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REVIEW

Review of physical layer networking for optical-wireless integration

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Abstract. We present a review of physical networking options and enabling system technologies for efficient unification of optical and wireless access backhaul infrastructure. Different physical layer integration architectures are reviewed in conjunction with the possible wireless signal transport schemes. We also review some of our research work as one possible physical layer integration technique using RF-overlay passive optical network incorporating an optical tandem single sideband (OTSSB) modulation scheme for simultaneous transport of wired and wireless signals. [DOI: 10.1117/1.OE.55.3.031113]

Keywords: optical-wireless integration; radio-over-fiber; optical tandem single sideband.

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1 Introduction

Wireless networks with ubiquitous coverage provide us with access to crucial data, social networking, entertainment, cloud services, and telecom services wherever and whenever with the convenience of not being physically connected or constrained. The globally connected community's ever-increasing demand for this crucial service has fueled the alarming growth rate of wireless data and a booming number of subscribers empowered with smart mobile devices with unprecedented capabilities. The barriers and stiff competition between cellular mobile network and wireless local area network (WLAN) no longer exist with the synergy of both of these technologies with techniques such as Wi-Fi offloading[1,2] to offload mobile data traffic to WLANs to uniformly share the wireless traffic load. Despite the efforts to increase the shared capacity and performance of the wireless networks, the explosive growth in the volume of data puts significant pressure on the current wireless infrastructure especially on the backhaul. There are many backhauling options to support the increasing traffic in the wireless networks including fiber, millimeter-wave wireless, cable, and free space. To minimize the cost associated with wireless backhauling, it is imperative to develop backhaul technology that leverages on existing infrastructure. With the high presence and increased penetration of fiber infrastructure in today's global telecommunication network, optical fiber with its inherent properties of large bandwidth, immunity to electromagnetic interference, and low loss is emerging as an ideal backhaul candidate despite the high initial cost. As many features of the next-generation fiber-based and wireless access solutions are complementary to each other, the merging of these two technologies is inevitable in the future. This hybrid technology is able to unify the telecommunication backhaul infrastructure by using a common optical fiber backhaul network to support both wired and wireless services. The integrated architecture is able to take advantage of the optical fiber bandwidth together with the mobility features of wireless communications.

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Optical-wireless integration has been actively researched over the last two decades and has gained significant momentum over recent years. Much research has been targeted toward wireless distribution over passive optical networks (PONs) and various wireless standards including 3G,[3,4] LTE-A,[5] WiFi,[6–8] WiMAX,[7–15] and UWB[16–19] have been demonstrated overlaying on PON infrastructure. In addition to these wireless standards, a significant amount of work has also been targeted toward millimeter-wave (mm-wave) wireless signals' distribution.[7,17,20–23] Although the integration of optical and wireless technologies is able to simplify the backhaul infrastructure for the wireless networks, the implementation of this hybrid infrastructure is not straightforward. There are a number of issues regarding wireless signal transport, network layout, integration with existing infrastructure, and energy efficiency that have to be addressed. In this paper, we focus on physical layer integration, in particular looking at various network layout architectures and subsystem technologies that accommodate for wired and wireless applications in these hybrid networks. The paper is organized as follows. Section 2 presents the different transport schemes with respect to their roles and the base station (BS) configurations in the hybrid fiber-wireless links and Sec. 3 describes the various network layouts for the hybrid fiber-wireless network that caters to both wired and wireless services. Section 4 focuses on the work we have carried out in optical-wireless integration using optical tandem single sideband (OTSSB) modulation format to seamlessly transport both wired and wireless signals. Section 5 concludes the paper.

2 Wireless Signal Transport

The most important criterion for a successful deployment of the hybrid fiber-wireless network is the seamless transport of the wireless signals over the optical platform. Technically, the wireless signals are not compatible with the optical signals which predominantly carry a digital data stream. In general, the transport schemes can be collectively grouped into five schemes, namely RF-over-fiber (RFoF), IF-over-fiber (IFoF), baseband-over-fiber (BBoF), digitized RF-over-fiber (DRFoF), and digitized IF-over-fiber (DIFoF). Figure 1

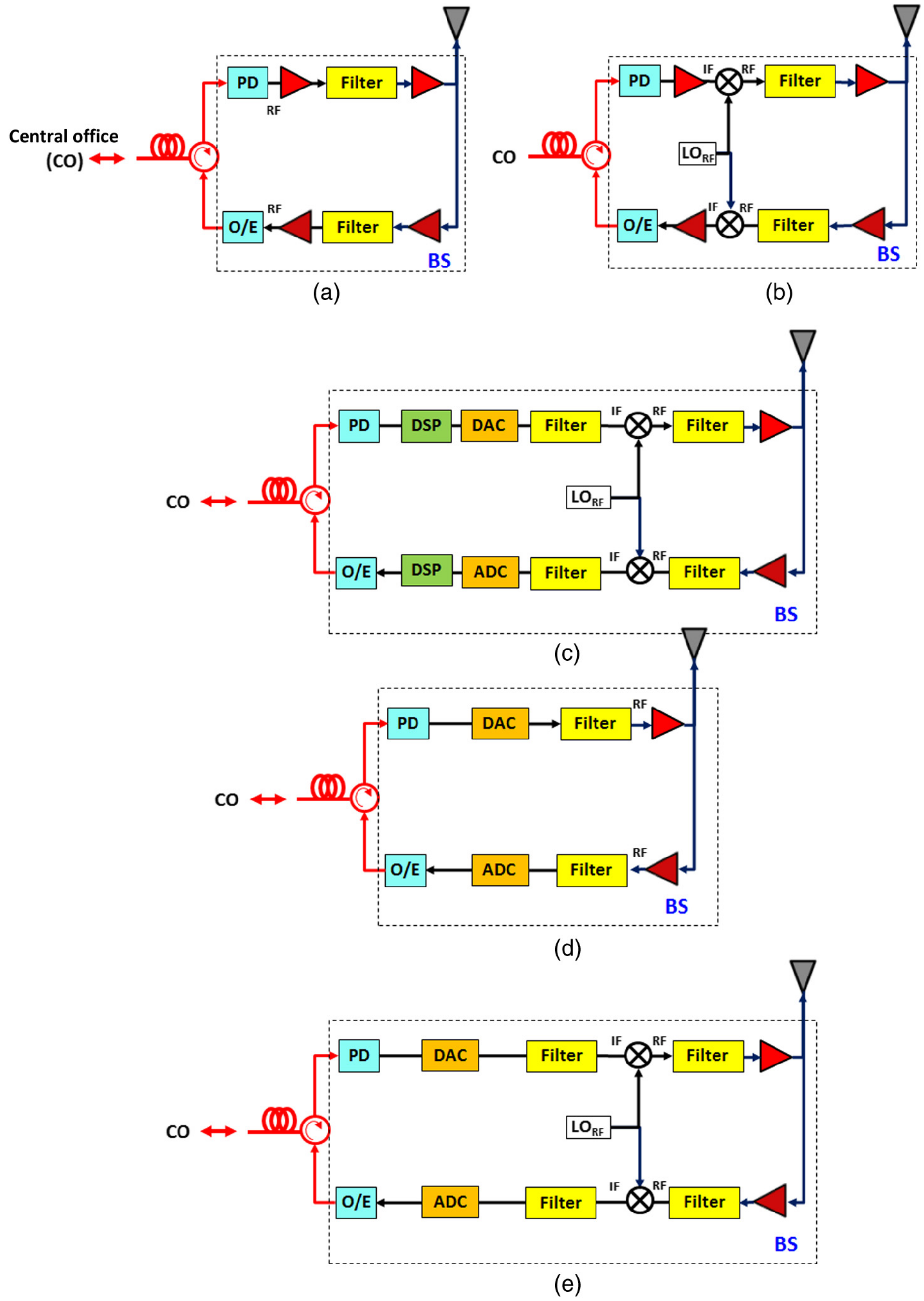

Fig. 1 Base station (BS) configurations for: (a) RF-over-fiber (RFoF) transport, (b) IF-over-fiber (IFoF) transport, (c) baseband-over-fiber (BBoF), (d) digitized RF-over-fiber (DRFoF) transport, and (e) digitized IF-over-fiber (DIFoF) transport.

shows the different antenna BS designs for the five wireless signals' transport schemes.

2.1 *RF-over-Fiber Transport Scheme*

The simplest technique to distribute the wireless signals over the optical platform is to transport the wireless signals at the wireless carrier frequency over the optical link as illustrated in Fig. 1(a). In this scenario, the wireless signals are transported in an analog format over the optical platform. Within the central office (CO), the wireless signals can either be directly or externally modulated onto an optical carrier resulting in an optical double sideband where the two sidebands are located at the wireless carrier frequency away from the optical carrier. At the remote antenna BS, the wireless signals are recovered via direct detection using a photodetector. This scheme does not require frequency translation stages in the BS. The RFoF transport scheme has the advantage of realizing a simple BS design with the additional benefits of centralized control and multiwireless band support. Despite the simple and elegant design, this scheme suffers from the impact of fiber chromatic dispersion that limits the fiber transmission distance and degrades the received RF power.[24,25] Another drawback is the requirement for optical devices with speeds matching the wireless carrier frequency, which becomes more stringent for wireless signals beyond submillimeter-wave bands.

2.2 *IF-over-Fiber Transport Scheme*

In contrast to RFoF transport, the wireless signals can be transported at a lower intermediate frequency (IF) over the optical link. This configuration is called the IF-over-fiber transport scheme and is shown in Fig. 1(b). IFoF overcomes the limitations of RFoF where relatively low-speed optoelectronic devices can be used and the optical distribution of IF signals has much reduced fiber chromatic dispersion effects. However, the complexity of the antenna BS design increases with IF signal transport as it now requires a stable local oscillator and linear mixers to perform frequency translation processes. The complexity increases with wireless carrier frequency and this may impede future network upgradability.

2.3 *Baseband-over-Fiber*

Figure 1(c) shows the architecture for BBoF transport, where the wireless data are transported as baseband data optically and the wireless signal is processed entirely in the antenna BS. This transport scheme is the most compatible with existing optical networks where the raw wireless data are transmitted in a predominately digital environment. Although the transport scheme simplifies the optical transport, the antenna BS for BBoF has to house additional hardware to electronically process the wireless signals. This complicates the BS architecture and also decreases the link transparency.

2.4 *Digitized RF-over-Fiber*

In recent years, a new transport scheme based on the digitization of the wireless signals has been proposed and demonstrated.[26,27] As opposed to BBoF transport where the wireless signal is transported at the information level and all the signal processing is performed in the antenna BS, digitized wireless signal transport essentially digitized the wireless signals before the optical transport. This digitized scheme can be further classified into DRFoF transport and digitized IF-over-fiber (DIFoF) transport. Figure 1(d) illustrates the BS design for the DRFoF transport scheme. The wireless signal is sampled and digitized at the wireless carrier frequency. This will generate a digital data stream in a serial format that can directly modulate an optical source. Similar to BBoF, this methodology also enables the use of a digital photonic link to transport the wireless signals over the optical platform overcoming the inherent issues related to analog photonic links. This scheme enjoys the benefits of digital photonic links with a dynamic range independent of the fiber transmission distance until the signal level goes beyond the link sensitivity. The major difference between digitized transport and BBoF transport is that most of the complex signal processing functionality is carried out in the CO while only a minimal set of frontend components consisting of the analog-to-digital (ADC) and digital-to-analog (DAC) converters are located in the antenna BS. The link is able to maintain its transparency as the BS does not need the full processing power as per the BS for BBoF transport scheme. For the DRFoF transport scheme, since the digitization was carried out on the wireless signal at the desired carrier frequency, no additional frequency translation stages will be needed in the antenna BS. This also means that the analog bandwidth of the ADC must be larger than the wireless carrier frequency and with sufficient sampling rate and resolution. This requirement becomes more stringent for wireless signals beyond the microwave bands.

2.5 *Digitized IF-over-Fiber*

To overcome this limitation, DIFoF is proposed whereby the wireless signal is first downconverted to an IF to cater for the limitations of current ADC technology. The BS architecture of this transport scheme is shown in Fig. 1(e). It is important to note that current open base station architecture initiative (OBSAI)[28] and common public radio interface (CPRI)[29] are based on DIFoF transport scheme. OBSAI and CPRI are initiatives to create an open market for cellular networks by providing specifications for interface of wireless BSs. In this scheme, there is an analog frequency translation stage located before the ADC in the uplink direction and after the DAC in the downlink direction. Figure 2 shows the BS design for DIFoF incorporating OBSAI/CPRI interface.

2.6 *Digitized Transport Using Bandpass Sampling*

It is important to note that the key enabler for the digitized transport schemes (DRFoF and DIFoF) is the ADC/DAC technology. Direct sampling requires a sampling frequency of at least twice the frequency of the largest wireless signal component. This requirement becomes extremely stringent for wireless signals beyond the microwave frequency band. To relax the requirements on the ADC, a bandpass sampling

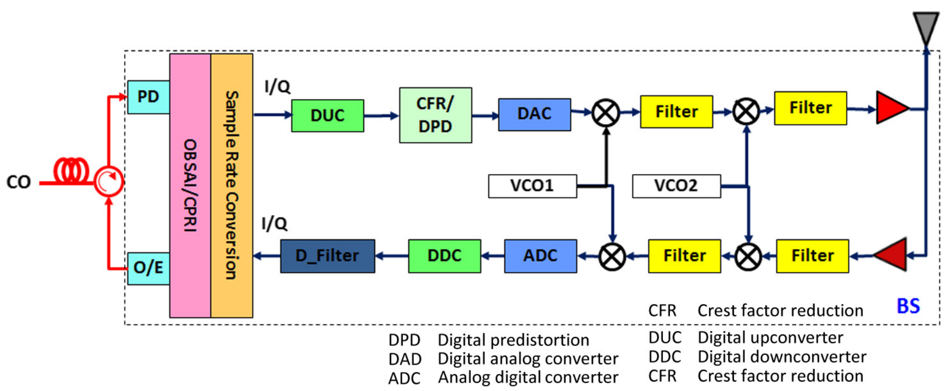

Fig. 2 Base station design incorporating OBSAI/CPRI interface for digitized IF-over-fiber (DIFoF) transport.

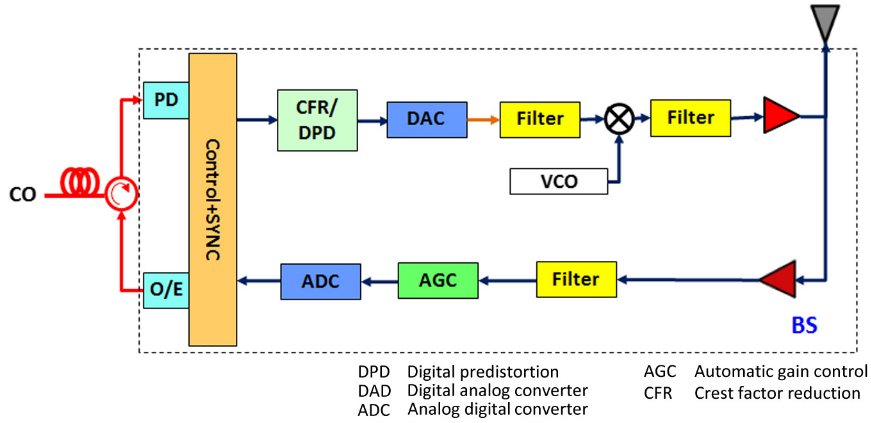

Fig. 3 Base station design for digitized transport using bandpass sampling.

technique[30] is used and it is compatible with wireless applications since for most wireless services, the required information bandwidth is only a small fraction of the wireless carrier frequency. Bandpass sampling under samples the wireless signal using a much lower sampling frequency that is comparable to the wireless message bandwidth instead of the wireless carrier frequency. In this scheme, an infinite number of image replicas of the wireless signal will be generated upon sampling.[26,27] Although the sampling frequency is much lower compared to direct sampling, the sampling frequency has to be carefully chosen to minimize noise aliasing from adjacent images. The wireless signal can be recovered using an appropriate bandpass filter from the infinite set of image replicas. Hence, using bandpass sampling, we are able to perform frequency translation without using LO and mixers. Figure 3 shows the BS design for digitized transport incorporating bandpass sampling. The obvious benefit of using bandpass sampling is reflected in the uplink direction where no frequency translation stage is needed which reduces the number of hardware components and further simplifies the BS design.

3 Integration of Wireless Network with Passive Optical Network

In the previous section, we discussed the different wireless signal distribution schemes and the corresponding BS architecture. There is no ultimate transport scheme and the type of transport scheme required for a hybrid fiber-wireless network depends on a number of factors including and not limited to overall network configuration, topology, layout, energy efficiency, and network performance. In this section, we review the various network layout options for merging the wireless applications with existing PON architecture.

Figure 4 shows a possible schematic of a hybrid optical-wireless integrated network incorporating PON architecture. It consists of an optical headend or CO that acts as the gateway to the optical metropolitan backbone while serving a large number of optical network units (ONUs) for wired applications and antenna BSs for wireless applications. In this integrated network, the wired data and wireless signals from the trunk network are combined in the CO before distribution to the respective wired and wireless customers via a remote node (RN) or a hybrid wired/wireless BS (ONU/BS).

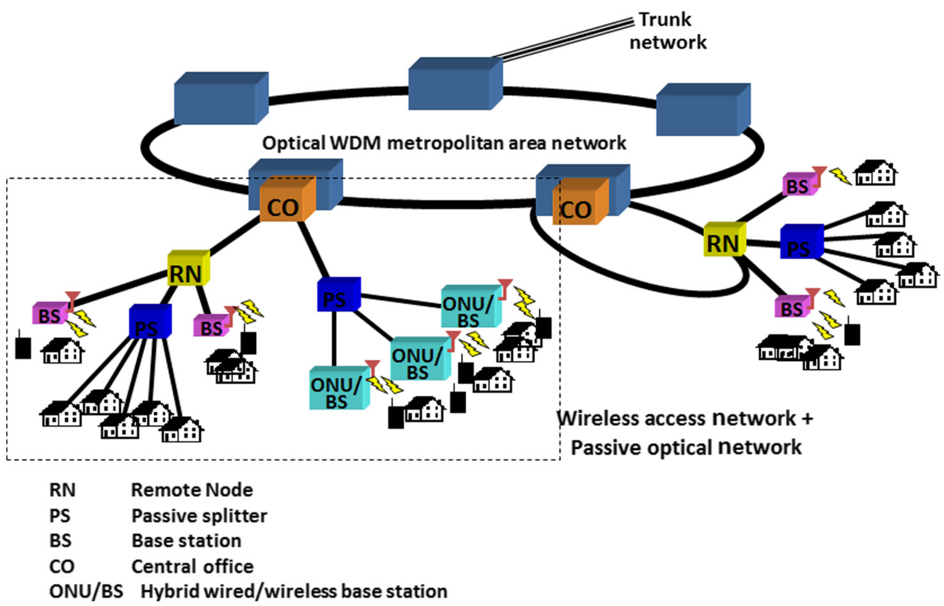

Fig. 4 Schematic of an integrated wireless access and passive optical network (PON).

In the following subsections, we will review different wireless-PON integrated architectures and the enabling subsystem technologies to efficiently transport both wired and wireless signals while maintaining maximum signal transparency.

3.1 *Point-to-Point Direct Fiber Architecture*

Figure 5 shows a network layout option based on point-to-point architecture. In this architecture, the configuration is relatively straightforward where the wireless system uses spare fibers in the existing access infrastructure to distribute the wireless signals. As shown in Fig. 5, an optical line terminal (OLT) of a PON may serve a few clusters of ONUs and at the same time have its spare feeder fiber leased out to serve an antenna BS of a wireless network. Such a configuration enables a completely independent wireless network operation and is totally transparent to the wired services. As the wireless services are in an independent fiber infrastructure, the wireless signals in this architecture can be transported in any of the transport schemes discussed in Sec. 2. In addition, since each BS has a dedicated fiber link, a better link budget can be achieved that can be translated to a longer transmission distance if required. Despite the simplicity of this architecture with dedicated fiber links for the wireless system, this merged architecture requires a significant amount of spare trunk fiber to provide dedicated connections to every antenna BS which may not be attractive and will place a significant burden on the available resources. Another important consideration is the uplink transmission (how wireless signals are transported back to the CO or OLT). For the point-to-point architecture, since a dedicated link is available between each BS and OLT, the uplink wireless signals from multiple users can either be frequency-division-multiplexed and transported using RFoF or IFoF back to the OLT or time-division-multiplexed and transported in a digitized format back to the OLT.

3.2 *Baseband Passive Optical Network*

Another network layout option for merging a wireless network with PON is based on the sharing of PON bandwidth as illustrated in Fig. 6. This architecture is called baseband PON. In this configuration, the PON infrastructure has to simultaneously support the wired and wireless traffic. The wireless signals are transported at the baseband and are encapsulated into frames that are compatible with the PON

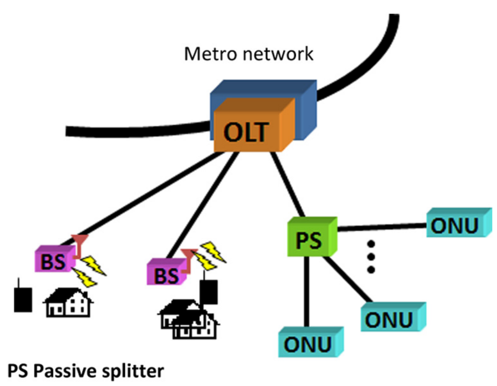

Fig. 5 Point-to-point direct fiber configuration for hybrid fiber-wireless integration.

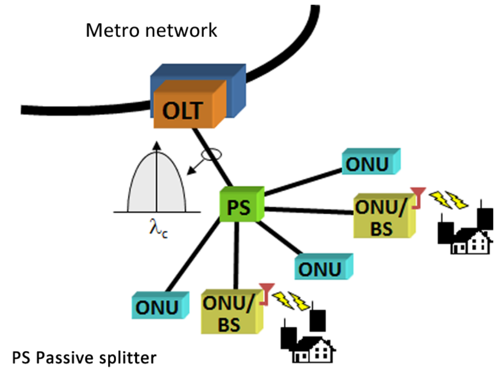

Fig. 6 Baseband-PON architecture for hybrid fiber-wireless integration.

wired network. The wireless signal frames will be combined with the wired line traffic. Essentially, the distribution of the wireless signal over this architecture shares the transmission bandwidth of the wired services in the PON. At the BS, the frames containing the wireless signals will be extracted from the PON frames. The wireless signals will be further processed to ensure that the wireless signals at the desired wireless carrier frequency are generated before they are sent to the customer units. In the uplink direction, the received wireless signals have to be downconverted and encapsulated into PON frames before optical transmission. In this configuration, the wireless signals can be transported using BBoF and it is also possible to include DRFoF and DIFoF transport schemes. Here, the wireless signals are digitized, coded, and then encapsulated into PON frames before being combined with the wired traffic. For the uplink direction, the uplink wireless signals are also digitized, coded, and encapsulated into PON frames before joining the uplink wired PON signals in a controlled manner as governed by the medium access control protocol to avoid collision. In both down and uplink scenarios, there is a danger of overutilizing the available bandwidth of the PON since the wireless signals are sharing the PON bandwidth.

3.3 *RF Overlay Passive Optical Network*

To overcome the bandwidth-sharing limitation of baseband PON architecture, the wireless network can be overlaid on the PON infrastructure. Such a layout is named RF overlay PON or RF-PON as shown in Fig. 7. In this configuration, the wireless signal is subcarrier multiplexed onto the PON

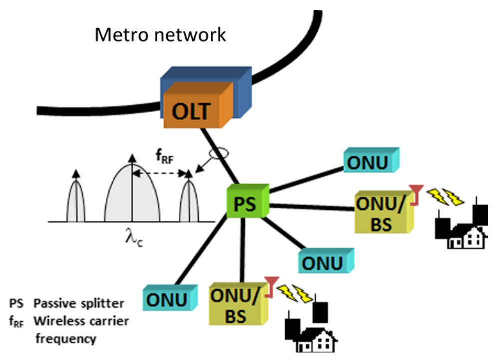

Fig. 7 RF-overlay-PON architecture for hybrid fiber-wireless integration.

signal before optical distribution. It can be seen in Fig. 7 that the resulting optical spectrum of the composite signal showing the PON data is carried by the optical carrier while the wireless signal at a carrier frequency of f_{RF} is subcarrier multiplexed onto the optical carrier. A demultiplexing interface within the hybrid ONU/BS is required to separate the wireless and wired signals. Therefore, standard ONUs can be used in addition to a multiplexing/demultiplexing subsystem interface for merging/separating the wireless signals before optical transport. In this configuration, the wireless signals are transported in an analog format where we can use either an RFoF or IFoF transport scheme as long as the f_{RF} or f_{IF} is larger than the data rate of the PON signals in order to minimize crosstalk between the wired and wireless signals. For the uplink transmission, the uplink wireless signals from multiple users can be frequency-division multiplexed electrically and converted into optical signals before combining with the PON signals and being transported back to the OLT. In this case, the transparency between the wired and wireless signals is still maintained.

Many different variations of the discussed subcarrier multiplexed RF PON scheme have been proposed and demonstrated with most focusing on maximizing signal isolation and transparency. These include optical carrier suppression using optical interleaver,[31] optical transport using OTSSB scheme,[15,32–34] direct modulation using reflective semiconductor optical amplifier,[35] and use of different bands in orthogonal frequency division multiplexing technology for carrying wireless and wired signals.[13] The performance of this scheme may be degraded from the impact of crosstalk between the wired and wireless signals.

3.4 *Coarse Wavelength-Division-Multiplexing-Passive Optical Network*

Despite the simplicity offered by merging a wireless network with a PON architecture, the wireless signals will either have to share the PON transmission bandwidth or have to be transported in efficient schemes to minimize crosstalk. Therefore, to guarantee more dedicated bandwidth for wireless signals' transmission without the use or deployment of additional spare fiber (point-to-point direct fiber architecture), wavelength-division-multiplexing (WDM) technology can be incorporated within the PON architecture. Figure 8 shows the network layout incorporating a coarse-WDM (CWDM) networking scheme. The channel spacing within the CWDM standard is defined to be 20 nm in the wavelength range of 1270 to 1610 nm. Using CWDM networking technology in an optical-wireless integrated architecture enables the wireless signals to be carried by a separate CWDM channel compared to that for PON traffic.[36] This enhances signal isolation and also enables more dedicated bandwidth allocation for wireless application. In this architecture, the wireless and PON signals are multiplexed in the headend or OLT before they are distributed via the feeder fiber to an RN that consists of a CWDM multiplexer/demultiplexer (MUX/DEMUX). The CWDM MUX/DEMUX separates the different CWDM wavelength channels and distributes them to the respective PONs serving optical subscribers and wireless BSs. Here, the wireless signals are virtually on an independent network that is isolated from the wired PON traffic by the CWDM wavelength separation. Hence, the wireless signals can be transported using essentially any of the transport schemes discussed in Sec. 2. Similarly in the uplink direction, the wireless signals and PON traffic use different CWDM channels for distribution over the optical network. They are multiplexed together at the RN before being transported back to the OLT.

3.5 *DWDM-Passive Optical Network*

With the ever increasing demand for broadband services in the access environment, one of the possible evolutions of the fiber access infrastructure is toward dense-WDM-PON (DWDM-PON). In a DWDM environment, the WDM channels are more densely packed which also means that there is more flexibility to merge different wireless applications onto the same PON platform. This layout is illustrated in Fig. 9, where the fiber-wireless integrated architecture incorporating a DWDM-PON that supports PON and multiple wireless standards is shown. In this architecture, different DWDM wavelengths are used to carry microwave wireless signals (λ_{mw}), millimeter-wave-based wireless signals (λ_{mmw}), and PON signals (λ_{PON}). These DWDM channels are multiplexed at the OLT and distributed via the feeder fiber to the RN which consists of a DWDM MUX/DEMUX that will demultiplex the signals before serving the appropriate networks. Here, the different wireless signals are transparent to each other and they are virtually on independent networks. Therefore, these wireless signals can be distributed using any of the previously discussed transport schemes (Sec. 2) as a result of this transparency. Similarly, for the uplink transmission, each of the uplink wireless signal bands is allocated with different DWDM wavelengths for uplink transmission to maximize the isolation between the wireless bands and also between the down and uplinks.

A number of simultaneous multiband wireless signals' transmission have been demonstrated on the same optical platform.[32,36–40] To ensure seamless integration, the enabling

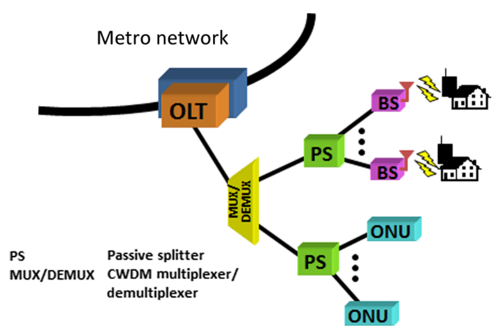

Fig. 8 Hybrid fiber-wireless integration based on CWDM-PON.

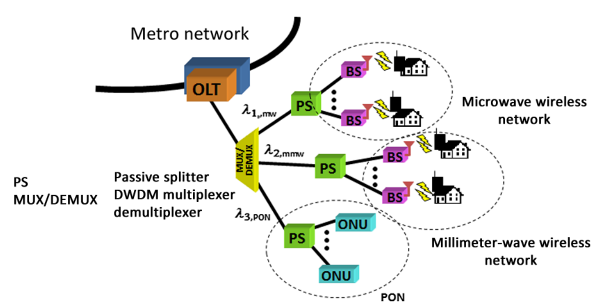

Fig. 9 Hybrid fiber-wireless integration based on DWDM-PON.

technology is the multiplexer and demultiplexer that are used to combine and separate the various signals. There have been many different techniques introduced including using an optical interleaver[36,37] and arrayed waveguide grating[38] to maximize the channels' isolation while seamlessly adding and dropping these multiband wireless channels and PON signals. In addition, it is also essential that these integration schemes introduce minimum changes and disruption to existing infrastructure setup for effective integration. With the emergence of time and wavelength division multiplexed passive optical network (TWDM-PON) as the NG-PON2 standard,[39] there have been a few demonstrations of hybrid optical-wireless access incorporating TWDM-PON.[41–44]

4 Experimental Demonstration: RF-PON

4.1 *RF-Passive Optical Network Incorporating Optical Tandem Single Sideband Modulation*

As discussed in Sec. 3, there are many challenges in implementing a hybrid fiber-wireless integrated network including the development of simple and low-cost interfaces to seamlessly combine and separate the wired and wireless signals and development of efficient merging schemes that minimize crosstalk and have good transparency.

We have previously developed an RF-PON using an OTSSB modulation format for simultaneous transport of wired and wireless signals.[33] The enabling technology is the passive optical interfaces within the hybrid RF-PON for seamless multiplexing and demultiplexing of the wired and wireless signals in the OTSSB format. The proposed scheme is based on an optical single sideband with a carrier (OSSB + C) modulation technique[25] that is commonly used in a fiber-wireless network to overcome fiber chromatic dispersion. Figure 10 shows the OTSSB scheme for simultaneous transmission of wired and wireless signals.[15] In this configuration, the PON baseband signal is upconverted to an RF frequency (f_{BB}) before driving the one arm of the 90 deg hybrid coupler. The wireless signal at the carrier frequency of f_{RF} drives the other arm of the hybrid coupler as indicated in Fig. 10. The combined output signals from the hybrid coupler then drive the two arms of the dual electrode Mach–Zehnder modulator (DEMZM). The DEMZM is biased at quadrature and the output of the modulator consists of wired and wireless signals in an OSSB + C configuration located at either side of the optical carrier, respectively. Both wired and wireless signals can be separated using optical filtering[34] or electrical filtering.[32] Our previous study has shown that optical filtering exhibits superior crosstalk isolation compared to electrical filtering.

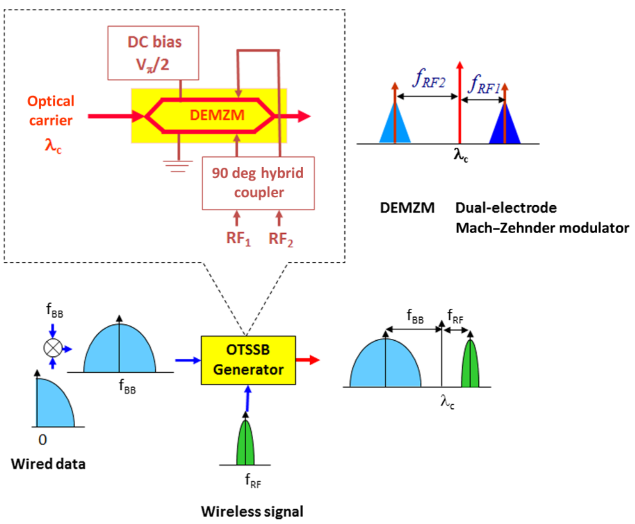

Fig. 10 Optical tandem single sideband (OTSSB) scheme for merging the wired and wireless signals for simultaneous transport.

4.2 *Crosstalk Investigations*

To quantify the performance of the OTSSB transport scheme as an efficient modulation format for simultaneous transmission of wired and wireless signals, we investigated the crosstalk and isolation between both wired and wireless signals.[15] In this investigation, we transmitted 2.5 Gb/s amplitude-shift-keyed baseband data to emulate the PON data with 622 Mb/s binary-phase-shift-keyed wireless data at 4 GHz. The 2.5 Gb/s baseband data were upconverted into 10 GHz, while the 622 Mb/s data were phase modulated onto a 4 GHz RF carrier. The experimental setup for the crosstalk investigation is shown in Fig. 11. The RF power of the two signals (wired and wireless) was electrically controlled using two tunable attenuators (ATT_1 and ATT_2) located before the hybrid coupler. The resultant signals drove the two arms of the DEMZM which was biased at quadrature. A tunable laser source at 1556.3 nm with an output power of +4 dBm drove the DEMZM and the resulting OTSSB signal was transported over 23 km of single-mode fiber (SMF) to the optical interface that separates the merged signals. The optical interface comprises a 3-port circulator and a narrowband fiber Bragg grating (FBG). The OTSSB signal entered the interface via port 1 of the circulator and the wireless signal (optical carrier and the 4 GHz sideband) was reflected by the FBG located at port 2 of the circulator while passing the sideband carrying the PON baseband data. The reflected wireless signal was dropped at port 3 and was detected using a 2 GHz avalanche photodiode (APD). The baseband data from the FBG were detected using a 10 GHz PIN photodiode (PD). The wireless data were recovered after one stage of downconversion.

For the crosstalk investigations, the RF power of the wireless/wired signal was systematically varied using ATT_1/ATT_2, while the bit error rate (BER) of the desired channel was measured. The inset of Fig. 11 shows the measured optical spectrum of the composite wired (at 10 GHz) and wireless (at 4 GHz) signals after transmission over 23 km of SMF when $ATT_1 = ATT_2 = 0$ dB. Figures 12(a) and 12(b) show the measured BER curves for 2.5 Gb/s baseband data and 622 Mb/s wireless data for different amounts of attenuation plotted as a function of the received optical power measured before the PD and APD. These BER curves were measured without any fiber transmission. The results show that the wireless signal suffers a minimal amount of crosstalk from wired data with a maximum variation of 0.7 dB at a BER = 10^{-9} (comparing the worst case scenario to the case when the wired data are completely off), while the wired signal suffers a maximum crosstalk variation of >3 dB. The high amount of crosstalk experienced by the wired data is attributed to the nonlinearity of the DEMZM where one of the second-order harmonic sidebands from the wireless signal falls within the band comprising the baseband data as illustrated in Fig. 13(a). This is confirmed by the results in Fig. 13(b)

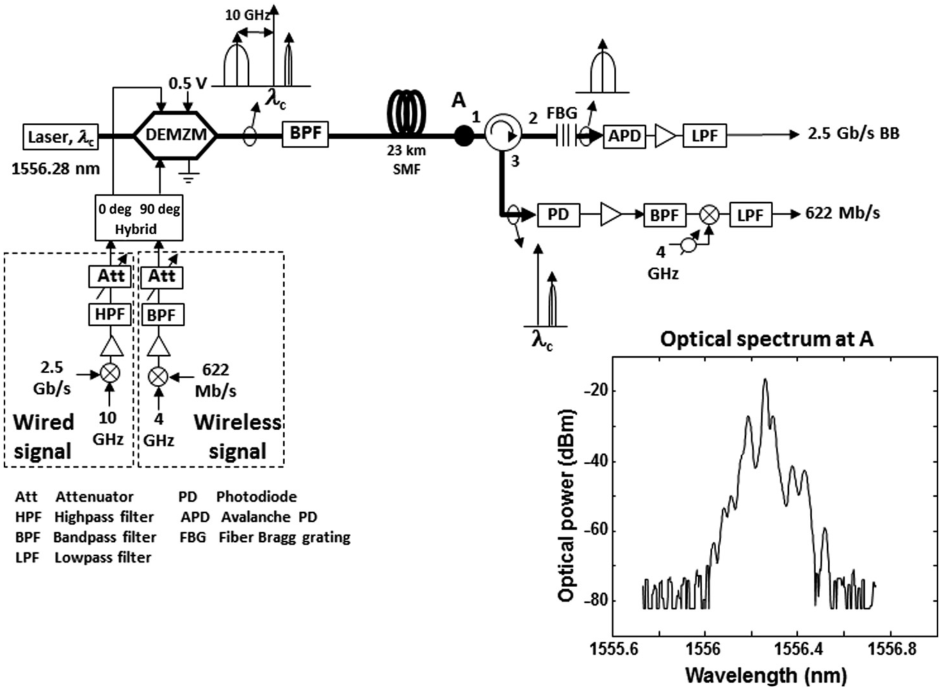

Fig. 11 Experimental setup for crosstalk analysis for OTSSB.

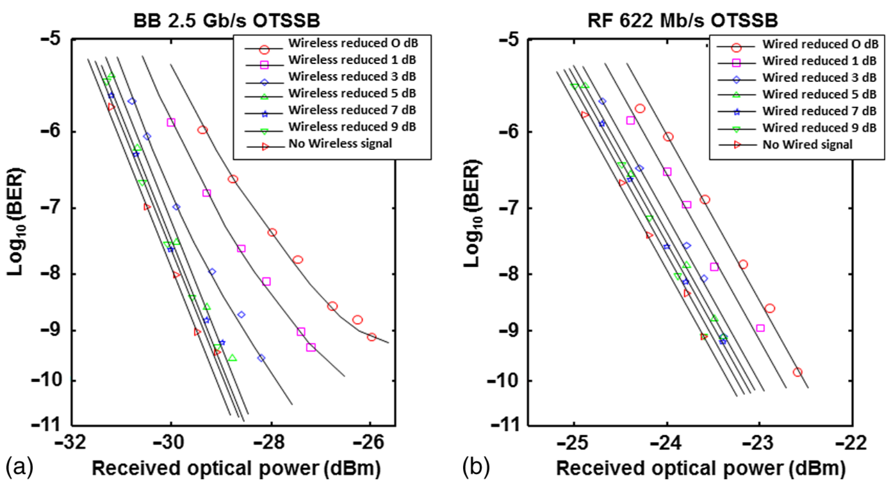

Fig. 12 Measured bit-error-rates (BER) curves for crosstalk investigation: (a) PON wired data and (b) wireless data incorporating OTSSB.

where the f_{BB} (frequency of the baseband placement) was varied from 10 GHz to 11 GHz and 12 GHz, plotted for crosstalk penalty (maximum crosstalk variation at BER $= 10^{-9}$) as a function of attenuation. As f_{BB} increases, the baseband data move away from the unwanted second-order sideband and eventually the second-order harmonic falls out of the baseband data band. We can see an improvement of >2.5 dB in the crosstalk penalty when $f_{BB} =$ 12 GHz [Fig. 13(b)]. The wireless signal is not affected by the crosstalk from the wired data and is independent of f_{BB} with a maximum crosstalk penalty <0.7 dB.

The choice of the f_{BB} relies not only on the wireless carrier frequency and the bit rate of the wired data, but also on the second-order harmonic sidebands from the wireless signal due to the nonlinear characteristics of the DEMZM. Our investigation also showed that the third-order harmonic sidebands from the wireless signal were relatively low and have a negligible impact on the baseband data performance.

4.3 *Full-Duplex Experimental Demonstration of RF-Passive Optical Network Incorporating Optical Tandem Single Sideband Modulation with Optical Interface in ONU/BS*

As discussed earlier, in addition to the efficient optical transport scheme to transparently transport the wired and wireless signals, another key enabler is the optical interfaces within the RN and hybrid ONU/BS (Fig. 4) that are capable of providing seamless adding and dropping of the wired and wireless signals. We have previously proposed passive optical interfaces within the RN and hybrid ONU/BS for an optical-wireless integrated network incorporating OTSSB.[33]

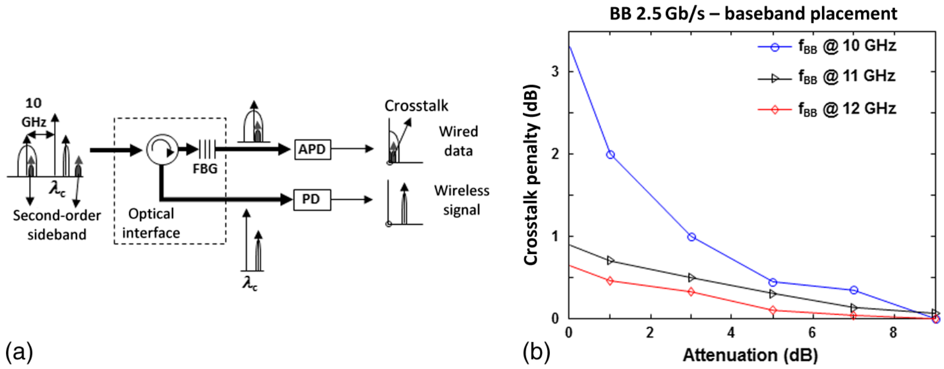

Fig. 13 (a) Schematic showing optical filtering for OTSSB modulation incorporating optical frontend nonlinearity and (b) measured crosstalk penalty as a function of attenuation for different baseband data placement (f_{BB}) for wired.

The hybrid ONU/BS has the capability to process both wired and wireless signals in-house and is able to simultaneously serve wired and wireless customers. Figure 14 shows the experimental demonstration of a full-duplex optical-wireless integrated network incorporating OTSSB. The proposed optical interface for simultaneous demultiplexing of the downlink wireless and wired data in OTSSB format and adding of the uplink optical signal is shown within the hybrid ONU/BS in Fig. 14. It consists of a 4-port circulator and an FBG with a reflective band that matches the optical carrier and the wireless sideband. The downlink OTSSB signal enters the interface via port 2 of the circulator and the FBG at port 3 reflects the wireless signal while letting the baseband signal through. The reflected wireless signal is dropped at port 4. The uplink optical signal carrying both the wired and wireless signals is transmitted back to the CO via port 1 of the circulator.

In this full-duplex experimental demonstration, we demonstrated an asymmetrical full-duplex link with a downlink (DL) transmission of 2.5 Gb/s of baseband data and 622 Mb/s wireless data using the OTSSB modulation format and uplink (UL) transmission of 1.25 Gb/s baseband data and 155 Mb/s wireless data using direct modulation of a vertical-cavity surface-emission laser (VCSEL).[33] As shown in Fig. 14, the experimental setup for the CO is similar to that in Fig. 11. The DL baseband at 2.5 Gb/s was first upconverted to 11 GHz and the wireless signal was generated using 622 Mb/s phase modulated onto a 4 GHz wireless carrier. The two signals were amplified and combined using a hybrid coupler before driving the two arms of a DEMZM biased at quadrature. A tunable laser at 1556.3 nm was used to drive the DEMZM. The generated OTSSB signal was optically amplified using an erbium-doped fiber amplifier to overcome the losses in the DEMZM and the relatively low optical power. After transmission over 23 km of SMF, the OTSSB signal was split using a 1:4 splitter before entering the optical interface within the hybrid ONU/BS, where the wired and wireless signals will be separated. The baseband signal was detected using a 2 GHz APD and the wireless signal was detected using a 10 GHz PIN PD. The wireless

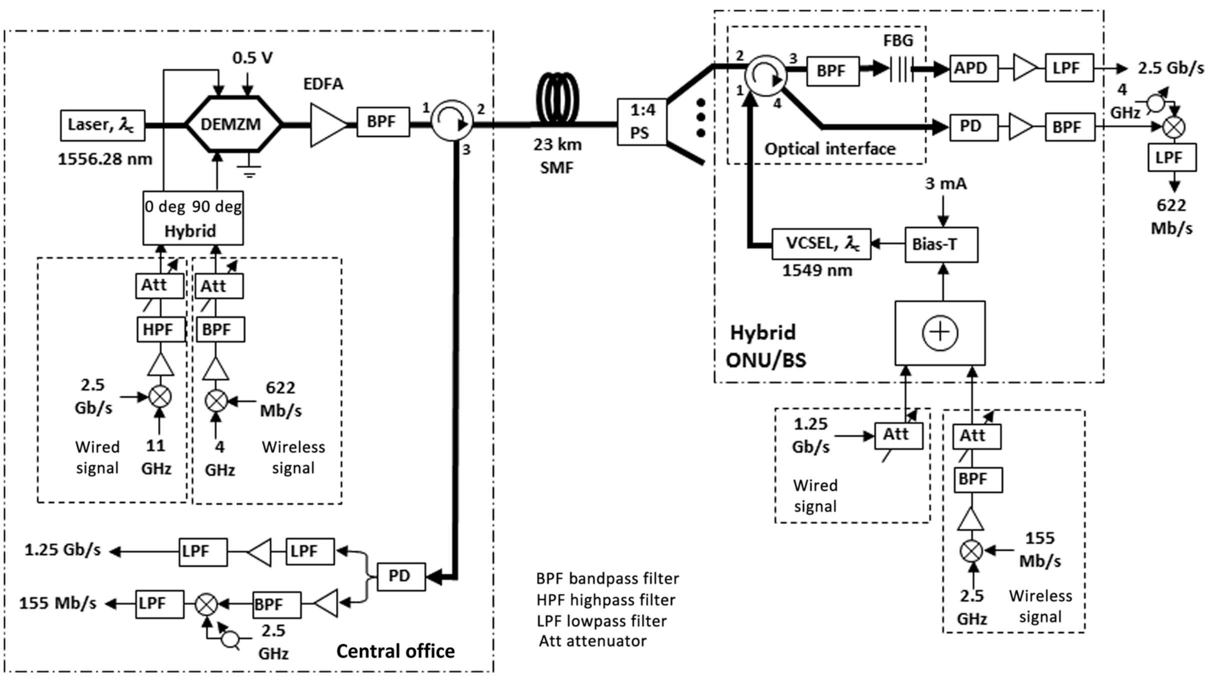

Fig. 14 Experimental setup for full-duplex demonstration incorporating optical interface in hybrid ONU/BS.

data were recovered after frequency downconversion. For the uplink transmission, 1.25 Gb/s baseband data and 155 Mb/s wireless data at 2.5 GHz were electrically combined before directly modulating a 1549.9 nm VCSEL. The optically modulated signal was sent back to the CO via port 1 of the interface using the same 23 km of feeder fiber. At the CO, the optical signal was detected using a 2 GHz APD. The wired and wireless signals were amplified and separated using electrical filters.

The performance of the full-duplex link was quantified and the measured BER curves are plotted in Figs. 15(a)–15(d). Figures 15(a)–15(b) show the measured BERs for DL baseband data and wireless signal transmission over 23 km of SMF plotted as a function of received optical power measured at the input of the APD and PD. The measurements were carried out with and without the uplink (UL on and off) and also with and without wired (BB on and off) and wireless signals (RF on and off) to evaluate the impact of crosstalk. Results show that the uplink has a minimal impact on the downlink performance and the crosstalk penalty between the wired and wireless is <1 dB, which is consistent with the results in Sec. 3. Figures 15(c)–15(d) show the measured BERs for UL baseband and wireless signals, respectively. Similarly, DL has a minimal impact on the performance of UL and both wired and wireless signals incurred a crosstalk penalty of approximately 1 dB.[33] We have also recovered the data from port 2 of the passive splitter with a similar performance as that of port 1, which indicates that data can be successfully recovered from any of the splitter ports.

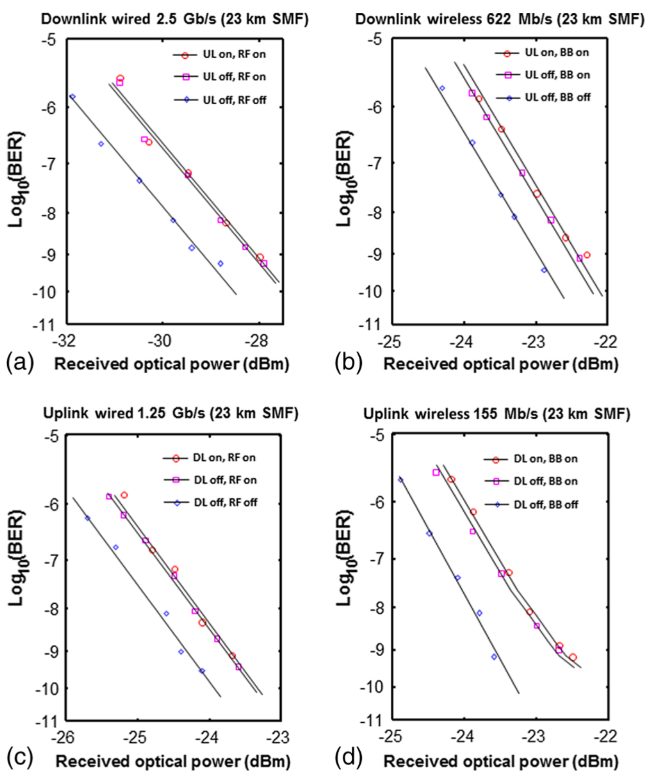

Fig. 15 Measured BER curves for full-duplex incorporating passive optical interface in hybrid ONU/BS for: (a) downlink (DL) PON wired data, (b) DL wireless data, (c) uplink (UL) wired data, and (d) UL wireless.

4.4 *Full-Duplex Experimental Demonstration of RF-Passive Optical Network Incorporating Optical Tandem Single Sideband Modulation with Optical Interface in RN*

Referring to Fig. 4, it can be seen that the function of an optical interface within an RN is slightly different from that in the hybrid ONU/BS. This interface has the ability to separate the wired and wireless signals before distributing them to their respective networks. In this architecture, both wired and wireless networks are physically isolated. The optical interface within the RN has to separate the downlink wired and wireless signals before serving two different networks and combining them before sending the composite signals back to the CO. Figure 16 shows the experimental setup for a full-duplex RF-PON transmission using OTSSB incorporating an optical interface in the RN. Here, the RN optical interface consists of a 4-port circulator and an FBG to enable the separation of the wired and wireless signals. In addition, the interface also comprises two 3-port circulators to distribute the wired and wireless signals to the respective network via port 2 of the 3-port circulators. This 3-port circulator also has the function of isolating the up and downlink transmissions. The uplink baseband signals from the ONU and the wireless signals from the antenna BS exit port 3 of the 3 port circulators before being multiplexed using a WDM coupler (WC) and transported back to the CO via port 1 of the 4-port circulator in conjunction with the feeder fiber.

The performance of the RN optical interface was evaluated in a full-duplex experiment. The experimental setup, as shown in Fig. 16, is similar to Fig. 14, with downlink (DL) transmission of 2.5 Gb/s baseband data and 622 Mb/s wireless data at 4 GHz using the OTSSB modulation format and uplink (UL) transmission of 1.25 Gb/s baseband and 155 Mb/s wireless data at 2.5 GHz. In the demonstration, the RN optical interface was located between the 23 km of feeder fiber and the ONUs and antenna BSs. The RN was assumed to service a cluster of 4 ONUs of a PON network and one antenna BS. The downlink wired and wireless signals were demultiplexed at the RN and distributed to a 1:4 passive splitter to serve the PON ONUs and the antenna BS, respectively. At the ONU, the 2.5 Gb/s baseband data were recovered using a 2 GHz APD. The uplink PON baseband data at 1.25 Gb/s directly modulated a 1529.9 nm VCSEL before transmitting back to the RN via a 3-port circulator located within the ONU. For the downlink wireless signal, the 4 GHz wireless signal was detected using a 10 GHz PIN PD and the 622 Mb/s wireless data were recovered using a downconversion circuitry. A separate VCSEL at 1549.9 nm was used as an optical transmitter for the uplink wireless signal of 2.5 GHz carrying 155 Mb/s wireless data. Similarly, the uplink wireless signal was transported back to the RN via port 1 of a 3-port circulator which was located in the antenna BS. At the RN, the uplink baseband and wireless signals exit their respective 3-port circulators and are multiplexed using a wavelength coupler (WC) and then transported back to the CO via port 1 of the 4-port circulator. At the CO, the uplink composite signals were dropped from port 3 of a 3-port circulator and the wired and wireless signals were separated using a tunable optical bandpass filter and were detected separately.

The measured BERs for the downlink wired and wireless signal transmission plotted as a function of received optical

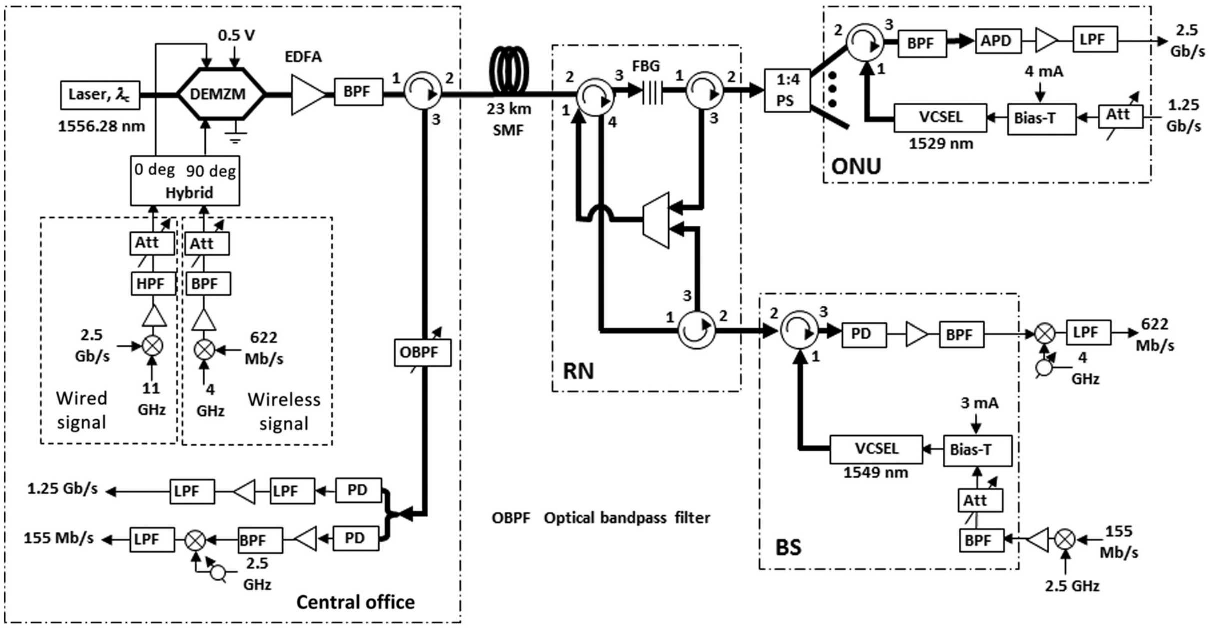

Fig. 16 Experimental setup for full-duplex demonstration incorporating optical interface in RN.

power (measured at the input of APD and PD) are shown in Figs. 17(a) and 17(b), respectively. The baseband data were measured at port 1 of the 1:4 passive splitter. Similarly, the measurements were carried out with and without UL transmission and with and without a DL wired or wireless signal to ascertain the level of signal isolation in relation to the performance of the RN optical interface. The results show that both downlink wired and wireless signals are not affected by the uplink transmission and the crosstalk penalty between wired and wireless signals is <1 dB. The measured uplink BERs for baseband and wireless signals are plotted in Figs. 17(c)–17(d). Both results show negligible crosstalk impact from the downlink transmission. The same experiment was repeated for the baseband signal recovered at port 2 of the 1:4 passive splitter (ONU2). The results are very similar to Fig. 17(a) which indicates that the ONU baseband data can be successfully recovered from any of the ports of the splitter.

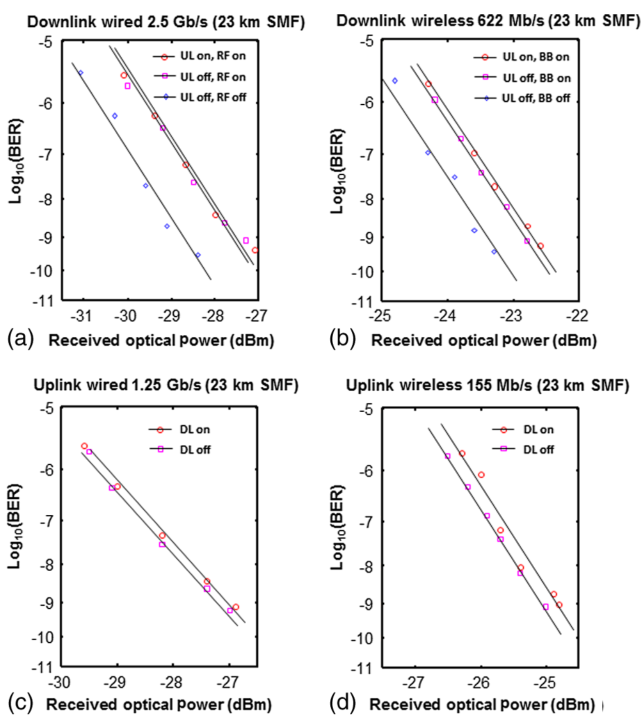

Fig. 17 Measured BER curves for full-duplex incorporating passive optical interface in RN for: (a) DL PON wired data, (b) DL wireless data, (c) UL wired data, and (d) UL wireless.

5 Conclusions

This paper provides a comprehensive summary and review on the different wireless signal transport schemes for transporting wireless signals in a hybrid optical-wireless integrated environment. We have also reviewed different optical network layout options for merging the wireless network and PON infrastructure. The review also includes merging incorporating WDM technology ranging from CWDM to DWDM to further optimize the performance of the integrated network. For each network layout option, we have discussed the possible transport schemes for seamless transport of the wireless signals for maximum transparency when integrated with a wired-based network. As an example, we have also reviewed a possible network layout for RF-PON using an OTSSB modulation scheme to maximize the wired and wireless signals' isolation. We have investigated the crosstalk performance and have introduced cost-effective passive optical interfaces for efficient multiplexing/demultiplexing of the wired and wireless signals. Our studies showed that the placement of the baseband data in the OTSSB modulation format has to be carefully tailored to minimize crosstalk from the wireless signal resulting from the impact of the nonlinear frontend especially for higher bit-rate transmission. The proposed optical interfaces in both RN and hybrid ONU/Bs were demonstrated and the performance was quantified in a full-duplex proof-of-concept experiment.

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