A Novel Passive Optical Network Architecture Supporting Seamless Integration of RoF and OFDMA Signals

Yu-Min Lin, Po-Lung Tien, Maria C. Yuang, Steven S. W. Lee, Jason (Jyehong) Chen, Shing-Yu Chen, Yi-Min Huang, Ju-Lin Shih, and Chih-Hung Hsu

***Abstract*—In this letter, we propose a novel passive optical network (PON) architecture supporting radio-over-fiber signals and orthogonal frequency-division multiple access (OFDMA) PON signals. The architecture transports upstream multiple remote antenna's wireless signals using only one upstream wavelength. In addition, the windowed-orthogonal frequency-division-multiplexing technique is employed to mitigate interference during the integration process. Experimental results shows that 10-Gb/s OFDMA and three radio-frequency signals at 2.1 GHz are successfully transmitted over 20-km single-mode fiber in a 32-optical-network-unit PON.**

***Index Terms*—Optical fiber communication, optical modulation, orthogonal frequency-division multiple access (OFDMA), passive optical network (PON), radio frequency (RF), radio-over-fiber (RoF).**

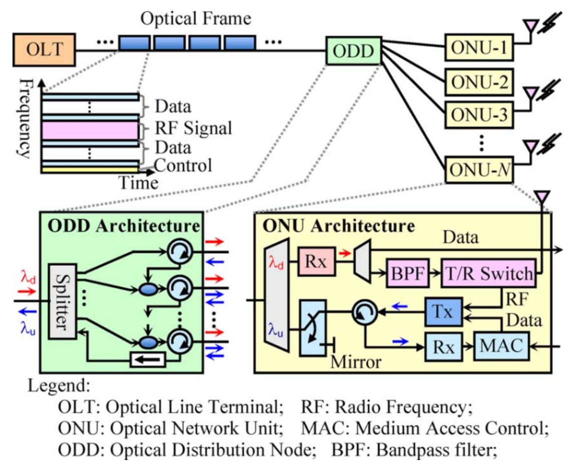

Fig. 1. OFDMA-PON architecture.

I. Introduction

BROADBAND wireless access systems have been successfully exploited to provide ubiquitous high-speed connectivity to end users. Next-generation passive optical networks (PONs) are thus expected to seamlessly transport wireless signals [1] to reduce the deploying cost while taking advantage of huge capacity of optical fiber. However, supporting multiple remote antenna ports in one trunk fiber gives rise to the optical beat interference (OBI) problem. To alleviate the problem, the approaches [2] exploit either wavelength-division-multiplexing (WDM)–PON or multiple upstream lasers at specially selected widely apart wavelengths, which are relatively expensive and impractical.

In this letter, we propose a new orthogonal frequency-division multiple access (OFDMA)-PON architecture without using WDM lasers. The architecture enables integration of broadband transport and wireless radio-frequency (RF) signals from multiple remote antennas. The integration unfortunately gives rise to the OFDMA signal interference to RF signals despite that several OFDMA subcarriers around the radio band are disabled. In this letter, we adopt a windowing technique at the OFDMA transmitter to mitigate the interference. Experimental results demonstrate that 10-Gb/s OFDMA signals and three RF signals at 2.1 GHz are successfully transmitted over 20-km single-mode fiber (SMF) in the new PON with 32 optical network units (ONUs).

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Y.-M. Lin, S.-Y. Chen, and C.-H. Hsu are with the Information and Communications Research Laboratories, Industrial Technology Research Institute, Hsinchu 31040, Taiwan.

P.-L. Tien, M. C. Yuang, J. Chen, Y.-M. Huang, and J.-L. Shih are with the Department of Communications Engineering/Computer Science/Photonics, National Chiao Tung University, Hsinchu 30010, Taiwan (e-mail: mcyuang@csie.nctu.edu.tw).

S. S. W. Lee is with the Department of Communications Engineering, National Chung Cheng University, Chiayi 62102, Taiwan.

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II. Network Architecture

The proposed OFDMA-PON [3], [4] (see Fig. 1) connects multiple ONUs to the optical line terminal (OLT) through an optical distribution node (ODD). The ODD is composed of one short section of drop fiber for each ONU and a set of optical circulators to direct signals among ONUs and OLT. The OFDMA-PON uses two wavelengths, λ_d and λ_u, to convey downstream and upstream data, respectively. To send data downstream, the splitter in ODD generates multiple signal copies, each of which passes a circulator before reaching the destined ONU.

For upstream data, ONU-1 first sends its upstream data and control information to ONU-2 through circulators. Upon having received data and control information on λ_u, the next ONU determines the subcarrier on which its upstream data is carried, and regenerates the OFDMA signal and sends it to the next ONU down the line. Finally, at ONU-N, the upstream wavelength is passed to OLT through the ODD. Moreover, the OFDMA-PON includes a 1-by-2 optical switch at each ONU's (upstream) to protect from accidental blackout or shutdown of ONUs.

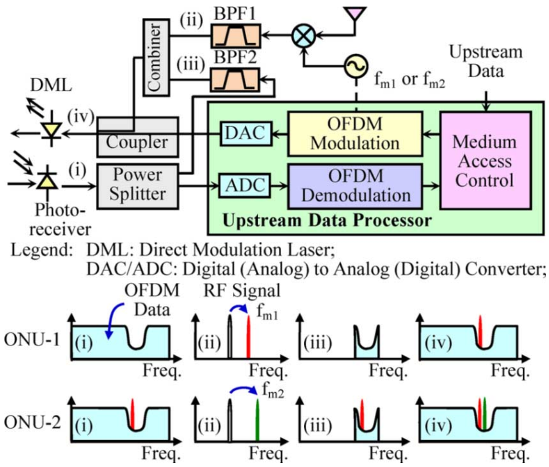

Fig. 2. RoF-signal overlay with OFDMA-PON data.

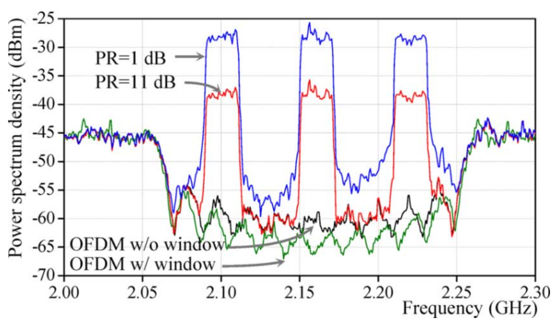

Fig. 3. Spectrum of radio band.

We illustrate in Fig. 2 that the wireless RF signals received by two remote antennas at ONU-1 and ONU-2, respectively, are overlaid with the broadband OFDMA signals. First, the wireless signal is frequency-shifted to the allocated band by a mixer, an oscillator, and a bandpass filter (BPF1). The shifted signal is then combined with the upstream OFDMA signal, which is together sent by the directed modulated laser to ONU-2. Upon receiving, ONU-2 first splits the received signal into two paths. The first path is for the regeneration of the upstream OFDMA PON signal. The process includes analog-to-digital conversion, original OFDMA demodulation, control-channel identification, adding of local data, the modulating OFDMA signal regeneration, and finally digital-to-analog conversion. For the other path, the system uses a bandpass filter BPF2 on the allocated radio band to remove the OFDMA signal but preserving all previous wireless signals intact. The RF combiner then combines the local antenna's signal from BPF1 with the previous ONU's wireless signals from BPF2. Finally, the system integrates the radio signal with the OFDMA PON signal via an RF directional coupler before driving the upstream laser.

III. Windowing Method to Reduce Interference

Due to the integration, the signal orthogonality can no longer be assured, resulting in the interference of OFDMA signal to RF signal. As shown in Fig. 3, the sidelobes of OFDMA subcarriers near the radio band determine the wireless signal's signal-to-interference ratio. To mitigate the interference by reducing the sidelobes, we employ time-domain windowing [5] of the orthogonal frequency-division-multiplexing (OFDM) symbol at the transmitter side.

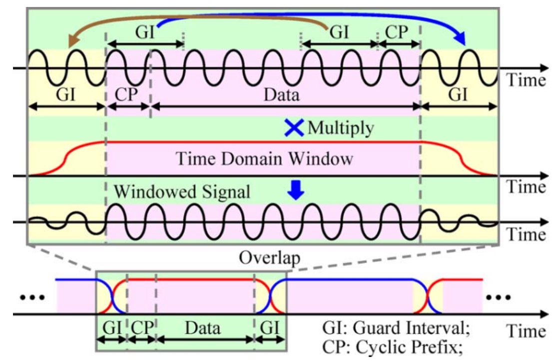

Fig. 4. Design principle of the windowing method.

The design principle behind the windowing technique is to reduce the degree of waveform discontinuity between adjacent OFDM symbols to suppress the out of band frequency component. We illustrate in Fig. 4 that the waveform of a subcarrier in the OFDM symbol is multiplied by a time-domain window to smooth the signal gradually around symbol boundaries. Notice that the employed window must not affect the original FFT period of the OFDM system. Therefore, a guard interval (GI), which is the cyclic extensions of the original signals, is added before and after the original OFDM samples. Note that the front GI can be overlapped with the rear GI of the preceding symbol, thereby reducing the overhead from 2*GI to only GI points.

In this work, we use the Nyquist windowing method, denoted as the second-order polynomial window (SOCW) [5]. The strength of the method is that its parameters can be optimized to suppress interference for a specific spectrum range. The Nyquist window $w_N(t)$ can be generally expressed as follows:

$$w_N(t) = \begin{cases} \frac{1}{T_u}, & 0 \le |t| < \frac{T_u(1-\alpha)}{2} \\ \frac{1}{T_u}\left[1 - x\left(-|t|\frac{2}{\alpha T_u} + \frac{1}{\alpha}\right)\right], & \frac{T_u(1-\alpha)}{2} \le |t| < \frac{T_u}{2} \\ \frac{1}{T_u}\left[x\left(|t|\frac{2}{\alpha T_u} - \frac{1}{\alpha}\right)\right], & \frac{T_u}{2} \le |t| < \frac{T_u(1+\alpha)}{2} \\ 0, & |t| \ge \frac{T_u(1+\alpha)}{2} \end{cases} \quad (1)$$

where $x(t) = 0.5 + a_1 t + (-0.5 - a_1)t^2$ is referred to as the normalized elementary function, α is the roll-off factor, and T_u is the OFDM symbol duration before adding the GI. Larger α means longer GI and hence low bandwidth efficiency. In the work, we choose α such that the GI overhead is limited to 5% (28 points). The resulting spectrum of windowed-OFDMA signal is shown in Fig. 3. It is obvious that the sidelobes in the radio bandwidth are lower by 1~3 dB when compared with traditional OFDMA spectrum.

IV. Testbed Experimentation

In the experiment shown in Fig. 5, the OFDM signal, which occupies 0.1- to 2.7-GHz bandwidth, is generated by an arbitrary waveform generator (AWG) with 10-GHz sampling rate. The inverse fast Fourier transform (IFFT) size is 512 points, from which 16-quadrature amplitude modulation (QAM) encoded 128 subcarriers are used for data transmission. The cyclic prefix is 8 points and the GI for the SOCW is 28 points. The allocated radio band is 200 MHz in width at frequency 2160 MHz to accommodate multiple wireless signals. Three

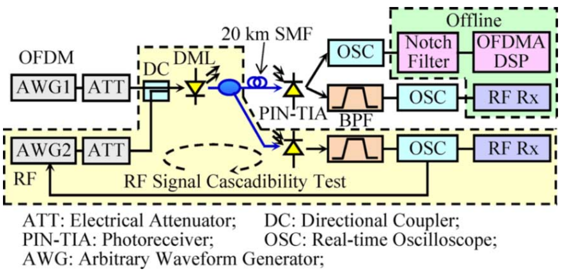

Fig. 5. Experimental setup.

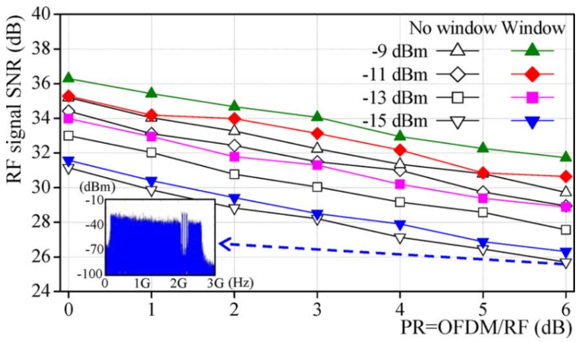

Fig. 6. RF signal's performance with respect to the driving power.

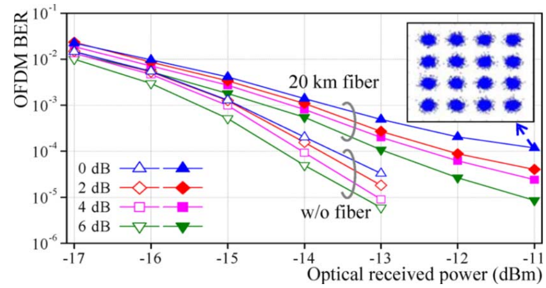

Fig. 7. OFDM BER curve under different PR settings.

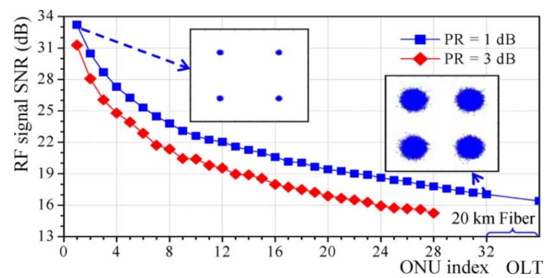

Fig. 8. RF signal's SNR in upstream path.

20-MHz WiMAX RF signal at 2100, 2160, and 2220 MHz, which are generated by AWG2 are used for the upstream test.

The experiment consists of two parts. OFDM and RF are first combined to drive a 3-dBm output power, 1550-nm direct modulated laser module. For the first part (a direct link test), a real-time scope captures the signal for offline signal demodulation. Over 1 million bits are compared before and after the link to obtain bit-error-rate (BER) results. A digital 200-MHz notch filter at 2160 MHz is used to remove the RF signals before the OFDM receiver. For the second part, we assess the performance of the RF signal via an offline recirculating loop experiment. After RF signals are extracted, a real-time scope captures and stores a section of waveform at a 12.5-GHz sampling rate in a file. The stored waveform is resampled to 10 GHz by a digital signal processing (DSP) program and fed to the AWG2 for the next hop transmission. For each hop, we load different OFDM signals to AWG1 so that each hop's interferences are not correlated. We can thus emulate the accumulated interference to RF signal from ONU-1 to ONU-32.

Define the power ratio (PR) as the OFDMA signal's driving power to the wireless signal's, assuming the overall modulation index is optimized in a weakly clipping condition. We show in Fig. 6 that the RF signal's signal-to-noise ratio (SNR) is dominated by the PR value and received power level. Although we intentionally zero 10 subcarriers for RF signal transmission, the inevitable OFDM sidelobes still affect the RF signal's quality. The windowing method provides 0.5- to 1.3-dB improvement on the RF signal's SNR. The inset of Fig. 6 shows the RF spectrum under PR $= 6$ dB. We show in Fig. 7 that the receiver sensitivity for BER $= 10^{-3}$, which is the error-free limit with forward error correction (FEC), is -15.3 dBm at PR $= 6$ dB and 0.5-dB penalty is observed if RF signal is increased to 0-dB PR. Note that a better sensitivity can be achieved by using the avalanche photodiode (APD)-based photoreceiver instead of the PIN-based receiver in our experiment. After the 20-km fiber transmission, the receiver sensitivity is degraded by 1.2 dB to -13.6 dBm. The fiber penalty comes from the laser diode's chirp effect. The OFDM constellation diagram is displayed in the inset of Fig. 7. Given an optical received power of -13 dBm at ONU and -15 dBm at OLT, as shown in Fig. 8, the SNR of RF signal degrades as the node number increases due to the interference from OFDM signal's sidelobes and optical–electrical–optical (O-E-O) conversion noise. If PR is equal to 1 dB, the SNR of the RF signal can still be above 16 dB (quadrature phase-shift keying (QPSK) error-free bound) after passing through 32 ONUs and a 20-km SMF.

V. Conclusion

We have proposed an OFDMA-PON architecture that integrates 10-Gb/s OFDMA and three wireless signals using a windowing method to reduce interference. Experimental results show that after-coding direct-detection receiver sensitivity of OFDMA over a 20-km fiber is -13.6 dBm. Under a PR of 1 dB and received power of -13 dBm at each ONU, the RF signal can be relayed in a 32 ONU's chain and recovered at OLT successfully.

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