simultaneously. This is achieved by employing additional RF tones on the inter-ONU traffic signal for ONU-VPG identification and access control. With the mature electronic processing technique, the RF tone generation and detection modules are simple and of low cost. Dynamic ONU-VPG formation could further be realized by employing frequency-tunable RF tone modules at the ONUs, which thus enhances network reconfigurability.

This paper is organized as follows. In Section II, the basic network topology and operation principle will be described. The ONU internetworking capability will be described in two scenarios: 1) ONU-broadcast scenario and 2) ONU-VPG communication scenario. The experimental demonstration and characterization will be illustrated in Section III. The network scalability and further discussion of the proposed scheme will be discussed in Section IV. Section V will summarize this paper.

II. NETWORK ARCHITECTURE

The ONU internetworking functionality could be implemented in two different scenarios, namely 1) ONU-broadcast and 2) ONU-VPG communication, as discussed in the previous section. The succeeding two sections would describe how these two scenarios could be realized.

A. ONU-Broadcast Communication

Fig. 2(a) and (b) illustrates our proposed ONU internetworking architecture for a WDM-PON with N ONUs in the ONU-broadcast scenario and the wavelength assignment, respectively. The ONU-broadcast architecture is based on the cyclic property of the $2N \times 2N$ AWG that is placed at the RN as well as the remodulation technique that is employed at the ONU. At the OLT, N transceivers are designated for the N respective ONUs. The downstream wavelengths and the upstream wavelengths for ONU i are designated as λ_{2i-1} (e.g., $\lambda_1, \lambda_3, \ldots, \lambda_{2N-1}$) and λ_{2i} (e.g., $\lambda_2, \lambda_4, \ldots, \lambda_{2N}$) (for $i = 1, \ldots, N$), respectively, as depicted in Fig. 2(b). They are chosen to match with the transmission passbands of the $1 \times 2N$ AWG (labeled as AWG1) at the OLT, as well as the $2N \times 2N$ AWG (labeled as AWG2) at the RN. The free spectral range (FSR) of the AWG1 is the same as that of the AWG2. All the downstream wavelengths and the upstream wavelengths are assigned within one FSR. At the OLT, they are multiplexed (or demultiplexed) via AWG1 and are delivered to the RN via the feeder fiber. At the RN, a $2N \times 2N$ AWG (AWG2) is employed to route the wavelengths to their destined ONUs, and its input port 1 (e.g., $I1$) is connected to the feeder fiber. Each ONU is connected with two output ports of the AWG2 via two respective distribution fiber links: The first one is to carry the downstream traffic, and the second one is to carry the upstream traffic, as well as the inter-ONU traffic. To achieve the ONU-broadcast functionality, a $1 \times (N-1)$ star coupler is also employed at the RN. The input port of the star coupler is connected to input port 2 (e.g., $I2$) of the AWG2, while the $(N-1)$ output ports of the star coupler are connected to the $2k$th $(k = 2, \ldots, N)$ input ports (e.g., $I4, I6, \ldots, I2N$) of the AWG2, as depicted in Fig. 2(a).

In our proposed scheme, the downstream signals are in optical differential phase-shift keying (DPSK) modulation format [11], [12]. Thus, the downstream optical carrier can be directly remodulated by the inter-ONU data traffic and is reused as the inter-ONU optical carrier. As the downstream DPSK modulation format exhibits constant intensity envelope, the possible interference to the remodulated inter-ONU data due to the downstream data can be kept minimal. Another feasible alternative is to employ ON–OFF keying (OOK) format for the downstream signal. However, the signal's extinction ratio has to be reduced to facilitate the remodulation for the inter-ONU data at the ONU. Thus, the OOK downstream signal would suffer from additional induced performance degradation [13]. Therefore, in this paper, we propose to employ DPSK format for the downstream signal. Each transmitter at the OLT comprises a precoder and an optical phase modulator. The N DPSK downstream signals are transmitted and routed to their destined ONUs via the downstream links. At each ONU, the received

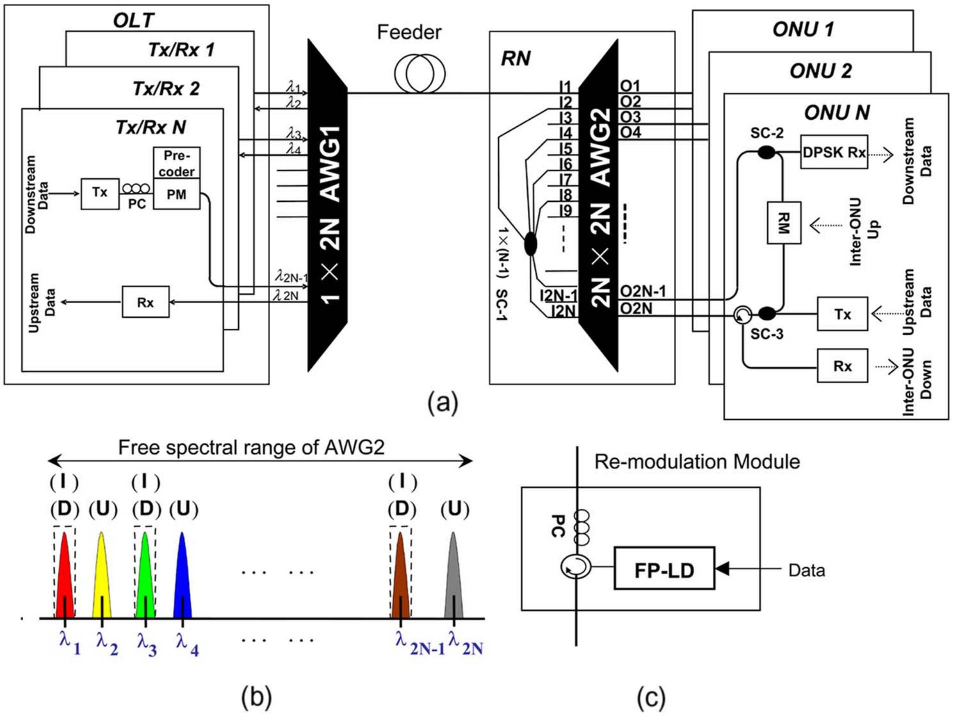

Fig. 2. (a) Proposed ONU internetworking architecture for WDM-PONs (PM: optical phase modulator, RM: remodulation module, SC: star coupler, PC: polarization controller). (b) Wavelength assignment plan (D: downstream wavelength, U: upstream wavelength, I: inter-ONU traffic wavelength). (c) Example remodulation module based on employing the injection locking of an FP laser diode.

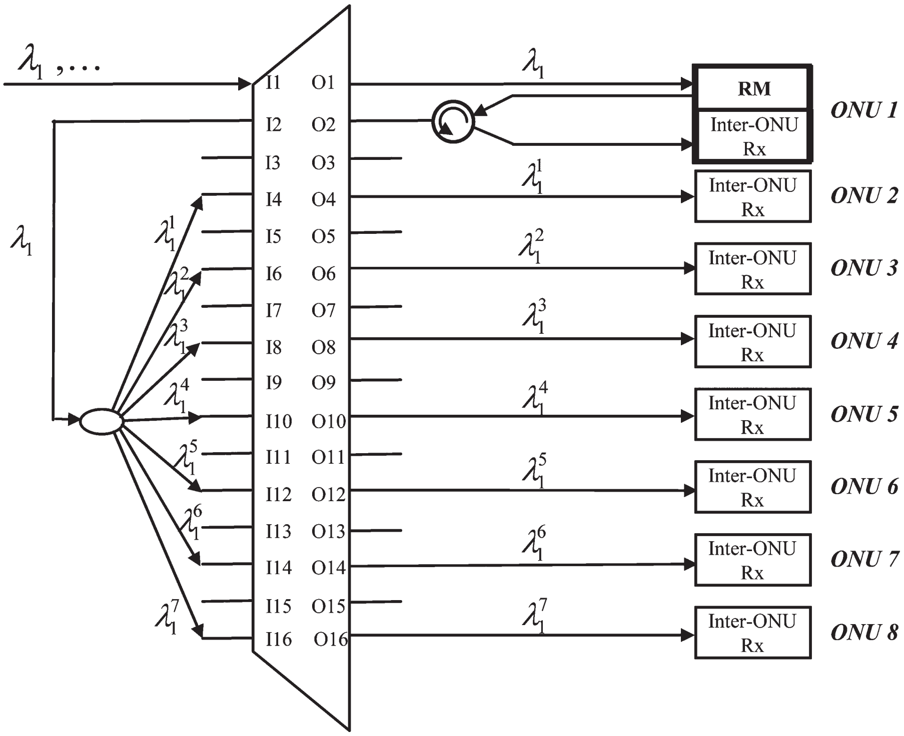

Fig. 3. Routing example of inter-ONU traffic from ONU 1 in a WDM-PON with eight ONUs.

DPSK downstream signal is split into two parts, via a 1 × 2 optical coupler. Part of the downstream signal is demodulated and received, via a conventional optical DPSK receiver, which comprises an optical delayed interferometer (DI), followed by a photodetector. Conventional optical DI has to be thermally stabilized. However, athermal optical DI is currently commercially available and thus greatly simplifies and eases the maintenance of the DPSK receiver. On the other hand, the other part of

TABLE I
ROUTING PATTERN EXAMPLE AMONG DIFFERENT ONUS

		Destination ONUs							
		ONU1	ONU2	ONU3	ONU4	ONU5	ONU6	ONU7	ONU8
Source ONUs	ONU1	–	λ_1^1	λ_1^2	λ_1^3	λ_1^4	λ_1^5	λ_1^6	λ_1^7
	ONU2	λ_3^7	–	λ_3^1	λ_3^2	λ_3^3	λ_3^4	λ_3^5	λ_3^6
	ONU3	λ_5^6	λ_5^7	–	λ_5^1	λ_5^2	λ_5^3	λ_5^4	λ_5^5
	ONU4	λ_7^5	λ_7^6	λ_7^7	–	λ_7^1	λ_7^2	λ_7^3	λ_7^4
	ONU5	λ_9^4	λ_9^5	λ_9^6	λ_9^7	–	λ_9^1	λ_9^2	λ_9^3
	ONU6	λ_{11}^3	λ_{11}^4	λ_{11}^5	λ_{11}^6	λ_{11}^7	–	λ_{11}^1	λ_{11}^2
	ONU7	λ_{13}^2	λ_{13}^3	λ_{13}^4	λ_{13}^5	λ_{13}^6	λ_{13}^7	–	λ_{13}^1
	ONU8	λ_{15}^1	λ_{15}^2	λ_{15}^3	λ_{15}^4	λ_{15}^5	λ_{15}^6	λ_{15}^7	–

the received downstream signal is remodulated by the inter-ONU traffic via a remodulation device, such as the injection-locking Fabry–Pérot (FP) laser [13], reflective semiconductor optical amplifier [14], etc. Therefore, the received downstream wavelength becomes the optical carrier for the inter-ONU traffic. Fig. 2(c) shows an example of a remodulation device including an optical circulator and an injection-locking FP laser. The inter-ONU carrier propagates back to the RN via the optical circulator and the upstream link, together with the respective upstream signal. The upstream signal is routed out from the first input port $I1$ of the AWG2 at the RN, where it is further delivered back to the OLT via the feeder fiber; on the other hand, the inter-ONU traffic signal is routed out from the second input port $I2$ of the AWG2, where it is further power split into $(N-1)$ copies by the $1\times(N-1)$ optical star coupler. The $j$the copy is denoted as $[\lambda_{2i-1}^j$ (for $i=1,\ldots,N$, $j=1,\ldots,(N-1)]$, where index i refers to source ONU i and the respective inter-ONU carrier is λ_{2i-1}. The jth copy is then fed into the $2(j+1)$th input port of the AWG2. Fig. 3 illustrates the ONU internetworking routing principle in a WDM-PON having eight ONUs, for instance. The inter-ONU traffic from ONU 1 is modulated onto the received downstream wavelength λ_1 before being routed back to the RN, where it is power split into seven copies. These inter -ONU traffic copies $(\lambda_1^1,\ldots,\lambda_1^7)$ are fed into the input ports $(I4, I6, I8, \ldots, I16)$ of the AWG2, respectively. Due to the input–output property of the AWG, they are routed to the output ports $(O4, O6, O8, \ldots, O16)$ of the AWG2, where they are further delivered to the respective ONU 2, ONU 3, ONU 4, …, ONU 8, via the respective distribution fiber links for the inter-ONU traffic. Therefore, the inter-ONU traffic from ONU 1 would be distributed to all other ONUs, except itself. With the same principle, the routing pattern among different ONUs in an eight-ONU WDM-PON is shown in Table I, in which λ_{2i-1}^j denotes the jth copy of the inter-ONU carrier λ_{2i-1} sent from ONU i to all other ONUs. In general, source ONU i could communicate with the other ONUs via the respective inter-ONU traffic signal copies λ_{2i-1}^j, which would not be routed back to its source ONU. Moreover, the upstream signals would not be affected by the inter-ONU traffic signals as they are transmitted on different wavelengths. Consequently, the ONU-broadcast functionality could be realized by the preceding proposed remodulation technique and wavelength routing mechanism.

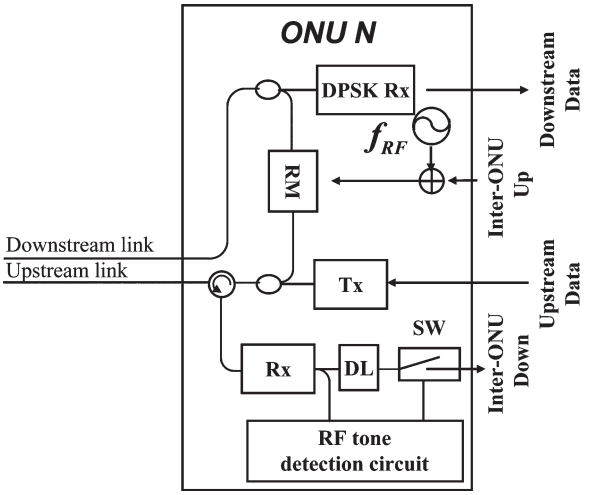

Fig. 4. Modified ONU structure for ONU-VPG communication (DL: electronic delay line, SW: electronic switch, RM: remodulation module).

B. ONU-VPG Communication

In the ONU-VPG communication scenario, a number of ONUs can be grouped together to form a virtual private group such that each ONU can broadcast its inter-ONU traffic only to all other ONUs in the same ONU-VPG. Depending on the connectivity requirement of the ONUs in the WDM-PON, a number of ONU-VPGs can be supported. This can be achieved by employing the same proposed network architecture and wavelength routing principles as in the ONU-broadcast case, except that additional RF tones are added to the inter-ONU signals at the ONUs for identification and access control. Each ONU-VPG is assigned with a distinct set of RF tone frequencies. Fig. 4 shows the modified ONU structure to support ONU-VPG communication. Whenever an ONU wants to broadcast a message within its own ONU-VPG, the outgoing inter-ONU traffic signal is first low-pass filtered before being multiplexed

TABLE II
RF TONE ASSIGNMENT EXAMPLE FOR FOUR ONU-VPGS. "0" STATE MEANS THE PRESENCE OF THE TONE, WHILE "1" STATE MEANS THE ABSENCE OF THE TONE

RF Tones	ONU-VPG#1	ONU-VPG#2	ONU-VPG#3	ONU-VPG#4
f_1	0	0	1	1
f_2	0	1	0	1

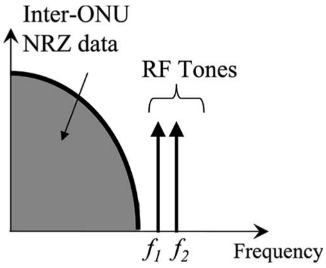

Fig. 5. Example spectrum for the inter-ONU traffic sent within ONU-VPG 4.

with a set of RF tones at distinct frequencies that are designated to its ONU-VPG. For a WDM-PON supporting M ONU-VPGs, $\log_2 M$ distinct RF tone frequencies are required at each ONU, such that the ON–OFF pattern of the individual tones serves as the identification tag to distinguish among the ONU-VPGs. Table II shows an RF tone assignment for each ONU-VPG in a WDM-PON with four ONU-VPGs, for instance, and Fig. 5 shows an example spectrum of the inter-ONU traffic that is sent within ONU-VPG 4. After the wavelength routing and broadcasting via the RN, all other ONUs on the WDM-PON would receive the same inter-ONU traffic signal that is sent from the source ONU. At each ONU, all incoming inter-ONU traffic signal is detected first. The detected signal is electronically buffered using electrical delay lines or memory chips, and part of it is fed through an RF tone detection circuit to determine whether the ON–OFF states of the received RF tones match with the designated identification tag for its own ONU-VPG. If they match, it means that the destined ONU belongs to the same ONU-VPG as the source ONU. This triggers to close the ON–OFF electronic switch; thus, the incoming inter-ONU traffic signal would be successfully received by that ONU. Otherwise, the incoming inter-ONU traffic signal would be blocked and discarded by leaving the electronic switch open. This way, only those ONUs that belong to the same ONU-VPG as the source ONU can properly access the incoming inter-ONU traffic signal.

For media access control (MAC) of the inter-ONU traffic, carrier sense multiple access with collision avoidance protocol [15] could be applied to resolve the possible collision during the inter-ONU traffic transmission. Before the inter-ONU traffic signal is sent, the source ONU would first broadcast a signaling message to all other ONUs to announce the occupancy of the following time slot for data transmission. All other destined ONUs would receive the signaling data and respond correspondingly by the MAC layer processing circuit. In the case of ONU-VPG communication, in order to enhance the flexible reconfiguration of the ONU-VPG, the RF tone generation, and detection circuit could be made with frequency tunability, i.e., a tunable bandpass filter [16] and a voltage-controlled oscillator [17] with the frequency tunable range covering all required tone frequencies are employed at each ONU. Moreover, these tunable electronics components can be integrated in a single chip with the mature semiconductor processing technique. In this way, the RF tone generation and detection unit in all ONUs could be made identical, thus enhancing its practicality and cost effectiveness. The reconfiguration of the RF tone frequencies could be easily controlled remotely at the OLT via some signaling protocols. Therefore, high flexibility in the ONU-VPG reconfiguration could be achieved. Compared with the multiple secure network proposal with electronic code-division multiple access in [7], the incorporation of RF tones would not suffer from the severe multiple access interference, which might limit the data rate of the inter-ONU traffic.

III. EXPERIMENTAL DEMONSTRATION

The performance of the downstream DPSK signal and the inter-ONU traffic for an ONU was experimentally investigated for both ONU-broadcast and ONU-VPG communication scenarios. The experimental setups for these two scenarios with two ONUs (ONU 1 and ONU 2) are the same, as depicted in Fig. 6, except that RF tone is not needed for the former one. At the OLT side, a distributed feedback laser at 1546.35 nm was externally modulated by a $\mathrm{LiNbO_3}$ optical phase modulator with 10-Gb/s nonreturn-to-zero (NRZ) $2^{31} - 1$ pseudorandom binary sequence (PRBS) to form the downstream optical DPSK signal. The polarization-offset technique [12] was employed during the generation of the optical DPSK signal to facilitate the injection locking of the FP laser diode and to enhance data remodulation at the ONU. The DPSK signal was amplified by an erbium-doped fiber amplifier before it was fed into a piece of 20-km single-mode fiber (SMF). At the RN, a 16×16 AWG with 100-GHz channel spacing and an FSR of 12.8 nm was used. An optical attenuator with 10-dB attenuation was employed at input port 2 of the AWG at the RN to simulate the power splitting ratio of the star coupler in a network with eight ONUs. At the ONU1, a 50/50 coupler was used to split the downstream signal for detection and inter-ONU data remodulation, respectively. In the case of ONU-broadcast communication, the FP laser at the ONU was directly modulated by the $2^7 - 1$ NRZ PRBS inter-ONU data signal. However, in the case of ONU-VPG communication, the inter-ONU data was first filtered by a low-pass filter (LPF1, $\Delta f_{3\mathrm{dB}} =$ 1000 MHz). It was then multiplexed with a locally generated RF tone at 1.5 GHz, which simulated the identification tag for its own ONU-VPG, before being fed into the FP laser for direct modulation. The inter-ONU traffic signal from ONU 1 was routed to ONU 2, via the RN, and was received by a p-type-intrinsic-n-type receiver at ONU 2 for RF tone detection circuit and inter-ONU traffic detection. An electronic switch was used at the receiver to control the reception of the inter-ONU traffic signal.

First, the power penalty of the inter-ONU traffic that is induced by the additional RF tone as the identification tag was investigated for the back-to-back case, and the measured results are depicted in Fig. 7. Here, the RF tone index was defined as the ratio of the peak amplitude of the RF tone to that of the data

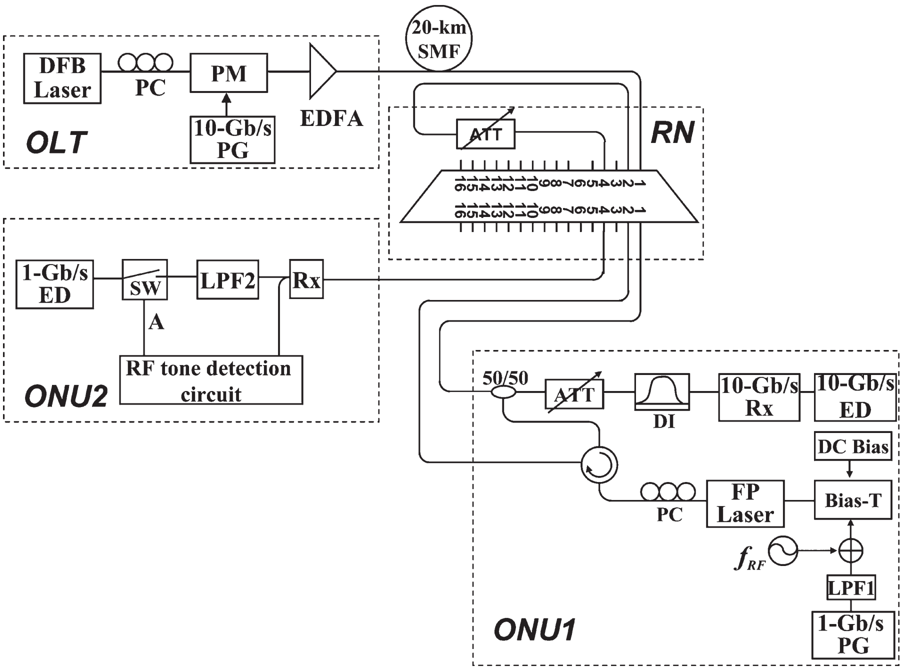

Fig. 6. Experimental setup (PG: pattern generator, ED: error detector, DI: delay interferometer, LPF: low-pass filter, PC: polarization controller).

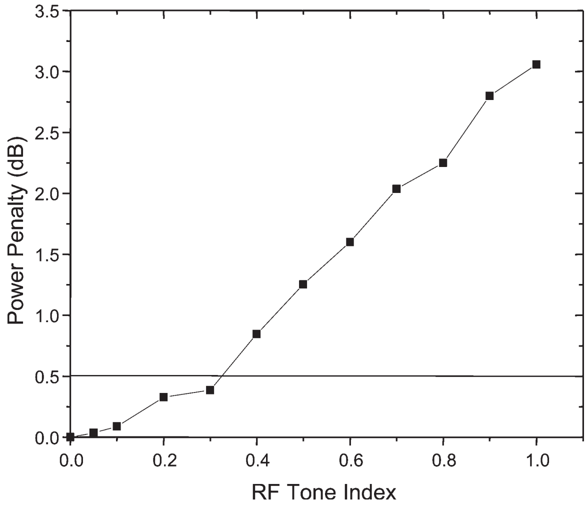

Fig. 7. Power penalty of the inter-ONU signal versus RF tone index per channel.

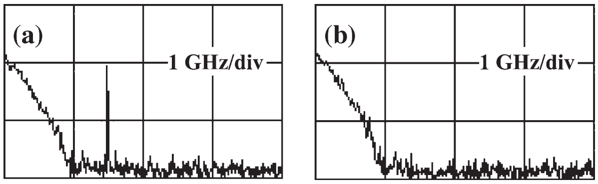

Fig. 8. RF spectra of inter-ONU traffic (a) with 1.5-GHz RF tone and (b) without any RF tone.

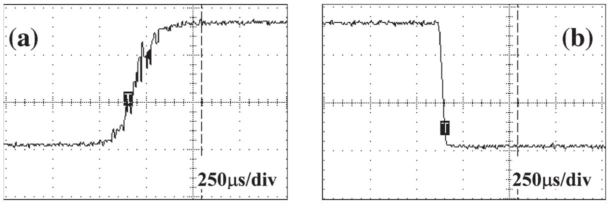

Fig. 9. Output transistor–transistor logic control signals for the electronic switch at the ONU to (a) discard and to (b) forward the received inter-ONU traffic signal.

signal. It is shown that the power penalty increased obviously when the RF tone index was increased beyond 0.3, where the power penalty was about 0.5 dB. With such low RF tone index, the possible optical beat interference as well as distortion that is induced by the RF tones would not be significant. With the chromatic dispersion after transmission in the distribution fiber, the power penalty could be even a little bit larger than that in the back-to-back case. Therefore, the RF tone index could be chosen as about 0.1 to assure a reasonably good performance, where the power penalty was less than 0.1 dB in the back-to-back case, and the power of the RF tone was strong enough for the RF tone detection circuit at the ONU. In our experiment, the peak amplitudes of the 1-Gb/s inter-ONU traffic signal and the added RF tone were 250 and 26.977 mV, respectively. It is shown that the RF tone can be clearly distinguished in the RF spectra of the received inter-ONU traffic signal with a 1.5-GHz RF tone and without any RF tone, as shown in Fig. 8(a) and (b), respectively. At the ONU, to extract and detect the RF tone from the received incoming inter-ONU traffic signal, a bandpass filter that is centered at 1.5 GHz was employed. A decision circuit with a preset amplitude threshold was built to determine the presence of the RF tone at that designated frequency, and its output was used to control the electronic switch to discard or receive the received inter-ONU traffic signal. Fig. 9(a) and (b) shows the measured switching states of the control signals that are applied to the electronic switch at point A in Fig. 6, and the switching time was measured to be about 250 μs. This switching time could be further improved with better circuit design and circuit integration.

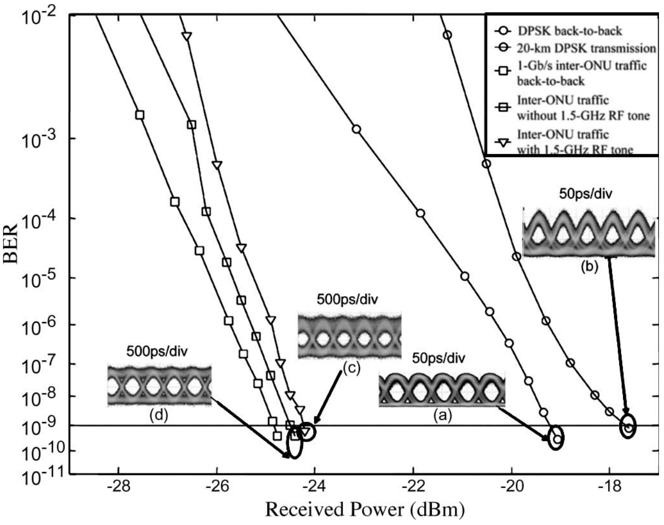

Fig. 10. BER measurement of 10-Gb/s DPSK downstream and 1-Gb/s OOK inter-ONU traffic. Insets: Eye diagrams of (a) DPSK back-to-back, (b) DPSK 20-km SMF transmission, (c) inter-ONU traffic with 1.5-GHz RF tone, and (d) inter-ONU traffic without 1.5-GHz RF tone.

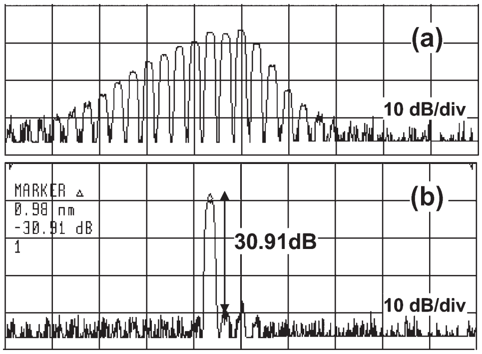

Fig. 11. Output optical spectra of the FP laser diode (a) before injection locking and (b) after injection locking.

TABLE III
POWER BUDGET OF 10-Gb/s DPSK DOWNSTREAM SIGNAL IN A WDM-PON WITH EIGHT ONUs

Output power from OLT (with EDFA) (dBm)	5
16 × 16 AWG (at RN) insertion loss (dB)	4
50:50 coupler loss (dB)	3.2
Single-ended DI insertion loss (dB)	4.7
Connector loss (dB)	2
17-km SMF (feeder fiber) loss(dB)	4.25
3-km SMF (distribution fiber) loss (dB)	0.75
Total loss budget (dB)	18.9
Injection power to FP laser at ONU (dBm)	-10
PIN receiver sensitivity (dBm)	-18

TABLE IV
POWER BUDGET OF 1-Gb/s OOK INTER-ONU SIGNAL IN A WDM-PON WITH EIGHT ONUs

Output power of injection-locked FP Laser (dBm)	1
Circulator loss (round-trip) (dB)	1.4
50:50 coupler loss (dB)	3.2
16 × 16 AWG insertion loss (round-trip) (dB)	8
Splitting loss of 1 ×8 star coupler (dB)	11
Connector loss (dB)	2
3-km SMF (distribution fiber) loss (round-trip) (dB)	1.5
Total loss budget (dB)	27.1
APD receiver sensitivity (dBm)	-33

Fig. 10 shows the bit error rate (BER) measurement results of the 10-Gb/s DPSK downstream and the 1-Gb/s OOK inter-ONU traffic signals. The induced power penalty of 10-Gb/s DPSK downstream was about 1.5 dB compared to the back-to-back case. The penalty was due to chromatic dispersion of 20-km SMF and the polarization-offset technique on the DPSK downstream signal [12]. Fig. 10(a) and (b) shows the respective eye diagrams for the back-to-back case and after 20-km SMF transmission, respectively. At the ONU, part of the received signal was fed into an FP laser diode for injection locking so as to perform data remodulation for the inter-ONU traffic. The injection power into the FP laser diode was about −10 dBm. The output power of the injection-locked FP laser diode was about −0.80 dBm at the output port of the optical circulator. Fig. 11(a) and (b) shows the optical spectra of the output from the FP laser diode before and after injection locking with the received downstream carrier, respectively. It is shown that the side mode suppression ratio of the injection-locked FP laser diode was greatly improved to about 30.91 dB. The outgoing inter-ONU traffic signal was sent to ONU 2, via the AWG at the RN, and it was measured to be about −21.40 dBm. The measured BER curves of the inter-ONU traffic signal with and without RF tone are also shown in Fig. 10. The 0.5-dB power penalty between the back-to-back case and the inter-ONU traffic with RF tone could be attributed to the slight mismatch between the transmission wavelengths and the passbands of the AWGs. On the other hand, the power penalty that is induced by the presence of RF tone was only about 0.2 dB, as compared with the case without RF tone. The eye diagrams of the two cases are also shown in Fig. 10(c) and (d), respectively. In the case of inter-ONU signal with RF tone, the *one* level appeared to be thicker than that in the case without RF tone. It might be attributed to the residual intensity fluctuation of the RF tone after the LPF. Nevertheless, such small induced degradation is negligible for practical implementation.

IV. DISCUSSION

Tables III and IV show the typical power budget plans for the 10-Gb/s DPSK downstream traffic and the 1-Gb/s OOK inter-ONU traffic, respectively, assuming that the network is constructed with commercially available components and that eight ONUs are supported. With the recent advances in materials and fabrication techniques, the optical components could be manufactured with very low insertion losses. For example, perfluorinated polymer AWGs have been fabricated with ultralow (< 3 dB) insertion losses [18]. Therefore, the loss budget could be potentially reduced, and more ONUs could be supported in the network.

In general, our proposed scheme can support internetworking capability in a WDM-PON with the conventional two distribution fibers per ONU. The architecture of the RN is required to be upgraded with passive components only, while the ONU is realized with flexible and potentially low-cost optical or electronic components. The bit rate of the inter-ONU traffic is chosen to be 1 Gb/s for the popular and cost-effective deployment of the gigabit Ethernet. Any upgrade of this bit rate is possible, as long as it satisfies the power budget constraint. In terms of the identification and access control of the ONU-VPGs, our proposed RF-tone-based scheme is nonintrusive to the baseband data. Another alternative for achieving this is to attach header bits to the data packets. However, bit-level synchronization and processing will be required and, thus, imposes overhead to the baseband data and decreases the data packet efficiency. Therefore, by incorporating the access control of the ONU-VPG in the physical layer using our proposed scheme, the higher layers can be off loaded and, thus, can improve the network efficiency. Besides, with mature semiconductor fabrication and processing techniques, all components that are required to perform RF tone identification can be integrated in one single chip and are potentially of low cost with volume production. All ONUs can even be made identical if frequency-tunable RF components are employed.

V. SUMMARY

We have proposed a novel ONU internetworking architecture over a WDM-PON. The ONU internetworking functionality of our proposed scheme could support ONU-broadcast communication as well as ONU-VPG communication. To achieve the arbitrary and flexible formation of ONU-VPGs, additional RF tones are incorporated to the inter-ONU traffic signal as the ONU-VPG identification tag with proper access control mechanism. A WDM-PON can support several ONU-VPGs, simultaneously. Moreover, dynamic ONU-VPG formation could also be realized by employing the frequency-tunable RF tone modules at the ONUs, thus enhancing the network reconfigurability. Such integrated RF tone generation and detection modules are simple and of low cost in high volume with the mature electronic processing and manufacturing technique.

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Qiguang Zhao received the B.Sc. degree in optoelectronic engineering from Huazhong University of Science and Technology, Wuhan, China, in 2004. He is currently working toward the M.Phil. degree with the Department of Information Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong.

His current research interests include optical communications and optical access networks.

Chun-Kit Chan (S’93–M’97–SM’04) received the B.Eng., M.Phil., and Ph.D. degrees from The Chinese University of Hong Kong (CUHK), Shatin, Hong Kong, all in information engineering.

In 1997, he joined the Department of Electronic Engineering, City University of Hong Kong, Kowloon, Hong Kong, as a Research Assistant Professor. In 1999, he joined Bell Laboratories, Lucent Technologies, Holmdel, NJ, as a member of Technical Staff, where he worked on control of widely tunable semiconductor lasers and realization of an optical packet switch fabric with terabit-per-second capacity. In August 2001, he joined the Department of Information Engineering, CUHK, where he is currently an Associate Professor. He has published more than 150 technical papers in refereed international journals and conference proceedings. He is the holder of one issued U.S. patent. His main research interests include optical access networks, optical packet switching, and optical performance monitoring.

Prof. Chan has served as the member of the technical program committee for OFC/NFOEC from 2005 to 2007 and for other international conferences. He is currently an Associate Editor for the *OSA Journal of Optical Networking*.