Performance evaluation for optical backhaul and wireless front-end in hybrid optical-wireless access network

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The hybrid optical-wireless access network (HOWAN) is a promising broadband access network. In this paper, the new architecture of the HOWAN is proposed and designed based on both a wavelengths division multiplexing/time division multiplexing passive optical network (WDM/TDM PON) at the optical backhaul and a wireless fidelity (WiFi) technology at the wireless front-end. The power budget of the optical backhaul based on maximum split ratio of 1/32 for each wavelength channel and a fiber length of 23 km from the central office (CO) to a 54 Mb/s access points (APs) along a 50 m outdoor wireless link is analyzed.

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1. Introduction

The high-speed broadband penetration and continuous growth of the Internet traffic among customers have been placing a huge bandwidth demand on the underlying telecommunications infrastructure which is produced by many new applications, such as multimedia applications. Since communication channel capacity is limited, it must be shared among users fairly, and a sufficient capacity should be assigned to applications depending on service requirements. Optical and wireless access networks have emerged to address the two significant issues which are created from the two ends of the bandwidth spectrum for different applications, appropriate in access applications today [3-6].

Next generation access network will require flexible deployment, large backbone capacity, upgrade ability, and scalable to user number and demand. Bandwidth demand in access networks will continue to grow rapidly due to the increasing number of technology-intelligent users. A HOWAN is an optimal combination of an optical backhaul and a wireless front-end for an efficient access network [1, 5]. The HOWAN is a highly desirable access network since the optical access is broadband, scalable, and reliable backhaul to collect and distribute wireless traffic; and the wireless access is ubiquitous, flexible penetration to end-users.

In this paper, the optical backhaul of the HOWAN is implemented by using a cost-effective WDM/TDM PON. WDM/TDM PON has been considered as a promising option due to its large throughput and quality of service (QoS) [8]. It supports data rate up to 2 Gb/s symmetrical operation. The wireless front-end is implemented by using WiFi (IEEE802.11a) technique which has many interesting characteristics such as low cost, high data rate, and easy deployment in wireless local area network (WLAN) [9]. IEEE802.11a supports data rate up to 54 Mb/s at 5.2 GHz carrier frequency.

The rest of this paper is organized as follows. In Section 2, the WDM/TDM PON-based HOWAN architecture is described and optical backhaul simulation are shown. The optical backhaul is integrated with the wireless front-end by using a WiFi (IEEE802.11a) technique in Section 3. The scalability of the HOWAN is investigated in Section 4. Section 5 is dedicated to describe the results and discussion. Finally, Section 6 concludes this paper.

2. Proposed access network architecture

The proposed HOWAN architecture is shown in Fig. 1. At the backhaul of the network, optical line terminal (OLT) is built in the central office (CO) and connected via an optical fiber. Then, a remote node (RN) distributes the data to multiple optical network units (ONUs). In the front-end, a set of wireless nodes (routers) forms a wireless mesh network (WMN). Mobile and stationery end users are connected to the network through these nodes, whose locations are fixed in the WMN. A selected set of these nodes (gateways) are connected to the optical part of the network. Usually, gateways are attached with one ONU [3]. As shown in Fig. 1, the wireless mesh routers automatically establish and maintain the connectivity as indicated by the dashed line, and the gateway router has a connection to the Internet via the optical backhaul. The upstream traffic from the end user is collected by the nearby mesh router. If the gateway router Gx is the destination gateway, the packets are relayed to this gateway router on one of the available paths, such as, the path P1 or P2.

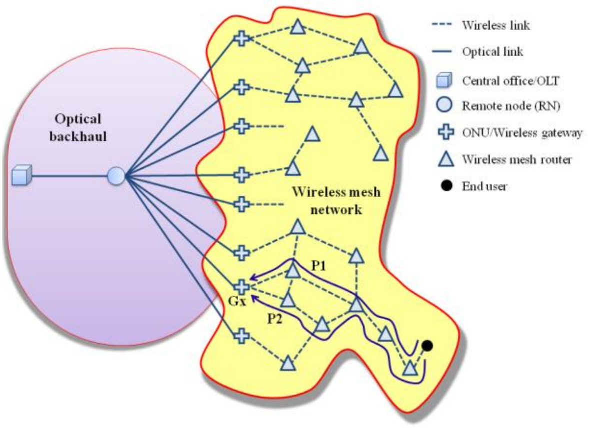


Fig. 1. HOWAN architecture.

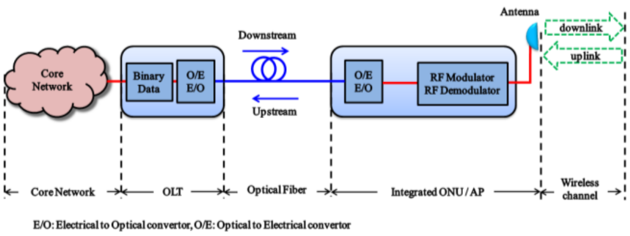


Fig. 2. Integrated optical-wireless system architecture.

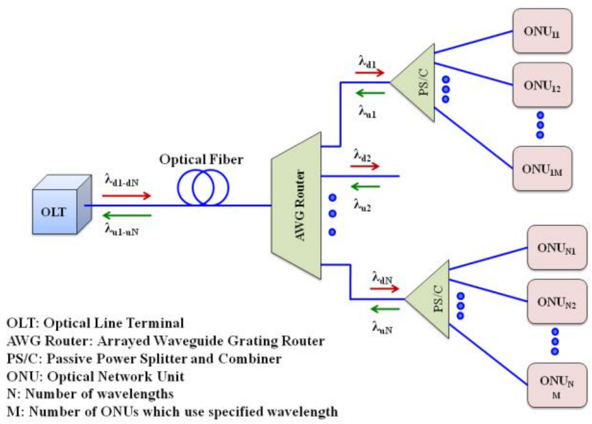


Fig. 3. Optical backhaul architecture.

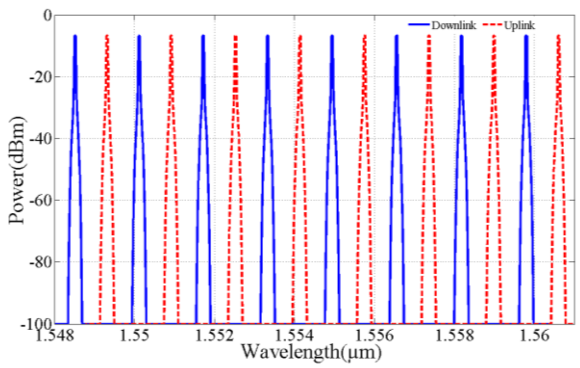


Fig. 4. Allocated wavelengths of the downlink/uplink channels for the optical backhaul.

In this work, the baseband-over-fiber scheme is used to transport the radio frequency (RF) wireless signals as a baseband signal over fiber. Then the system upconverts the data to the required radio frequency in the antenna gateway AP. So ONUs are equipped with functions of both traditional ONUs in PON and gateways in WMN to implement the integration of the optical backhaul and the wireless front-end. Fig. 2 shows the integrated optical-wireless system architecture. The downstream optical signals are created by the OLT and propagated along the optical fiber to the integrated ONU/AP. The ONU/AP in the HOWAN converted the downstream optical signals received from the RN into downlink wireless signals that will be sent to the WMN. At the upstream direction, the uplink wireless signals are received by the ONU/AP and converted to the upstream optical signals that will be sent to the CO. This scheme has the advantage of using mature digital and electronic circuitry for signal processing at the AP. Further, it also enables low-speed optoelectronic devices to be used within the AP [4]. The OptiSystem 8.0 and Advanced Design System (ADS) 2008 software tools are used to accomplish design and simulate the performance of the HOWAN.

3. Simulation design

HOWAN design comprises of multiple users connected to a CO represented by an OLT connected to multiple ONUs through 20 km of single mode fiber (SMF) by neglecting the distance between RN an ONUs. The system uses WDM/TDM PON with wavelength assignment and bandwidth allocation done at the OLT. Each ONU is integrated with an AP. The HOWAN is designed to operate at 2 Gb/s symmetrical for each wavelength at BER of 10^{-9}. The wireless access used is the WiFi (IEEE802.11a) technology with a data rate of 54 Mb/s.

a) Optical backhaul design

The optical backhaul is implemented by using WDM/TDM PON as shown in Fig. 3. The OLT assigns N = 8 wavelengths to transmit the downstream which propagates along 20 km SMF with attenuation 0.2 dB/km. The downstream is demultiplexed according to their wavelengths by the arrayed-waveguide-grating (AWG) router. Then it splits at passive splitter/combiner (PS/C) to M optical signals (according to split ratio of the PS/C). The upstream data is transmitted in the reverse way from each ONU to OLT. Fig. 4 shows the allocated wavelengths of the downlink/uplink channels which are selected from conventional band (CB) with 200 GHz (1.6 nm) channel spacing for each link. Also the uplink channels are separated by 100 GHz downlink channels.

b) Wireless front-end design

In this design, only the wireless gateway AP is considered as the main part, which is integrated with ONU. In addition, single-hop is considered in this design. 5.2 GHz is allocated as the carrier frequency for up and down conversion. Fig. 5 shows the orthogonal frequency division multiplexing (OFDM) based IEEE 802.11a transceiver of the AP which consists of two main parts: WLAN digital signal processing (DSP) subsystem and RF modulator/demodulator. The generation of OFDM is done in baseband using DSP, where a serial stream of bits C[n] is first demultiplexed into 52 parallel streams $C_0[n], C_1[n], \ldots, C_{51}[n]$. Each parallel stream is then mapped to a symbol stream using phase shift keying (PSK) or quadrature amplitude modulation (QAM) modulation constellation, after which an inverse fast Fourier transform (IFFT) is computed on each set of symbols, giving a set of complex time-domain samples. These samples are converted to the analog domain using digital-to-analog converters (DACs) and then quadrature-mixed with 5.2 GHz RF carrier (upconverted) at the transmitter [9]. Correspondingly, the receiver downconverts the transmitted RF signal, filters and does an FFT to retrieve the original coefficients.

4. Scalability analysis

In this section, the scalability of the optical backhaul in terms of the number of supported AP and link reach range are analyzed. The number of ONU/APs is limited by the power budget of the link and available wavelengths. The link budget determines both the link reach range and the splitter ratio of the PS/C. In terms of the splitter ratio, the port size of the AWG router in the optical transmission link and the number of supported APs is determined by the available wavelengths for the system. Additionally, the approximated number of APs can be estimated according to the common specifications of optical components as summarized in Table 1.

The link budget for the downlink/uplink can be expressed as [2]:

$$P_T - 2 \times IL_{AWG} - \alpha \times L - IL_{SA} - 10\log_{10}(S) \geq R_{sen} \quad (1)$$

where P_T is the transmission power, R_{sen} is the receiver sensitivity, IL_{AWG} is the insertion loss of AWG router, L is the fiber length, α is the fiber attenuation, IL_{SA} is the loss of splicing and aging in the link, and S is the splitter ratio of the PS/C.

Based on current standards, a PON can cover a typical link reach range of 20 km from the OLT to the ONU [1].

Table 1. Common specifications of optical components.

Symbol	Description	Value	Unit
P_T	Transmission power	0	dBm
R_{sen}	Receiver sensitivity	-30	dBm
IL_{AWG}	Insertion loss: AWG	4	dB
α	Attenuation	0.2	dB/km
L	Fiber length	20†	km
IL_{SA}	Splicing and aging loss on the link	2	dB
S	Splitter ratio of PS/C	4 – 32	none

†Here the fiber length between the RN and ONU is neglected.

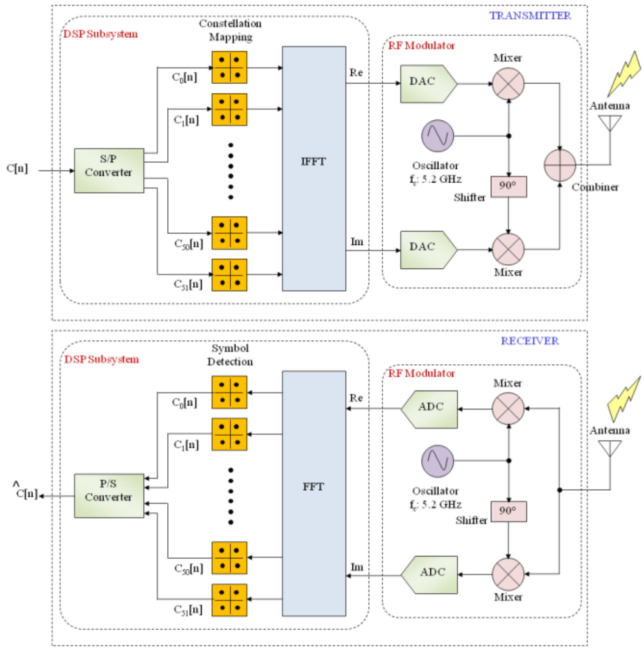


Fig. 5. OFDM based IEEE 802.11a transmitting and receiving systems.

According to Eq. (1), the maximal splitter ratio of the PS/C is then limited by:

$$10\log_{10}(S) \leq 16 \rightarrow S \leq 39 \quad (2)$$

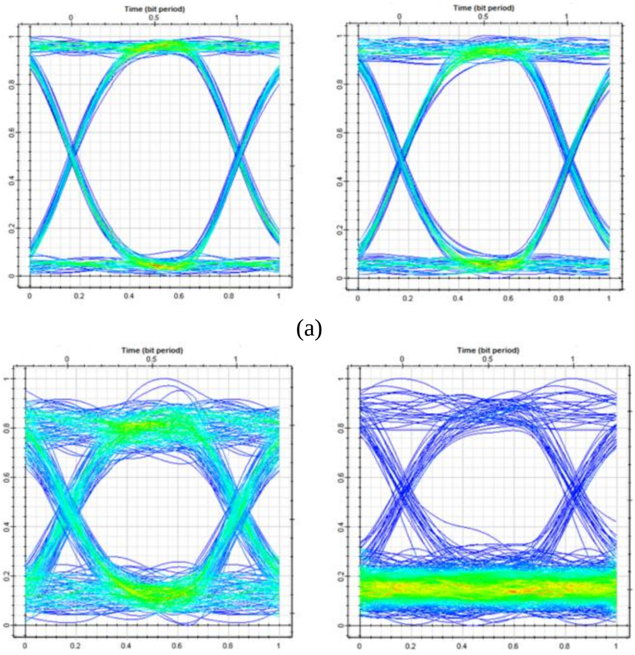
Therefore the maximum number of supported APs is 32 for each wavelength up/downlink. Since the link rate of each wavelength is 2 Gb/s, the maximum data rate per AP is 62.5 Mb/s.

The split ratio of the PS/C and the receiver sensitivity determines the maximum fiber length from OLT to ONU. Considering the common specifications of optical components as in Table 1 and Eq. (1), the link reach range (L) is 25 km where the split ratio of the PS/C is 1/32. In this study, the dense urban scenario of WMN is considered with fiber length between OLT and AWG router of 20 km and 5 km between AWG router and Aps.

5. Results and discussion

The eye diagram and bit error rate at different situations are shown to evaluate the proposed system performance. The simulated eye diagrams of the received signal at ONU and OLT for the downlink /uplink of the optical backhaul are shown in Fig. 6 (a) and (b) for split ratios of 1/8 and 1/32 respectively at the same fiber length of 20 km. The eye diagram shows a good quality system at BER of 10^{-9} in each link.

Power budgeting for an optical communication system is one of the main parameters to identify how far or big the network architecture can be deployed. Figs. 7-8 show the downlink and uplink BER measurement versus fiber length between AWG router and ONU in km respectively. The split ratio in this case is 1/32. The comparison between downlink and uplink is done and the best fiber length between AWG router and ONU is about 3 km to get 2 Gb/s data rate at BER of 10^{-9}. According to Eq. (1) and Table 1, the total length of the fiber (from OLT to ONU) is 25 km theoretically. That means the maximum fiber length between AWG router and ONU is 5 km, where the fiber length between OLT and AWG router is 20 km. The warping in some curves in Figs. 7-8 is due to the fiber nonlinearity. In wavelength division multiplexing nonreturn to zero (WDM-NRZ) system, the major manifestation of the fiber nonlinearity is collision-induced timing jitter which produces changes in the bandwidth and the BER [11].



(a)

(b)

Fig. 6. Eye diagrams of the optical backhaul measured at ONU (left) and OLT (right) with split ratio (a) 1/8 (b) 1/32.

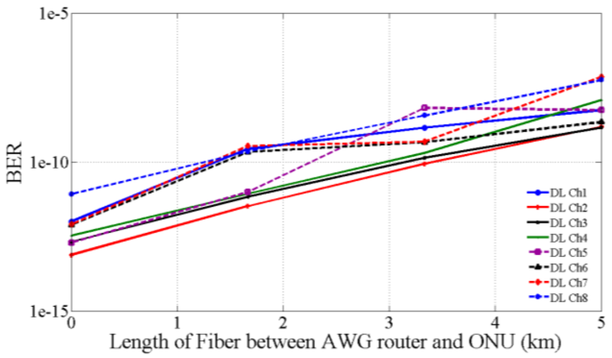


Fig. 7. Downlink BER versus fiber length between AWG router and ONU.

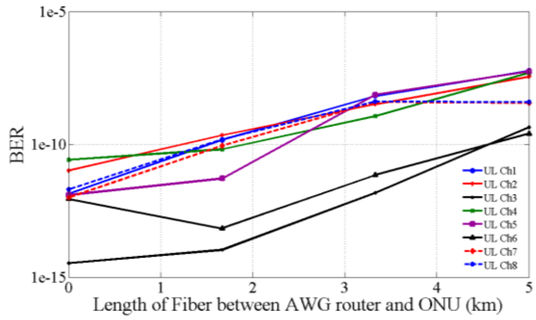
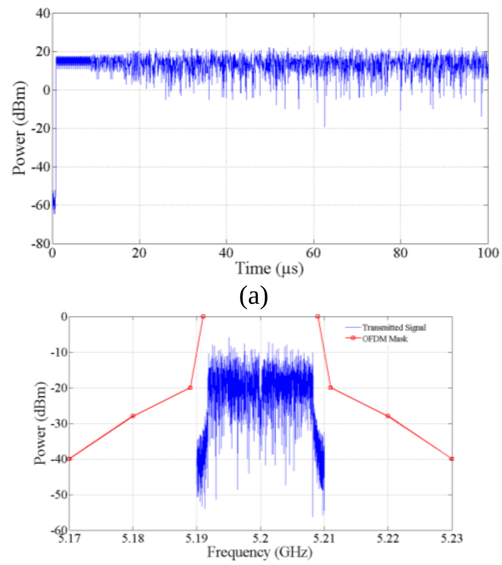


Fig. 8. Uplink BER versus fiber length between AWG router and ONU.

The electrical signal of the detected data at ONU is amplified, recovered and then inserted to the transmitter of the AP. The IEEE 802.11a with data rate of 54 Mb/s is used. Fig. 9 (a) shows the RF transmitted power signal from the AP in the time domain. The preamble and signaling take the first 20 µs of the frame, while the remaining 80 µs of the frame is used for the data. Signaling bits are modulated in one OFDM symbol by using PSK technique. On the other hand, the data is modulated in many OFDM symbols by using 64 QAM technique. Fig. 9 (b) shows spectrum of the RF transmitted power signal. The carrier frequency 5.2 GHz with the bandwidth of 20 MHz is investigated. In addition, Fig. 9 (b) shows the transmit spectrum mask. Typically, the spectrum mask is defined by the reference level power which gives the maximal allowed out-of-band radiation power at a given frequency [12]. As shown in Fig. 9 (a), the average transmitter power is 16 dBm.

Since the resultant RF signal is transmitted through a 50 m wireless channel, the transmitted and received constellations for 64 QAM are shown in Fig. 10. The clear scatter-plot is achieved, for a SNR of 20 dB and BER of 10^{-5}, allows a perfect symbol detection, since the received vector constellation is very close to the transmitted. This previews the good performance of the proposed system.



(a)

(b)

Fig. 9. The transmitted RF power signal at AP (a) in time domain (b) in frequency domain.

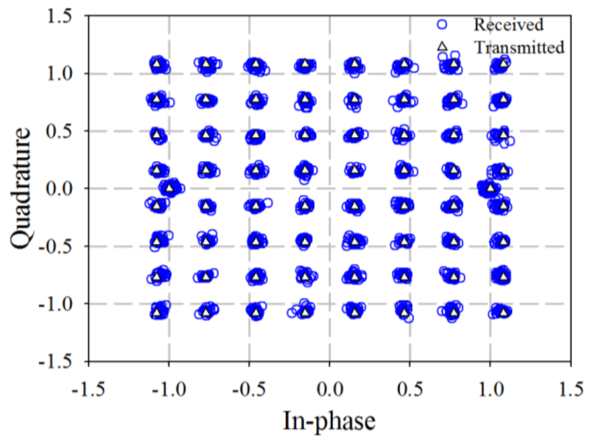


Fig. 10. The constellations of the transmitted and received RF power signal.

6. Conclusions

In this paper, architecture of HOWAN was proposed and designed as a suitable technique for future access networks. The scalability of the optical backhaul in terms of the number of supported AP and link reach range were analyzed. In conclusion, the proposed HOWAN achieved the data rate of 2 Gb/s for downstream/upstream over 23 km fiber length followed by 50 m outdoor wireless link with a data rate of 54 Mb/s. In order for further improvement of this work, the bandwidth of wireless front-end can be enhanced by using the WiFi (IEEE802.11n) technology which depends on a multiple input multiple output system and provides a maximum data rate of 600 Mb/s on the wireless link.

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