

Time- and Wavelength-Division Multiplexed Passive Optical Network (TWDM-PON) for Next-Generation PON Stage 2 (NG-PON2)

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Abstract—The next-generation passive optical network stage 2 (NG-PON2) effort was initiated by the full service access network (FSAN) in 2011 to investigate on upcoming technologies enabling a bandwidth increase beyond 10 Gb/s in the optical access network. The FSAN meeting in April 2012 selected the time- and wavelength-division multiplexed passive optical network (TWDM-PON) as a primary solution to NG-PON2. In this paper, we summarize the TWDM-PON research in FSAN by reviewing the basics of TWDM-PON and presenting the world's first full-system 40 Gb/s TWDM-PON prototype. After introducing the TWDM-PON architecture, we explore TWDM-PON wavelength plan options to meet the NG-PON2 requirements. TWDM-PON key technologies and their respective level of development are further discussed to investigate its feasibility and availability. The first full-system 40 Gb/s TWDM-PON prototype is demonstrated to provide 40 Gb/s downstream and 10 Gb/s upstream bandwidth. This full prototype system offers 38 dB power budget and supports 20 km distance with a 1:512 split ratio. It coexists with commercially deployed Gigabit PON (G-PON) and 10 Gigabit PON (XG-PON) systems. The operator-vendor joint test results testify that TWDM-PON is achievable by the reuse and integration of commercial devices and components.

Index Terms—Next-generation passive optical network stage 2 (NG-PON2), time- and wavelength-division multiplexed passive optical network (TWDM-PON), tunable receiver, tunable transmitter.

I. INTRODUCTION

THE next-generation passive optical network stage 2 (NG-PON2) project was initiated by the full-service access network (FSAN) [1] community in 2011. It investigates on optical fiber network technologies enabling a bandwidth increase beyond 10 Gb/s in the access network. Operators' NG-PON2 requirements include a set of access performance descriptions.

Manuscript received May 23, 2012; revised August 17, 2012; accepted August 20, 2012. Date of publication August 28, 2012; date of current version January 09, 2013.

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Digital Object Identifier 10.1109/JLT.2012.2215841

Major requirements are at least 40 Gb/s aggregate rate in downstream or upstream, 40 km reach, 1:64 split ratio, 40 km differential reach, and at least 1 Gb/s access rate per optical network unit (ONU).

Many passive optical network (PON) technologies have been proposed to provide broadband optical access beyond 10 Gb/s. There are the 40 Gigabit time-division multiplexed PON (XLG-PON) proposal [2] which increases the single carrier serial downstream bit rate of a 10 Gigabit PON (XG-PON) [3] to 40 Gb/s, the time- and wavelength-division multiplexed PON (TWDM-PON) proposal which stacks multiple XG-PONs using WDM [4], a group of WDM-PON proposals which provide a dedicated wavelength channel at the rate of 1 Gb/s to each ONU with different WDM transmit or receive technologies [5], [6], a set of orthogonal frequency-division multiplexed (OFDM)-based PON proposals which employ quadrature amplitude modulation and fast Fourier transform to generate digital OFDM signals for transmission [7], [8].

Among all of the aforementioned proposals, TWDM-PON has attracted the majority support from global vendors and was selected by the FSAN community in the April 2012 meeting as a primary solution to NG-PON2. TWDM-PON increases the aggregate PON rate by stacking XG-PONs via multiple pairs of wavelengths. An XG-PON system offers the access rates of 10 Gb/s in downstream and 2.5 Gb/s in upstream. A TWDM-PON system with four pairs of wavelengths is able to provide 40 Gb/s and 10 Gb/s in downstream and upstream, respectively. Each TWDM-PON ONU can provide peak rates up to 10 Gb/s downstream and 2.5 Gb/s upstream. This meets the rate requirements of NG-PON2.

In this paper, we review the TWDM-PON solution by walking through it as follows. Section II introduces the TWDM-PON architecture. Section III discusses wavelength plans and possible loss budgets. Section IV investigates key technologies enabling tunable ONUs in TWDM-PON. We demonstrate the world's first full-system 40 Gb/s TWDM-PON prototype in Section V. Section VI concludes this paper by highlighting future research directions.

II. TWDM-PON ARCHITECTURE

A. Baseline Architecture

The basic TWDM-PON architecture is shown in Fig. 1. Four XG-PONs are stacked by using four pairs of wavelengths (e.g., wavelength pairs of $\{\lambda_1, \lambda_5\}$, $\{\lambda_2, \lambda_6\}$, $\{\lambda_3, \lambda_7\}$, and

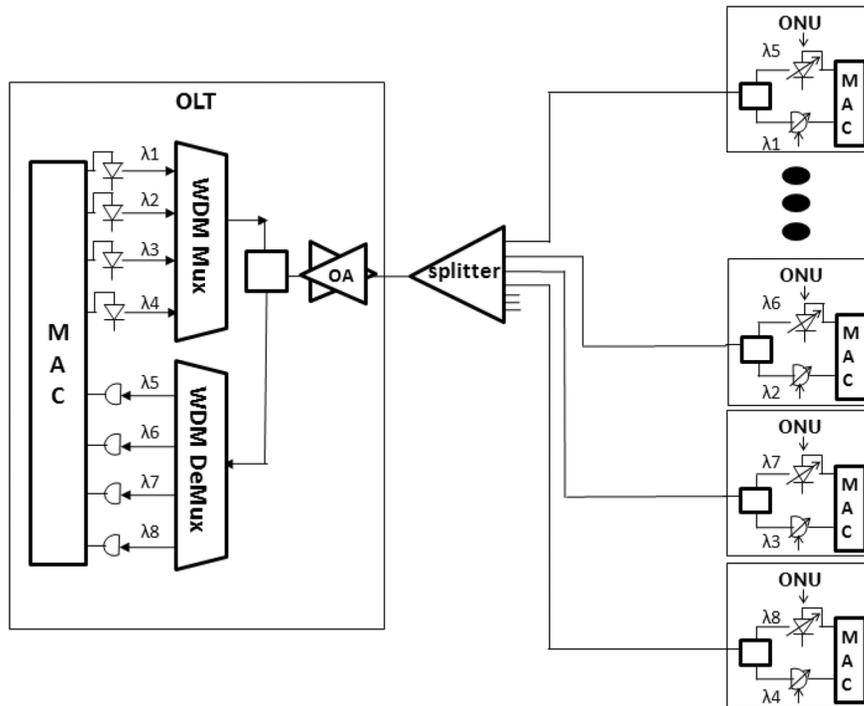


Fig. 1. TWDM-PON system diagram.

$\{\lambda_4, \lambda_8\}$ in Fig. 1). For simple network deployment and inventory management purposes, the ONUs are equipped with tunable transmitters and receivers. The tunable transmitter is tunable to any of the four upstream wavelengths. The receiver is tunable to any of the four downstream wavelengths.

In order to achieve power budget higher than that of XG-PON, optical amplifiers (OAs) are used at the optical line terminal (OLT) side to boost the downstream signals as well as to preamplify the upstream signals. The optical distribution network (ODN) remains passive since OA and WDM Mux/DeMux are placed at the OLT side.

Options to the baseline architecture include more pairs of wavelengths and different rates for stacking. For example, TWDM-PON could support eight pairs of wavelengths. This type of system is valuable in the market where multiple operators share one physical network infrastructure. Another example is to provide Gigabit PON (G-PON) [9] rates in each pair of wavelengths. This would relax the TWDM-PON optics requirements.

B. Key Applications

As compared to the next-generation passive optical network stage 1 (NG-PON1) system (e.g., XG-PON), TWDM-PON delivers higher rates in both downstream and upstream. The multiple wavelength feature of TWDM-PON could be applied for other applications.

The first one to consider is for pay-as-you-grow provisioning. The TWDM-PON system could be deployed starting with a single wavelength pair. It could be upgraded by adding new wavelength pairs to increase the system capacity. In this way, the operators can address the bandwidth growth demand by investing for what is needed and to expanding on-demand.

Another application of TWDM-PON is for local loop unbundling (LLU). A TWDM-PON with multiple OLT arrangement is shown in Fig. 2 for LLU. Each operator would have their own OLT, each of which would contain some set of wavelength channels. A wavelength-selective device would be used to multiplex the OLT ports onto a single fiber. The wavelength-selective device could be as simple as a filter-based demultiplexer, or it could be an arrayed waveguide router type of device. This scheme unbundles the shared infrastructure for multiple operators. It also offers the possibility of every operator's OLT being the same (containing all the wavelengths), and a single operator could add OLT resources as they want.

III. WAVELENGTH PLAN AND LOSS BUDGET

Coexistence with previous generations of PONs in the legacy ODN relies upon the TWDM-PON wavelength plan. There are several options for the TWDM-PON wavelengths.

The first option is to reuse the XG-PON wavelength bands. It defines a finer grid inside of the previously defined bands as was described in the NG-PON1 study. This wavelength plan leverages the development work that has gone into XG-PON optics. It is compatible with G-PON [9] and the 1555 nm radio frequency (RF) video overlay channel, but blocks standardized XG-PON. Its loss budget is similar to that of XG-PON. A typical loss budget value is about 33 dB. Fig. 3 shows an example of this wavelength plan.

The second option is to redefine the C-band enhancement band to contain both the upstream and downstream wavelengths. This has attractive optical characteristics of using erbium-doped fiber amplifiers (EDFAs) for signal amplification, and of lower transmission fiber loss. Such a system has a higher power budget and a longer reach. Fig. 4 shows an example of this wavelength plan. It is compatible with G-PON

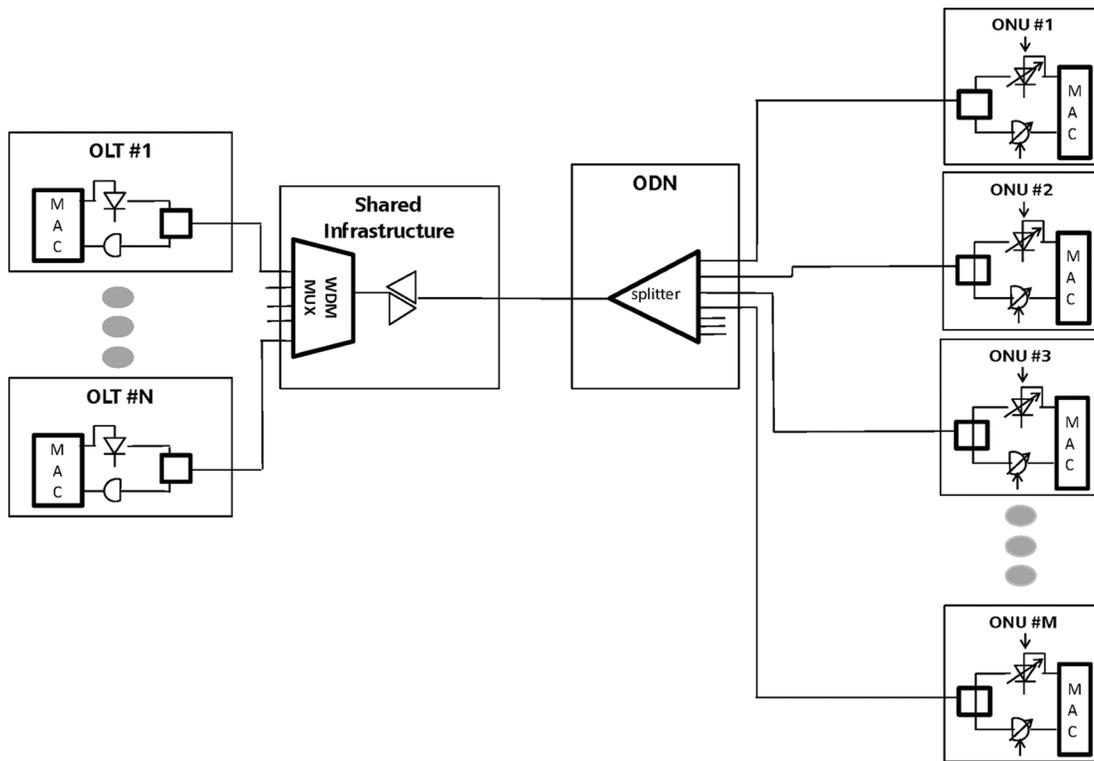


Fig. 2. TWDM-PON with multiple OLTs for LLU.

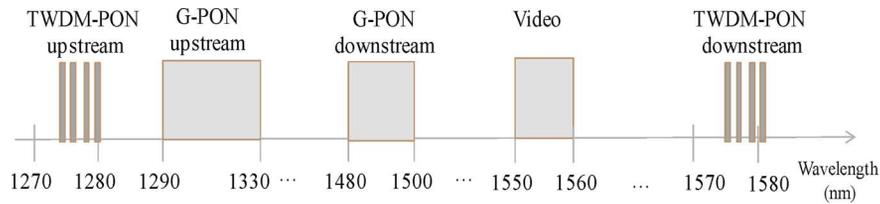


Fig. 3. XG-PON wavelength reuse.

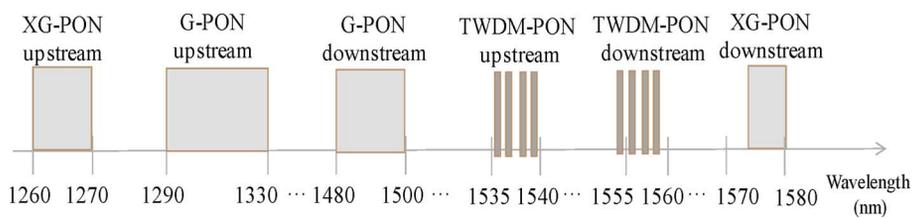


Fig. 4. C-band wavelength plan.

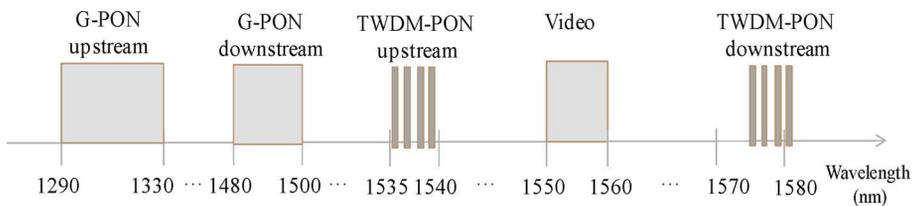


Fig. 5. C-minus/L-minus band wavelength plan.

and XG-PON. The RF video overlay channel is blocked. With EDFAs, this wavelength plan could achieve a loss budget of about 38 dB.

Another option is a mixture of the above two plans. The downstream channels are designed in the *L*-minus band. The

upstream channels are located in the *C*-minus band. This plan is shown in Fig. 5. It maintains the G-PON and RF video channels. The upstream transmission is similar to the wavelength plan of Fig. 4. This wavelength plan is compatible with G-PON and the RF video overlay channel, but blocks XG-PON. *C*-band

components could work with an EDFA preamplifier to provide a higher power budget. In the downstream, an *L*-band amplifier is needed to improve the power budget. A loss budget of about 38 dB could be achieved.

IV. KEY TECHNOLOGIES

Most of the TWDM-PON components are commercially available in access networks today. As compared to previous generations of PONs (e.g., G-PON, XG-PON), the only significantly new components in TWDM-PON are the tunable receivers and tunable transmitters at the ONU. Technology options to implement the required wavelength tuning functions at the ONU are summarized as follows.

ONU Tunable Receiver: The TWDM-PON ONU receiver should tune its wavelength to any of the TWDM-PON downstream wavelengths by following the OLT commands. This function can be implemented by using candidate technologies such as thermally tuned Fabry–Perot (FP) filter [10], angle-tuned FP filter, injection-tuned silicon ring resonator [11], liquid crystal tunable filter [12], and thermally tunable FP detector [13].

ONU Tunable Transmitter: The ONU transmitter can tune its wavelength to any of the upstream wavelengths. The implementation technologies are distributed feedback (DFB) laser with temperature control (TC) [14], DFB laser with partial TC [15], multisection distributed Bragg reflector laser (electrical control) without cooling [16], external cavity laser (ECL) with mechanical control without cooling [17], ECL with thermo/electro/piezo/magneto-optic control without cooling [18], [19].

Note that tunable receivers and tunable transmitters have been a research topic of optical transport networks for more than a decade. There is a great deal of development practice in this area. The TWDM-PON application takes advantage of the optical transport network component effort in a couple of ways. First, the TWDM-PON tunable transceivers reuse the mature tunable optical transport network components. If one technology does not perform to expectation, there are always other options to provide the required functions. This reduces the risk of component availability. Second, TWDM-PON provides significant relief on the specifications of tunable optical transport network components. Because the TWDM-PON wavelength tuning performance could be relaxed from that of the optical transport network and TWDM-PON channel rates are widely used in the optical transport network, critical tuning requirements, such as wavelength tuning range, tuning speed, channel spacing, can be dramatically relieved. Such performance relaxation offers significant yield improvements during the mass production and cost reductions for tunable transceivers.

V. 40 GB/S TWDM-PON PROTOTYPE

A. Prototype System

In this section, we demonstrate the first full-system 40 Gb/s TWDM-PON prototype. This prototype employs the C-band wavelength plan shown in Fig. 4 to achieve coexistence with the previous generations of PONs. The four downstream

wavelengths are spaced 200 GHz apart. The output power for each downstream wavelength is about 10 dBm after the EDFA booster. The four upstream wavelengths are 100 GHz apart. The TWDM-PON OLT is designed to be integrated into a Huawei OLT chassis.

The ONUs are equipped with tunable transmitters and tunable receivers. The ONU tunable transmitter is based on thermally tuned DFB laser with more than 400 GHz wavelength tuning range. The ONU tunable receiver is based on thin film tunable filter in front of a 10 Gb/s APD ROSA. Its wavelength tuning range is more than 800 GHz. An ONU is able to tune to any channel upon software command from the PON control logic.

The medium access control (MAC) layer functionalities are based on XG-PON transmission convergence layer specifications in ITU-T Recommendation G.987.3 [20]. The TWDM-PON MAC is implemented in a commercial FPGA. Modules such as dynamic bandwidth allocation, forward error correction (FEC), scrambling, XG-PON encapsulation mode (XGEM) are integrated to demonstrate a full-system operation.

As compared to previous research [21], a major contribution of this work is the reuse and integration of commercial devices for a 40 Gb/s broadband access system which meets the NG-PON2 requirements. Key components, such as EDFAs, tunable transmitters, tunable filters, and coexistence filters, are from the market. The TWDM-PON MAC implementation reuses the XG-PON MAC development effort in the industry. Therefore, the prototype system demonstrates the TWDM-PON maturity and availability.

Fig. 6 shows the prototype system diagram. Huawei G-PON and XG-PON OLT cards are placed into the same chassis of the TWDM-PON OLT card. The ODN contains two stages of splitters. A 1:8 splitter is followed by a 1:64 splitter to provide a total split ratio of 1:512. The feeder fiber length is 20 km. A snapshot of the prototype system in the test lab is shown in Fig. 7. Note that depending on the legacy ODN deployment, the first splitter can be 1:16 (or 1:32) and the second one can be 1:32 (or 1:16). Also note that the split ratio and reach distance can be adjusted to meet the legacy ODN deployment. For example, 1:512 split with 20 km can be safely converted into 1:128 split with 40 km or 1:64 split with 60 km. A G-PON ONU and an XG-PON ONU are connected to the first stage of splitter (i.e., the 1:8 splitter). This is to evaluate the performance of G-PON, XG-PON, and TWDM-PON coexistence.

B. Operator-Vendor Joint Test Results

The 40 Gb/s TWDM-PON prototype was jointly tested by China Telecom and Huawei in September 2011. Three sets of tests were conducted to evaluate the TWDM-PON performance.

The first test set is for the downstream performance evaluation. Fig. 8 shows the receiver sensitivity for one of the four downstream wavelengths when each signal is modulated using $2^{31} - 1$ PRBS at the rate of 10 Gb/s. When the bit error rate (BER) is 10^{-3} , the measured receiver sensitivity is about -30 dBm. With 10 dBm output power of each downstream wavelength after EDFA, the downstream power budget can reach 40 dB. Downstream signal spectra after transmission are shown in Fig. 9.

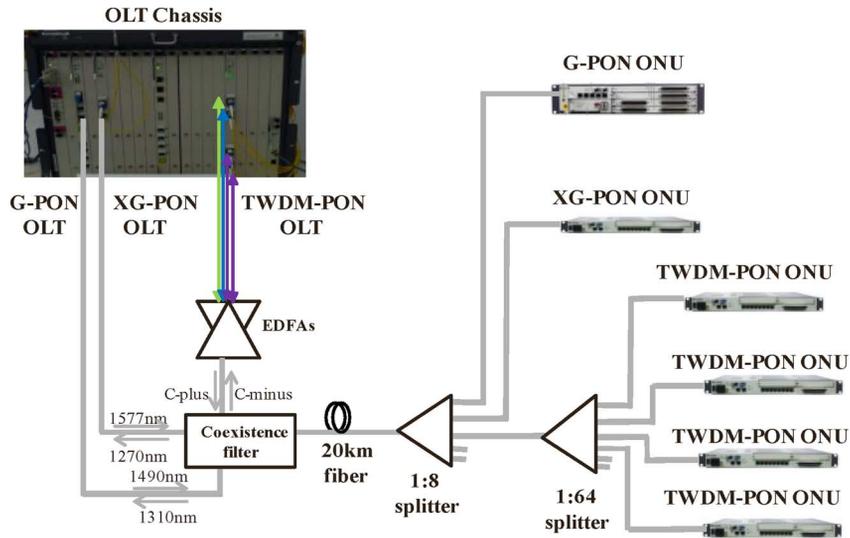


Fig. 6. 40 Gb/s TWDM PON prototype system and its coexistence with G-PON and XG-PON.

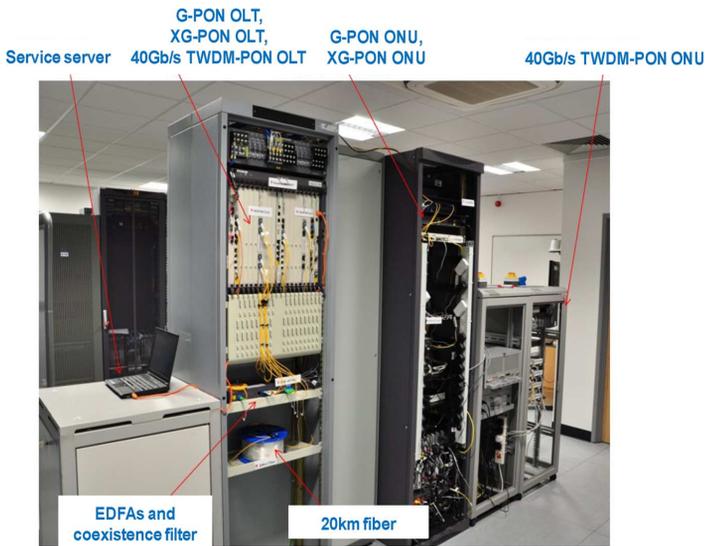


Fig. 7. Prototype system snapshot.

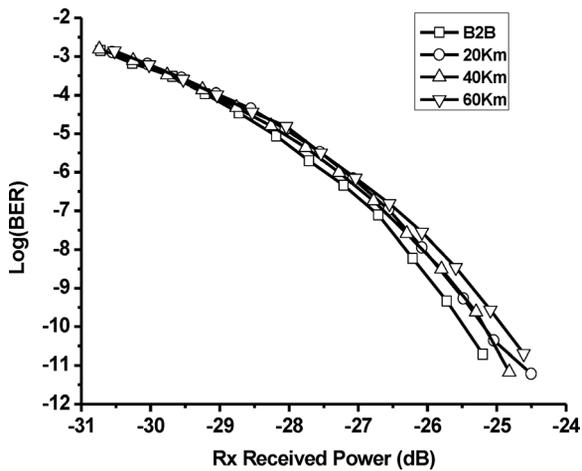


Fig. 8. Rx sensitivity of 1557.36 nm downstream signal.

The second set of tests evaluates the upstream performance. Fig. 10 shows the upstream power budget when tuning two

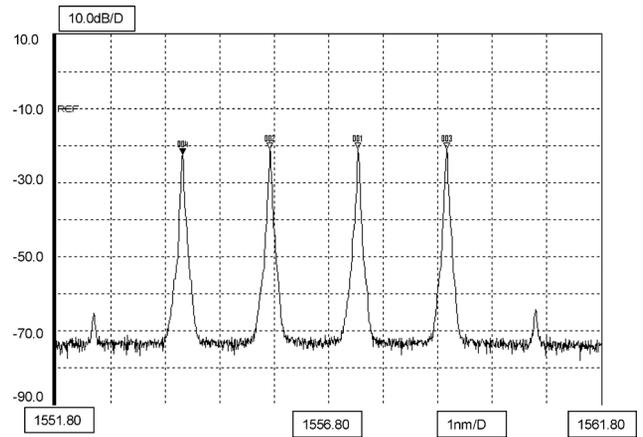


Fig. 9. Downstream signal spectra after 20 km & 1:512.

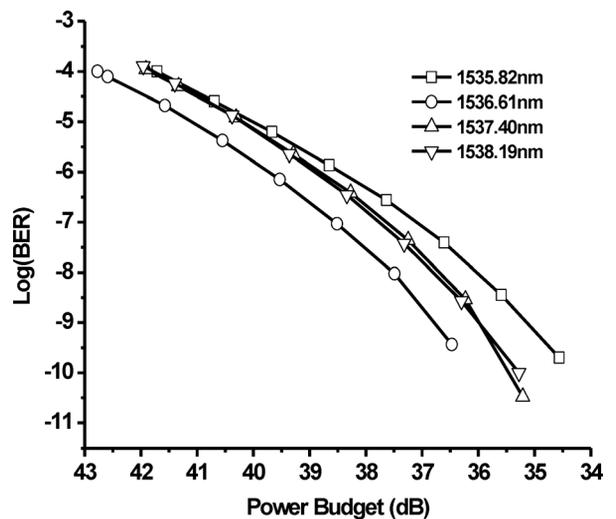


Fig. 10. Upstream power budget with 20 km fiber.

ONU lasers to different wavelengths with 20 km fiber transmission. The initial wavelengths of the two lasers are 1535.82 and 1538.19 nm. They are tuned to other wavelengths by changing the temperature of the TEC and bias currents.

In the upstream power budget tests, the input signal is modulated using $2^{31} - 1$ PRBS at the rate of 2.5 Gb/s. The FEC function was disabled in this group of tests. When the BER is 10^{-7} , the sensitivity is about -36 dBm. With 2 dBm output power of the ONU, the upstream power budget can reach 38 dB, with a deviation of around 1.5 dB. It is expected when the FEC function is enabled the power budget for all of the four upstream wavelengths can be about 40 dB when the BER is 10^{-12} .

The third set of tests is to evaluate the coexistence performance with legacy PONs in the same ODN. The coexistence test setup is shown in Fig. 6. Three streaming IP video users are connected to the G-PON ONU, XG-PON ONU, and one of the four TWDM PON ONUs, respectively. There was no packet loss observed during the lab test for all the downstream and upstream wavelengths in the three PONs.

In addition to the above measurement, voice and data services have been tested in the prototype. There was no interference between services over TWDM-PON and over other two PONs. This shows that 40 Gb/s TWDM-PON successful coexists with both G-PON and XG-PON while reusing the same ODN.

We also changed the ODN configuration into 1:128 split with 40 km and 1:64 split with 60 km to evaluate the prototype system performance. Similar results to the ODN of 1:512 split with 20 km have been achieved in the joint tests.

VI. CONCLUSION

In this paper, we have investigated the basics of TWDM-PON and reviewed its critical features to meet the NG-PON2 requirements. TWDM-PON leverages the research and development effort in PON industry by stacking four XG-PONs to reach an aggregate access rate of 40 Gb/s. As the primary solution to NG-PON2, TWDM-PON balances the network upgrade requirements and the cost model consideration in the access network market. After introducing the baseline architecture, we explore TWDM-PON valuable applications for pay-as-you-grow operation and LLU. Major wavelength plans have been discussed and their loss budgets have been evaluated. Key enabling technologies of tunable ONUs have been investigated. Our research shows there are multiple candidate technologies; if one technology does not perform to expectation, there are always other options to implement the required functions.

For the first time, we demonstrate a full-system TWDM-PON prototype. This prototype integrates commercial components to provide 40 Gb/s in downstream and 10 Gb/s in upstream. Tunable lasers and tunable filters are employed in the colorless ONUs. 40 dB power budget in the downstream and 38 dB power budget in the upstream have been achieved. The prototype system supports a total split ratio of 1:512 and a distance of 20 km. The joint lab test demonstrates the successful coexistence of G-PON, XG-PON, and TWDM-PON without service degradation.

Our future research on TWDM-PON would be steered in three directions. First, we would further explore the TWDM-PON wavelength plan options. In this direction, relevant factors such as fiber loss and chromatic dispersion would be thoroughly investigated, and a single wavelength plan should be selected for the purpose of standardization and mass volume production. The second research direction is

the TWDM-PON loss budget investigation. This includes the study of OLT and ONU transmitter launch power, the OLT and ONU receiver sensitivity, optical path penalty, and signal loss in connectors, coexistence filters, splitters, and WDM Mux and DeMux. The third direction would focus on the low cost tunable ONUs research. Among the enabling technologies of tunable transmitters and tunable receivers, solutions with low cost should be further explored with high priorities.

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He witnessed the early development of the FSAN initiative and the development of the APON standard. In 2000, he moved to Quantum Bridge Communications (now a part of Motorola), where he managed system engineering in their PON division. His work supported the development and standardization of advanced optical access systems based on B-PON and G-PON technologies. In 2006, he became the Director of FTTx in the Advanced Technology Department of Futurewei Technologies, Bridgewater, NJ. He remains heavily involved in standards work, and has been the leading contributor and Editor of the major PON standards in the ITU. In 2008, he became the Chairman of ITU-T Q2/15—the group that creates standards for optical access systems. He and his team work on forward-looking fiber and copper access technologies, including the 802.3av 10G EPON and ITU XG-PON topics. Notably, his team supported the world's first trials of XG-PON and 40G-PON. In 2011, he was named as a Fellow of Huawei, Bridgewater and, in 2012, was promoted to VP of access research.

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