Soft-Stacked PON for Soft C-RAN

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***Abstract*—Cloud radio access networks (C-RANs) feature central pooling baseband processing units (BBUs) and low-cost remote radio headends (RRHs) with fiber-connected fronthauls between them, and they are promising for 4G. Researchers are redesigning the C-RAN with different split approaches to relax the fronthaul capacity for 5G with massive antennas, which is termed soft C-RAN. In this paper, we propose a soft-stacked passive optical network (PON) to support the soft C-RAN as an integrated solution. Two approaches are investigated in this paper. The first one is realized by employing an arrayed waveguide grating router (AWGR) and directly modulated tunable lasers, and it is promising for digital fronthaul and midhaul transmission and switching. The second is realized by employing wavelength-selective switches (WSSs) to allocate one-to-one and many-to-many connections, and it is promising for analog fronthaul transmission and switching. Their performances are analyzed and measured with directly modulated lasers (DMLs) that are either fixed or tunable. A delay interferometer is used for the DMLs' chirp and fiber dispersion management. The result is significant for future soft C-RANs and stacked PON.**

***Index Terms*—Base stations; Optical fiber networks; Radio access networks; Wavelength division multiplexing.**

I. Introduction

With the boom of ubiquitous mobile Internet and various smart devices, the population and bandwidth accessing the Internet are increasing continuously. Today's 4G provides 100 Mbps to 1 Gbps bit rate, which is projected to 10 Gbps in the future 5G era [1–4]. Meanwhile, fiber-to-the-home (FTTH) is being deployed worldwide to provide access capacity of 10 Gbps, which is projected to 40–100 Gbps in next-generation passive optical networks (NG-PONs) [5–7]. It is regarded that 4G consumes more power than FTTH at higher bit rates and longer distances. Therefore, it is significant to design and deploy both together to reduce the cost and power consumption. In an FTTH global conference, one hot topic was entitled "The mobile and fibre convergence—Why FTTH loves mobile and mobile needs FTTH" [8].

The central office is the hub for the mobile and fiber access network. Currently, operators are redesigning their central offices and, for example, demonstrating a joint project called Central Office Re-architected as a Datacenter (CORD). The mission is to bring datacenter economies and cloud agility to service providers for residential, enterprise, and mobile customers using an open reference implementation, which is built from commodity servers, white-box switches, disaggregated access technologies, and open source software [9]. Both radio access networks (RANs) and PONs are being reshaped as soft clouds.

In this paper, we will report a soft-stacked PON for a soft cloud radio access network (C-RAN), which is a solution to integrate the access network between 5G and NG-PON. In Section II, we will review the soft C-RAN and focus on the long and short fronthual and midhaul and their requirements for the fiber transmission. In Section III, we will describe the soft-stacked PON with optical transceiver pooling. In Section IV, we will report a soft-stacked PON using an arrayed waveguide grating router (AWGR) and tunable lasers. In Section V, we will report another soft-stacked PON using wavelength-selective switches (WSSs) and parallel signal detection (PSD). Finally, a summary is given in Section VI.

II. Requirements of Soft C-RAN for Optical Transmission and Transport

The left part of Fig. 1 shows the conventional C-RAN architecture, which is a centralized, collaborative, cloud, clean RAN [1–4]. The digital baseband processing units (BBUs) are pooling in the central office to serve a large group of remote radio heads (RRHs). The link between them is termed a long fronthaul in the range of 10–20 km. The common public radio interface (CPRI) specifies the transmission of digitized radio signals (I/Q) across this interface along with control and management, synchronization, and other auxiliary information [10]. One CPRI link contains one or multiple I/Q flows, each carrying the data of one antenna for one carrier. The total bit rate of the CPRI link is proportional to the number of sectors and antennas per sector, the sample rate and the number of bits per sample, the bandwidth of the radio channel, and the overhead of the framing, including the synchronization and control [1–4]. Current analysis shows that the bit rates of the current 3G and 4G systems are usually no more than 10 Gbps

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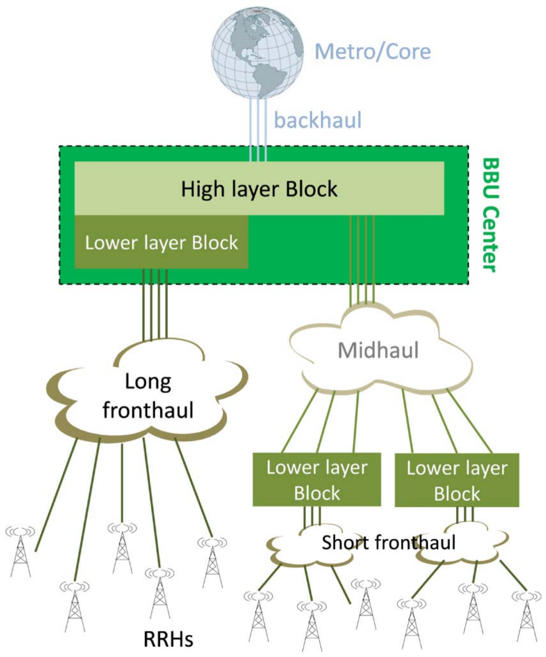

Fig. 1. General layered structure of soft C-RAN. It consists of two parts. The left part is the layered C-RAN, and the right is a re-split soft C-RAN by decoupling the LLB to the RRH side.

and are cheaply transferred with optical transceivers and fibers. C-RAN is good for 4G, but not for 5G.

For the 5G system, however, which uses massive MIMOs with several hundred MHz per channel, the CPRI link will be several hundred Gbps to 1 Tbps if one uses the same method of CPRI. Currently, there is much effort to address this challenge. One way is to reduce the capacity by compressing the sampling data [1–4]. The second way is to increase the CPRI line rate to 24 Gbps [10]. The third way is to transfer the radio signal over a fiber with analog modulation [11,12]. The fourth is to redesign the C-RAN architecture with different split points between the BBUs and RRHs, and therefore, a new kind of interface, called midhaul, is proposed [1–4,13].

The right part of Fig. 1 shows the redesigned architecture by decoupling the lower layered blocks (LLBs), which include fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT), resource mapping, and demapping, to the RRH side. The high layered blocks, which include modulation and demodulation, bit-level processing, high and low media access control (MAC), radio link control protocols, and packet data convergence protocols, stay at the BBU center. China Mobile reported a next-generation fronthaul interface (NGFI) architecture [1,2]. Some other researchers use the new term midhaul for the newly split interface [3], and the traditional fronthaul is shrunken to a small area and hereinafter will be called the short fronthaul in this paper.

The midhaul (and NGFI) has the following advantages: its data rate is traffic dependent and supports statistical multiplexing, the mapping between the BBU and RRH is of one-to-many reconfigurable connections, it is independent of the number of antennas, and it is packetized and transferred on IP networks [1,2].

The fronthaul and midhaul would both be able to establish one-to-many connections between any of the centralized BBUs and any of the RRHs geographically distributed. It requires that the fiber network connecting BBUs and RRHs would be switchable, with a dynamic reconfiguration. When we apply the stacked PON to it, we would make the PON switchable. This is called a soft-stacked PON, and it is described in the next section.

III. Generic Architecture of a Soft-Stacked PON

Some operators use dark fibers and WDMs to connect the fronthaul link, but the connections are fixed even though they are simple. Consider the BBUs and optical line terminal (OLT) that are both placed in the central office: if the BBUs are pooling, it is better to make the optical transceivers of the OLT pool simultaneously. Originally, the soft C-RAN was proposed as copying the tidal effect among the adjacent and close base stations. It is found, however, that a lot of smartphone subscribers driving several tens of miles go on and off the network between their homes and businesses, and the traffic tide happens between the base stations located at their homes and those at their business areas, which are separated by tens of miles [14]. The capacity of the BBUs to pool themselves is not big enough to deal with such a large-scale tide. Fortunately, the coverage of PON is typically 20 or 40 km or larger. It is a good solution to use a switchable and reconfigurable PON to connect multiple pooling BBUs serving the above-mentioned home and business areas. That is, one OLT pool can support multiple BBU pools and thus can enlarge the scale of soft C-RAN.

Figure 2 shows the schematic structure of the soft-stacked PON. In the central office, all the optical

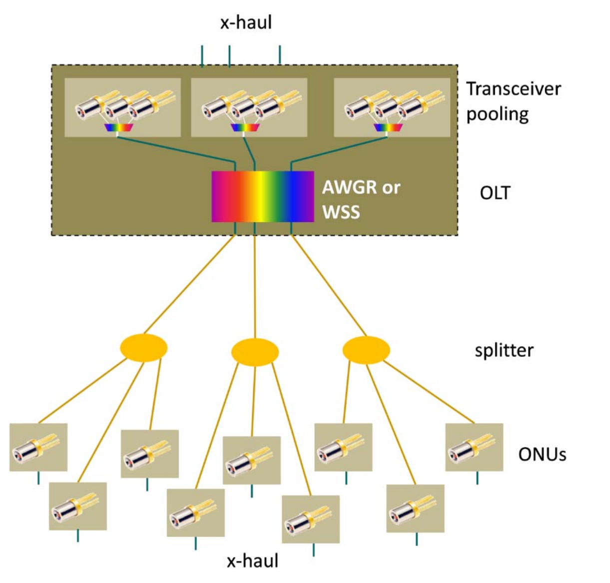

Fig. 2. Schematic structure of a soft-stacked PON. The optical transceivers are pooling with the help of an arrayed AWGR or a WSS.

transceivers are pooling with the help of the tunability of the transceivers and the reconfiguration of either an AWGR or a WSS. One way is to use the AWGR and tunable transmitters on both the OLT and optical network unit (ONU) sides [15–18]. This kind of switching structure has been effective in past optical packet and burst switching scenarios (OPS/OBS) and is scaled out in a multiple-stage network [19]. It is significant that the AWGR is a kind of passive component that is manufactured in the similar process as a splitter and therefore fits the PON structure well. The connection between each pair of transceivers between the OLT and ONUs is realized by tuning the transmitters accordingly [15–19]. The second way is to use a WSS to realize reconfiguration between the pair of fixed transceivers between the OLT and ONU [20]. The benefits of the soft-stacked PON include sharing the transceivers to save the optical components and power consumption. The experimental setup and performance will be reported in Sections IV and V, respectively.

The soft-stacked PON is applicable to the WDM-PON and time- and wavelength-division multiplexed PON (TWDM-PON) as well. The latter was proposed as a stacked NG-PON solution [21] and finally adopted by the ITU-T organization [22]. Later on, a point-to-point (PtP) WDM was introduced to the TWDM-PON architecture to support the CPRI link. It should be noted that the PtP WDM for fronthaul works at the framing defined by the CPRI standard to ensure the strict frequency and time (phase) synchronization [10], and the other wavelengths in TWDM-PON operate in transmission convergence framing with the TDMA and dynamic bandwidth assignment (DBA) mechanism.

In the midhaul approach, it reduces the transmission capacity and loses the time and frequency synchronization greatly, and, as a result, the transport of the midhaul data could be accomplished by Ethernet, so it can be mapped into the present PON's framing with synchronization enhancement [1–4].

The stacked TWDM-PON can provide fronthaul transport with PtP WDM and midhaul with TWDM wavelengths. Moreover, for the soft C-RAN, the network of fronthaul and midhaul support one-to-many connections dynamically. Since the stacked wavelengths can operate in independent framing, it will support the transfer of the fronthaul, midhaul, and backhaul data and simultaneously the household data as well. This means that the soft-stacked PON platform is fit for full service.

IV. Soft-Stacked PON Using Passive AWGR and Directly Modulated Tunable Lasers

Though the switching structure using passive AWGR and tunable lasers was verified in the OPS/OBS scenario, there are some specialties when it is applied to the soft-stacked PON scenario. First, the cyclic AWG with multiple free spectrum ranges (FSRs) was proposed in TWDM-PON to narrow down the tuning range of lasers within one FSR, where the laser is located initially. Second, the motivation of laser tuning in PONs is to align the wavelength, to make traffic balance between all wavelengths, and to power on or off the lasers according to the traffic tide. The tuning time is a microsecond, so either thermally tuned distributed feedback (DFB) or electrically tuned distributed Bragg reflection (DBR) can be used in PONs. Third, PON places a large cost pressure on optical components, and a low-cost direct modulation scheme is preferentially adopted. We will investigate the three specialties in detail in the subsequent subsections.

A. General Architecture With Multiple FSR AWGRs

We propose to use multiple FSR AWGRs and directly modulated tuning lasers to realize a soft-stacked PON, as shown in Fig. 3. The multiple (M) FSR AWGRs are used to accommodate more wavelengths to increase the capacity of the OLT. On the left side of the figure, K of M wavelengths for BBU pooling are (de-)multiplexed with K $1\times M$ waveband AWGs. On the right side, N normal $1\times MN$ AWGs are used for N RRU cells. For each input port of the AWGR, M tunable lasers are parallelly combined by a $1\times M$ waveband AWG. Each tunable laser is able to be routed to any output port of the AWGR according to its tuned wavelength. Though M FSRs are used, the tuning range of each laser only needs to cover one FSR. The equivalent dimension of non-blocking switching is $MN\times N$. It should be noted that the AWGR is located on the OLT side, that is, equipped in the central office without changing the passive property of the remote node.

Furthermore, some tunable lasers can be replaced with fixed ones to save on costs. The fixed wavelengths are used to copy the background traffic, and the tunable ones are used for tidal traffic. The cyclic property and wavelength allocation of the fixed and tunable wavelengths are shown in Fig. 4. This architecture features a graceful upgradation. What is more, when a laser fails to work, one of the idled lasers can be tuned as a backup to enhance the PON resilience [23].

B. Chirp Management of Multiple DML Channels

Directly modulated lasers (DMLs), such as DFB, DBR, etc., have the advantages of small size, low power

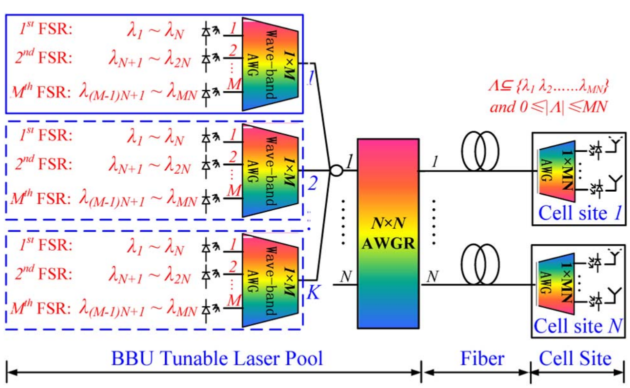

Fig. 3. Proposed soft-stacked PON architecture based on AWGRs operating in several FSRs.

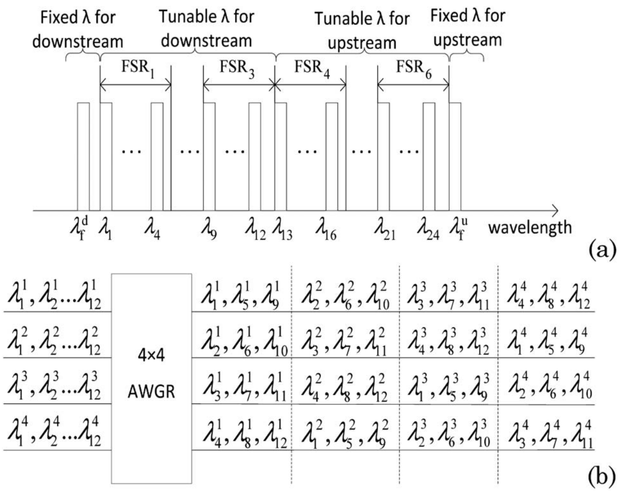

Fig. 4. Cyclic property of a 4 × 4 AWGR and wavelength allocation. (a) Wavelength allocation and (b) wavelength routing regulation.

consumption, high output power, and, most importantly, a low cost. It is very attractive to use a DML in a PON system. However, it has a high chirp effect and expands the signal pulses after a long-distance fiber transmission [24]. There are several methods to address the interaction of the chirp of DML and dispersions of the fiber, including digital signal processing, dispersion compensation of negative dispersion fibers, and optical spectrum shaping.

There are multiple equally spaced wavelengths in a WDM and TWDM-PON system. We propose to use a delay interferometer (DI) to control the chirp of multiple wavelengths in a bi-directional fiber [25–28]. The DI is equipped on the OLT side as a bypass and periodical notch filter to suppress the chirp for all down and upstream wavelengths simultaneously. The DI at the OLT suppresses the residual frequency chirp to achieve a clear eye opening. In this configuration, a single DI in an OLT can manage the dispersion for all down and upstream wavelengths, and no other dispersion compensation is required. It is also applicable to burst-mode data [25].

In an experiment of a 100 km fiber transmission, the FSR of a DI is set at 25 GHz for simultaneous multiple 100 GHz-spaced wavelength operations. In practical applications, the DML's wavelengths need to align with the DI by feedback control. Then, a ±5 GHz frequency drift deteriorates the extinction ratio by less than 1 dB. By suppressing the long wavelength chirp corresponding to the bit 0 level, the extinction ratio is improved and the eye becomes clearly open [28].

C. Increasing the Optical Power Budget

The optical power budget is a key parameter for the PON system, since it implies the ability of the coverage and fan-out of the splitter of a PON. It is the difference value of the laser output power and the sensitivity of the receiver.

TABLE I
Summary of the Power Budget by Using Different Modulations at 10 Gbps

Transmitter	EML	MZM	DML + DI
Launch power (dBm)	14	16	20
Sensitivity (dBm)	−31	−31	−34
Budget (dB)	45	47	54

In general, the output power of an external modulated laser is no larger than 13 dBm. On the contrary, the DML chirp broadens the spectrum to decrease the peak power. Comparing the spectra of the EML, MZM, and DML signals at 10 Gbps, it is observed that the former two have strong carrier components, whereas the DML has a much lower carrier component and allows a higher launch power. We measured the sensitivity for the three kinds of signals after a 100 km transmission. The optical power budgets were calculated and are summarized in Table I. Among them, the DML with the DI allows for a 20 dBm launch power and −34 dBm sensitivity and therefore has the largest budget of 54 dB [25]. That is quite attractive to the PON deployment.

D. 4 × 25 Gbps PON for CPRI 7.0

The IEEE organization is discussing an NG-PON with a 4 × 25 Gbps configuration. At the physical layer, researchers are trying to reuse optical devices of 10 GHz to achieve 25 Gbps and save on costs, and pay more attention to the on–off keying (OOK) modulation, duobinary, and pulse amplitude modulation (PAM-4) [5–7]. We also evaluate and compare them at the same DML and receiver in the experimental setup shown in Fig. 5 [5].

For the OOK modulation, we applied the 25 Gbps signal directly to a 10 GHz DML. Since the spectrum width is narrower than the bit rate requires, the optical spectrum equalization technique is introduced. We use an optical filter to suppress the low-frequency component of the OOK signal. The result is shown in Fig. 6. The filtered signal spectrum becomes more symmetrical at 25 Gbps. Then, the transmission bit error rate (BER) was measured. At the 1×10^{-3} BER level, the sensitivities of the back-to-back, 20, and 40 km transmission were −19.0, −17.7, and −17.5 dBm, respectively. This means the penalty is 1.3 to 1.5 dB.

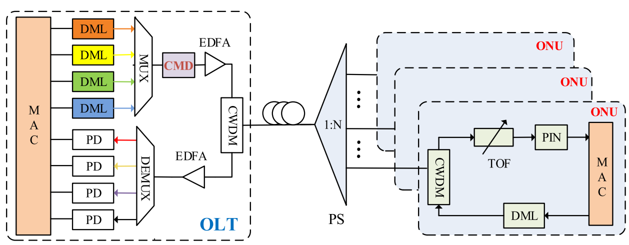

Fig. 5. 4 × 25 Gbps PON setup using DML with OOK, duobinary, and PAM-4 modulations.

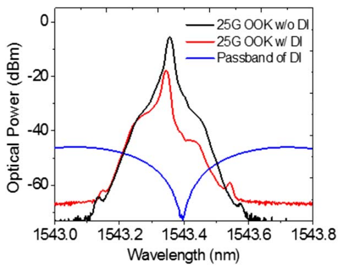

Fig. 6. Optical spectrum of original and optically equalized 25 Gbps OOK signal with DI filtering.

For the duobinary modulation, it has the features of a narrower spectrum and a good ability to achieve fiber dispersion and a non-linear effect. Typically, it is generated with a 1-bit delay and add or low-pass filtering methods. Usually, one applies a precode to the original signal to eliminate the correlation between adjacent bits. Without chirp management, the signal is deteriorated, as shown in the upper array in Fig. 7. So we apply a DI to control the chirp and the signals become clearly open, as shown in the bottom array of Fig. 7. We also measure the BER, and the penalty is derived as about 1 dB after 20 and 40 km.

For the PAM-4 modulation, it is generated with two 12.5 Gbps, then combined together after one of them is attenuated by 3 dB. Considering the imperfect linear modulation of the DML, one can adjust each of the four level amplitudes of the eye diagram to make it uniformly distributed. We also applied a DI to control the DML chirp and measured the BER. At a 1×10^{-3} BER, the sensitivities of the back-to-back, 20, and 40 km transmission were measured as −12.5, −11.3, and −11.0 dBm. The penalty is derived as 1.2 to 1.5 dB.

Table II summarizes the performance of the three modulations comparatively [5]. The OOK allows a higher launch power of 18.5 dBm and a better sensitivity of −17.5 dBm, and it has the largest power budget of 36 dB, whereas the duobinary and PAM-4 have 31 and 26, respectively. Furthermore, the receiving technology of OOK is not as complex as the other two, so it has more potential for the low-cost transmission of the 4×25 Gbps fronthaul, midhaul, and PONs.

TABLE II
Comparison of Duobinary, PAM-4, and OOK Modulations

Modulation	OOK	Duobinary	PAM-4
Bit rate (Gbps)	25	28	25
Distance (km)	40	40	40
Launch power (dBm)	18.5	16	15
Sensitivity (dBm)	−17.5	−15	−11
Budget (dB)	36	31	26
Complexity	Low	Moderate	High

E. Directly Modulated DBR Laser

The DFB is thermally tuned in the ~5 nm range at a magnitude of microseconds. In this subsection, we use a three-section DBR to enlarge the tuning range and shorten the tuning time. Figure 8 shows the measured wavelength tuning performance on the phase and DBR currents, respectively. The wavelength tuning is realized by jointly continuously tuning the phase section and by the step-like tuning of the DBR section as well. The tuning range is ~10 nm when the injected currents of the DBR section and phase section are within 100 and 5 mA, respectively.

As mentioned above, the DML has a strong chirp and leads to signal impairment with fiber dispersion. We investigate the interaction between laser chirp and fiber dispersion, and optimize the DBR bias current to address the chirp problem based on the dispersion-supported transmission theory [30]. Figure 9(a) shows the measured optical power versus the injected gain current. The DBR laser enters stimulated emission and starts lasing when the injected gain current is above the threshold current of ~28 mA. The maximum optical power is larger than 5 mW (7 dBm) and satisfies the requirements of a PON system. Figures 9(b) and 9(c) show the eye diagrams of the 10 Gbps OOK signal with 90 and 130 mA bias, respectively, after 20 km transmission. We also investigate a gain-adaptive scheme over directly modulated DBR lasers for 100 km

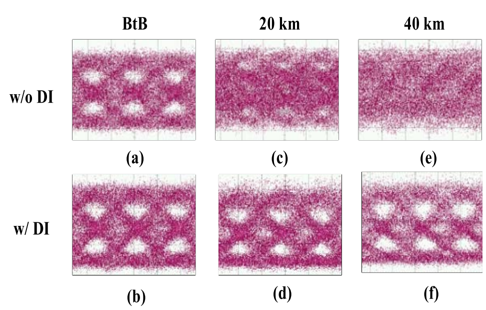

Fig. 7. Eye diagrams of signal with and without DI in back-to-back, 20, and 40 km transmissions.

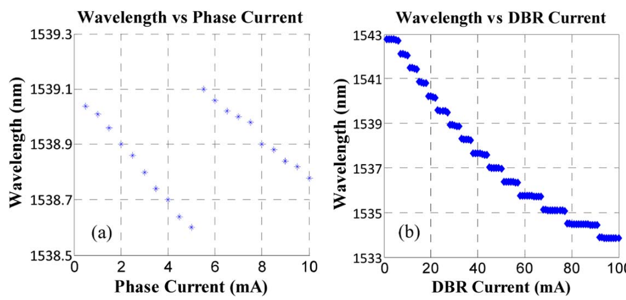

Fig. 8. Measured tuning performance of the DBR laser. (a) Wavelength versus phase current, and (b) wavelength versus DBR current.

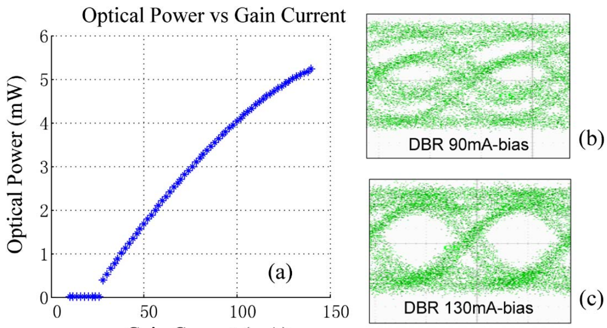

Fig. 9. Relation of optical output power with the gain current, and the eye diagram at different bias currents. (a) Measured optical output power versus gain current curve of the DBR, (b) and (c) 10 Gbps OOK signal with 90 and 130 mA bias after 20 km.

PONs. The transmission impairment produced by the chirp and dispersion is alleviated when the bias current in the gain sections of directly modulated DBR lasers is optimized according to the fiber transmission distance. The experimental results demonstrate that the nearly uniform optical power budgets of 34.9, 34.9, 34.2, 32.7, 33.0, 34.5, 35.3, 35.6, 35.8, 36.4, 36.8, and 35.9 dB are achieved at fiber distances of 0, 5, 10, 15, 20, 25, 30, 35, 40, 60, 80, and 100 km. For the PON system, the value of the fiber distance can be obtained from ranging protocols, which are used to adjust the optimum bias current [29].

V. Soft Stacking Using WSS and Parallel Signal Detection

The transmission of an analog signal over a fiber is another attractive approach. The antenna carriers (AXCs) are converted to different intermediate frequencies (IFs), which are modulated on different wavelengths. In the downstream, the IFs are optically multicast to and selected by each cell site, then are converted to radio frequency (RF) to emit. In the upstream, the reverse operation is applied. But in order to share receivers, a WSS is employed in place of optical filters or demultiplexers, and parallel signal detection (PSD) is used to share optical components [20]. This is reported on in the following subsection.

A. Architecture With WSS and PSD

Figure 10 shows a WSS-based PON architecture for the soft C-RAN. In the downlink direction, all transmitters aggregated to the WSS are delivered to some subsets to their corresponding cells. Conversely, in the uplink direction, RFs are converted down to different IFs, then are carried by the uplink wavelengths. All the uplink wavelengths are coupled into a WSS at the central office and are allocated to each receiver. During the low traffic period, the WSS is set to select several wavelengths with stagger IF allocation into one receiver. The other receivers with no wavelength injected are powered off. It should be noted

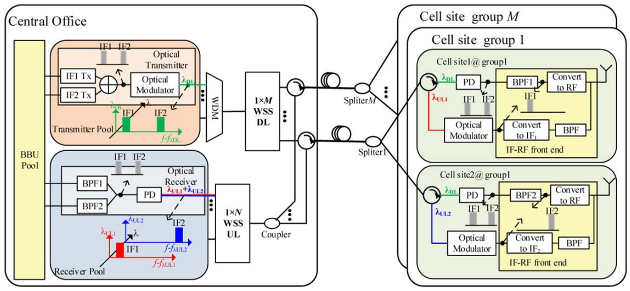

Fig. 10. Architecture of WSS-based soft-stacked PON with optical resource sharing for soft C-RAN. BBU, baseband unit; BPF, bandpass filter; WSS, wavelength-selective switch; RF, radio frequency; IF, intermediate frequency.

that a receiver can receive one or multiple wavelengths if the IFs carried by these wavelengths are allocated separately; this is called the parallel signal detection method [31].

This architecture has the following merits. First, it uses fixed lasers instead of tunable ones. Second, intensity modulation/direct detection (IM-DD) is adopted instead of coherent detection. Third, no frequency offset occurs in the electrical domain after detection, so there is no need to set a guard band to avoid spectrum collision.

B. Performance

We did experiments to verify the feasibility of parallel signal detection. Following a configuration of 4^{+}G, which is assumed to have 3 sectors, 5 aggregated 20 MHz carriers, and 8×8 MIMOs for each cell [31], the traffic of a cell takes 12 IFs to transmit a 100 MHz carrier-aggregated orthogonal frequency division multiplexing (OFDM) signal. The 12 IFs are allocated at $i \times 150$ MHz, where $i = 1, 2, \ldots, 12$, with 50 MHz guard bands between two adjacent IFs. For one experimental example, 12 IFs are produced from 4 cells at different wavelengths, each of which has 3 IFs at lower

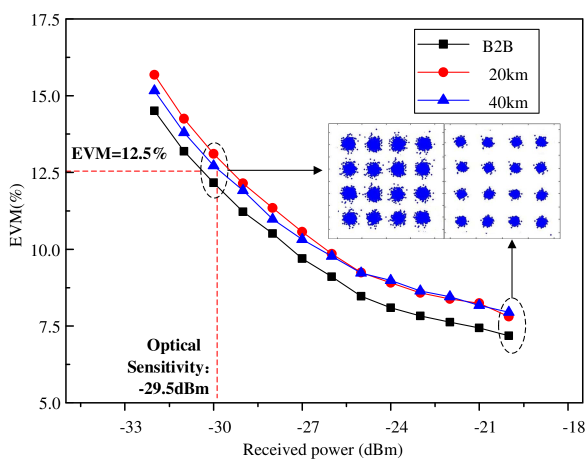

Fig. 11. Mean EVM of uplink received OFDM signal. Constellations at EVM = 7.5% and 12.5% are inserted.

traffic times, and are received by a 12.5 GHz avalanche photodiode (APD). The detected signal is captured by a 10 GS/s real-time digital storage oscilloscope (DSO) for digitization and offline processing, including manual timing synchronization, appropriate filtering, down conversion, and OFDM demodulation. The measured error vector magnitudes (EVMs) are illustrated in Fig. 11. Since the received powers of each wavelength are equal, the performances of each IF are almost the same. Only the mean EVMs of 12 channels are shown: 12.5% (EVM antenna limit for 16-QAM signal specified in 3 GPP standard [15]) is achieved at a −29.5 dBm received power per wavelength. Since the output power of the MZM is 1 dBm at the bias voltage and the insertion loss of the WSS is 4.5 dB, about a 26 dB power budget is achieved. The dispersion penalty is considered to be negligible because the total bandwidth is only less than 2 GHz.

VI. Conclusion

The convergence of soft C-RAN and soft-stacked PON has attracted much attention. Researchers are trying to relax the fiber capacity by redesigning the soft C-RAN, soft-stacked PON, and even the central office to bring datacenter economies and cloud agility to the access network. In this paper, we reported two soft-stacked PON approaches by employing low-cost DMLs and DI for chirp and dispersion management to achieve 25 Gbps, a passive AWGR to realize switchable connections for digital fronthaul and midhaul, and WSS to realize many-to-many connections for analog IFs. The performance is measured, and their feasibility is confirmed.

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