Fixed and Mobile Convergence with Stacked Modulation

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***Abstract*—We propose a stacked modulation mechanism to realize the transmission convergence of fixed broadband and wireless access networks. As an integrated solution, the direct current biased analog signal for wireless data is multiplied by the digital optical signal carrying fixed broadband service, where the low-speed analog signal becomes an envelope of the high-speed digital signal. At the receiver, the analog signal is firstly recovered with the image edge detection algorithm, after which the digital signal is recovered with the least-square algorithm. This scheme can realize fixed and mobile convergence with a single wavelength, which reduces the access network cost in terms of number of transceivers. Besides, the link capacity and spectrum efficiency are also improved. Moreover, this method is compatible with the existing access networks since the transceivers can be adopted to the scenario by turning off the unused modules. Simulation results show that in case of intensity modulation direct detection system sensitivity, penalty of only 1~2 dB can be obtained for the 10Gbps/λ passive optical network when broadband access services are favored. Meanwhile, the wireless service needs more power than the broadband service to achieve the QoT requirements, and it has a higher penalty (~ 5 dB) compared with broadband access services.**

***Index Terms*—Fixed and mobile convergence, stacked modulation, optical access network, wireless access network.**

I.2 Introduction

With the massive deployment of novel wired and wireless applications, the high bandwidth requirements have put great pressure on communication infrastructure. To solve the capacity bottleneck, optical fiber communication is considered as an attractive technology to enable fixed and mobile convergence (FMC) [1-5], especially point-to-point (PtP) and wavelength division multiplexing passive optical network (WDM-PON), which provide a dedicated channel with ultra-high data rate. FMC allows operators to offer various services through a common infrastructure and hence leads to a great potential for cost saving.

The current research on FMC [4] is mainly addressing the network layer, focusing on the sharing and reconfiguring network infrastructure and functional units to realize the convergence. However, the transmission equipment to support fixed broadband and mobile services is still developed separately. One of the key reasons is that the fixed broadband and mobile systems utilize different transmission technology. For instance, digital signals, such as on-off keying (OOK), are often used for fixed broadband access, while in radio access network analog signals are recognized as promising candidates [5]. Although the fixed and mobile services can be carried out in the common network infrastructure, they need independent channels for their own transmissions. Thus, it is not possible to share the transmission equipment, leading to high cost and low flexibility. To solve these challenges, two major convergence technologies are proposed in physical layer based on digital and hybrid transmission.

The digital transmission convergence solution attempts to digitize the wireless analog signal and then transmit it in the optical fiber, e.g., enhanced common public radio interface (eCPRI) [6] for fronthaul, which can be further multiplexed with the digital fixed broadband data by using time division multiplexing (TDM) or WDM techniques [7-8]. Here some costly devices for high-speed analog-to-digital converter (ADC) and digital-to-analog converter (DAC) are needed. Besides, the multiplexing of digitized wireless and wired signals requires a very high capacity fiber links and worsens the latency performance. On the other hand, the hybrid transmission convergence technology is realized by overlaid modulation techniques [9-11] or simply putting together the baseband optical data and analog wireless data [12,13], which are multiplexed in frequency domain. Overlaid modulation is realized by modulating low speed digital data on top of the high-speed analog data, such as cascading optical lasers [9], modulating control or monitoring signal over analog data signals [10-11], etc. However, specially designed signals for FMC are utilized in [9-13], which is not efficient in the real deployment scenarios where the challenges, such as the modulation crosstalk interference and system inefficiency due

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to the additional overhead need to be addressed.

In this paper, we propose to stack analog modulation on top of the digital signals. It leads to a hybrid transmission of both analog and digital signals over a single wavelength channel, which not only enhances the link capacity and spectrum efficiency, but also reduces the network cost compared with two separated transmission systems for fixed broadband and mobile services. Besides, some digital signal processing (DSP) modules can also be switched off to allow compatibility with the legacy infrastructure. The simulation results show that the proposed scheme utilizing an intensity modulation direct detection (IM/DD) system only causes a minor sensitivity penalty (1~2 dB) for the 10Gbps/λ PON after optimization for broadband access services. At the same time, the wireless service needs more power than the broadband service to achieve the QoT requirements, and it has a higher penalty (~ 5 dB) compared with broadband access services.

II.2 Operational Principles

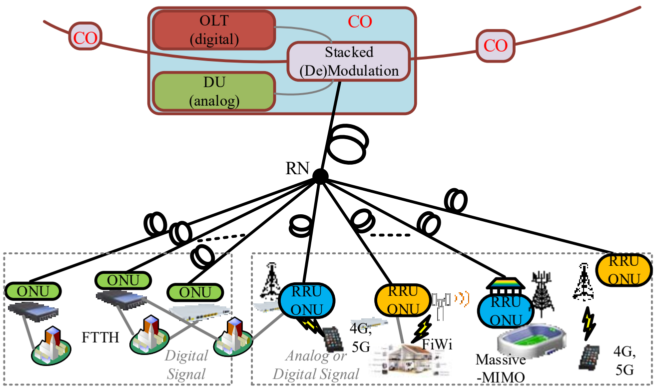

Fig. 1. Schematic architecture supporting FMC by using the proposed stacked modulation scheme.

Fig. 1 shows the schematic architecture supporting FMC by utilizing the proposed stacked modulation scheme. As shown in Fig. 1, the wireless analog signal at distributed units (DU) and optical digital signal at optical line terminals (OLT) are stacked modulated at the integrated central office (CO). The stacked modulated signal is injected into the feeder fiber and broadcasted at the remote node by optical splitter. At each optical network unit (ONU) or wireless access point (e.g., remote radio unit (RRU), base station), the digital or analog signal is received accordingly. For instance, FTTH users (ONUs) would need digital signal transmission, while RRU nodes prefer to deal with analog signals. The optical and radio signals from the user side can also utilize this stacked modulation for the upstream transmission. The system architecture with stacked modulation are described in *Section. II. A*, while the transmitter and receiver design of stacked modulator along with the corresponding mathematical expressions are presented in *Section. II. B and C,* respectively.

A. System Architecture

Fig. 2 shows the architecture of a stacked modulation system for both upstream and downstream transmission. In the downstream direction, the biased wireless access signal (e.g. orthogonal frequency division multiplexing, OFDM) is multiplied by a digital signal coming from the fixed broadband access network (e.g. on-of-keying, OOK), then the multiplied signal is modulated to optical domain with the optical modulator. The signals from different transmitters are multiplexed by WDM. The remote node (RN) delivers the signal to each ONU. Considering NG-PON2, where WDM-PON variant is included, the RN in Fig. 2 can either be power splitter which is compatible with the legacy PON deployment or wavelength-sensitive component (like arrayed waveguide grating AWG) that can split wavelengths to different ONUs. If the splitter is used at the RN, at the receiver a filter is required before photo-detector. The analog signal is first recovered by envelope detection, then, the digital signal is recovered by least-square solution. The principle can also be applied to the upstream, where the stacked signal is transmitted to the central office and recovered by the proposed demodulation schemes.

B. Transmitter Design

Without loss of generality, we consider OFDM as an example for analog signal and OOK (realized by non-return to zero, NRZ format) as an example of digital signal here. Fig. 3 (a) shows the scheme of transmitter based on the proposed stacked modulation for FMC. In such a transmitter, the wireless user data in the frequency domain is modulated by quadrature amplitude modulation (QAM) format. After QAM modulation and subcarriers mapping, data is forwarded to inverse fast Fourier transform (IFFT) implementation. After that, the cyclic prefix (CP) is inserted in front of the multicarrier signal, and then the parallel to series converted (P/S) time-domain signal $\boldsymbol{V_a}$ is multiplied by a extinction factor $\boldsymbol{\alpha}$ to adjust the power ratio between the analog and the digital signal. Then, $\boldsymbol{\alpha V_a}$ is added with a direct current (DC) offset $\boldsymbol{V_{DC}}$ to make the

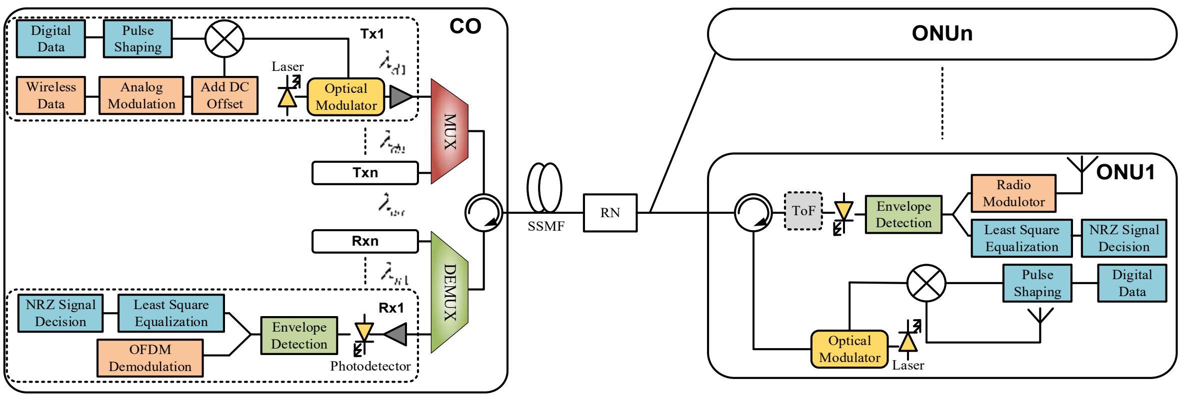

Fig. 2. System architecture of stacked modulation.

minimum value of analog signal larger than the minimum value of digital signal V_d. Finally, the analog signals and digital signals are multiplied to generate the stacked modulated signals V_t. The mathematical expression is shown in Eq. 1.

$$V_t = (V_{DC} + \alpha V_a) * V_d \tag{1}$$

To be able to also generate pure analog or digital signals, there are two decision modules. First, if the transmitter needs to generate pure analog signals, it directly jumps to the DAC module to generate analog signals. In the second decision module, if the transmitter only needs to generate digital signals, it directly jumps to the DAC module to generate the digital signal. Thus, in case FMC is not needed, this transmitter can also generate either pure digital or analog signals.

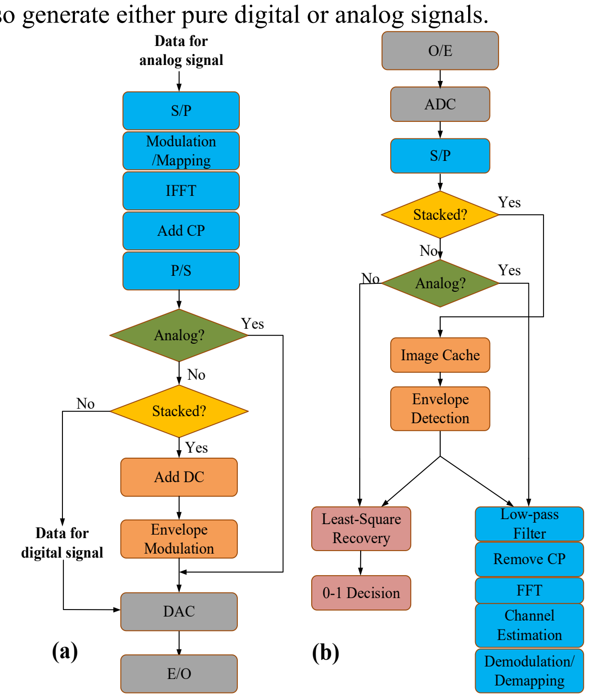

Fig. 3. (a) Transmitter design for the proposed stacked modulation, (b) Receiver design for the proposed stacked modulation.

C. Receiver Design

The stacked modulated signals are transmitted into the fiber, detected by photoelectric detector, and converted to electrical domain. It can be expressed by Eq. 2 where the channel distortions $h(t,f)$ and noise V_w induced by chromatic dispersion and fiber transmission attenuation are considered. In the mathematical model shown in Eq. 2, ⊗ means the convolution for channel response.

$$V_r = V_t \otimes h(t, f) + V_w \tag{2}$$

Fig. 3 (b) shows the receiver design to support the proposed stacked demodulation for FMC. At the receiver side, the analog signals are first abstracted from the received signal V_r by image edge detection algorithm. More specifically, the symbol of the stacked modulated signals is stored as a two-valued image by image cache, and then the envelope of the stacked signals, i.e., the DC-biased analog signals, are recovered by edge detection $E\{.\}$. In this paper, Canny edge detection algorithm [14] is adopted, which followed a list of criteria, such as low error rate, well localized edge points, one response to a single edge, to improve accuracy edge detection. Based on these criteria, the Canny edge detector first soothes the two-valued image of stacked modulated signal to eliminate the noise. Then, it finds the image gradient to recognize regions with high spatial derivatives. The algorithm then tracks along these regions and suppresses any pixel that is not at the maximum. After that, hysteresis is used to track along the remaining pixels that have not been suppressed. Finally, the edge of stacked modulated signal is abstracted and converted to the analog signal after normalization. The algorithm flow is shown in Fig. 4.

***Algorithm 1*:**

Input: two-valued image of stacked modulated signal V_r
Output: envelope of stacked modulated signal (analog signal) V_a'

Step 1: Apply Gaussian filter to smooth the image;
Step 2: Recognize regions with high spatial derivatives;
Step 3: Tracks along the regions in *Step 2* and suppresses any pixel that is not at the maximum;
Step 4: Hysteresis:
Finalize the edge detection $E\{.\}$ by suppressing the other weak edges .

end

Fig. 4. Description of edge detection algorithm.

The recovered analog signals are modulated to the radio frequency, and finally transmitted to the wireless user by antenna. After removing the envelope of the recovered signal, a least-square algorithm is used to recover the digital signals. The mathematic model is shown in Eq. 3.

$$V_s = \begin{cases} V_r (V_{DC} + \alpha E\{V_r\})^{-1}, \text{digital} \\ E\{V_r\} - mean(E\{V_r\}), \text{analog} \end{cases} \tag{3}$$

Meanwhile, demodulation is also made for evaluating the upstream performance of analog signals, e.g., OFDM, the serial-to-parallel (S/P) converted signal first passes through the low pass filter and removes the CP, and then it is sent to the FFT implementation. After subcarriers de-mapping, the pilot based channel estimation (CE) method in our previous work [15] is used. After the CE, the symbols are sent to the QAM demodulation module for user data recovery.

Similar as the transmitter design, there are also two decision modules in the receiver which get the recognition of the modulation types from the network control layer. First, if the signals are stacked modulated, the image edge detection algorithm is utilized to recover the analog signals and then recover the digital signals. If purely analog signal is considered, it directly jumps to the branch for analog signal demodulation. Otherwise, it directly jumps to the branch for digital signal demodulation (e.g. 0-1 decision) module.

III.2 PERFORMANCE EVALUATION

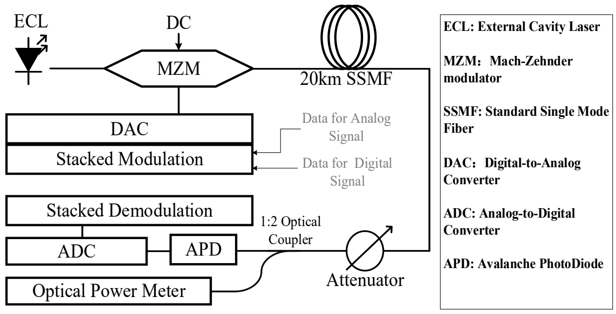

Fig. 5. Simulation setup

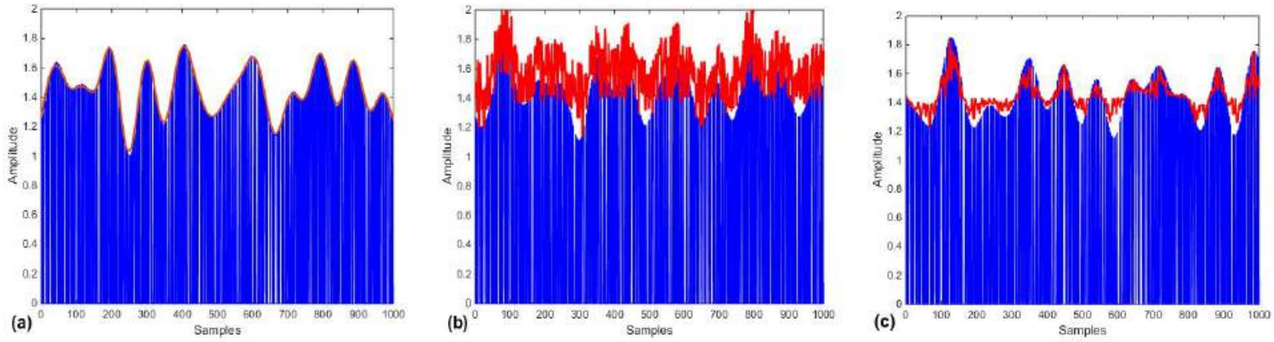

Fig. 6. Envelope detection with (a) image edge detection, (b) bandpass FIR filter and (c) Hilbert transform method. (the original stacked modulated signal (blue curve) and the one detected by different methods (red curve))

To demonstrate the feasibility of the proposed solution, we have implemented our approach in the simulation tools using *MATLAB* 2014b and *Optisystem* 7.0. The OOK signal is randomly generated with 10Gbps data rate. The IFFT point of OFDM signal is 16384 and analog signal bandwidth is 200MHz. The QAM order is 16. The simulation is carried out by optical intensity modulation and direct detection transmission (IM/DD) system. The simulation setup is shown in Fig. 5. The amplified signals are downloaded to the DAC. A MZM is used for modulation with an ECL (15dBm, 1550 nm). Optical signal is transmitted over 20km SSMF. At the receiver, a variable optical attenuator (VOA) is used to change the received optical power for bit-error ratio (BER) measurements. The signal is detected by an APD. Then, the signal is captured by ADC.

First, to confirm the feasibility and effectiveness of the envelope detection in stacked modulation scheme to distinguish the OFDM signals from OOK signals, we test the image edge detection algorithm and compare it with band-pass FIR filter method [4] and Hilbert transform method at ideal channels (i.e. no channel noise). The results are shown in Fig. 6. For comparison, we plot the original stacked modulated signal (blue) and the one detected by different methods (red) in each sub-figure in Fig. 6. It can be easily seen that image edge detection algorithm can perfectly recover the analog OFDM envelope. Moreover, its complexity and overhead are comparable with the other methods. On the other hand, band-pass FIR filter method and Hilbert transform method cannot perform as good as the proposed image edge detection algorithm. Since the multiplication will bring frequency overlap, simple filtering operations cannot filter out the distortions, and the last two schemes cannot mitigate the modulation crosstalk.

Secondly, to evaluate the influence of extinction factor $\boldsymbol{\alpha}$ and DC offset $\boldsymbol{V_{DC}}$ on the stacked modulation format, we have shown the BER performance of OOK and OFDM in terms of α and $\boldsymbol{V_{DC}}$ in Fig. 7. The received optical power levels are -32dBm and -24dBm, respectively. With the increase of extinction factor $\boldsymbol{\alpha}$, the performance of OFDM becomes better since it has more power in the stacked modulation, while the performance of OOK becomes worse. With a smaller value of $\boldsymbol{\alpha}$, the performance of OOK becomes better since its power ratio is larger and the waveform becomes flatter. For DC offset $\boldsymbol{V_{DC}}$, the trend is opposite. When the DC offset $\boldsymbol{V_{DC}}$ increases, there is more power allocated to OOK signals and its performance is enhanced. When $\boldsymbol{V_{DC}}$ decreases, the power of OFDM is higher, and it outperforms the OOK in the stacked modulation. Overall, there is a clear trade-off between digital and analog transmission in stacked modulation format. In the real implementation, the power ratio between digital and analog signals can be flexibly configured to meet requirements on quality of transmission (QoT). If QoT requirement of analog signal is high, then α should be increased and $\boldsymbol{V_{DC}}$ should be decreased. Otherwise, α should be decreased and $\boldsymbol{V_{DC}}$ should be increased.

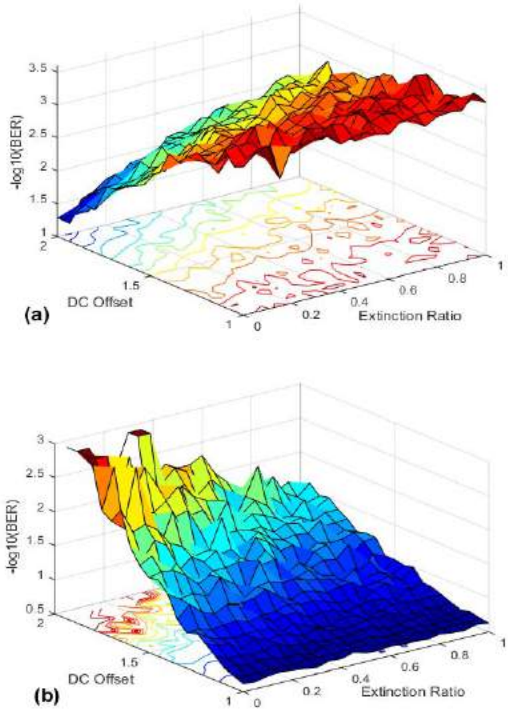

Fig. 7. BER performance of (a) OOK and (b) OFDM in terms of $\boldsymbol{\alpha}$ and $\boldsymbol{V_{DC}}$.

Finally, to demonstrate the impact of stacked modulation on the existing PON and wireless access network (e.g. mobile fronthaul) transmissions, the BER versus received optical power of OFDM and OOK are shown in Fig. 8 and 9, respectively. Here, the extinction factor $\boldsymbol{\alpha}$ and DC offset $\boldsymbol{V_{DC}}$ are chosen to give more power to OOK transmission in PON, which is shown as an example for flexible QoT choice. The common schemes of digital and analog modulations are also realized by turning off modules in stacked modulations. It can be seen from Fig. 8 and Fig. 9 that the power penalty of stacked modulation compared to purely OOK transmission in 10Gbps/λ PON is 1 ~ 2 dB at hard-decision forward error correction (HD-FEC) threshold at BER=3.8e-3 [16], which will not obviously influence the power splitting ratio and access point numbers of the legacy PON infrastructure. Besides, it is also shown that considering physical layer constraints, the eCPRI (digital) transmission [6] can also be supported by stacked modulation.

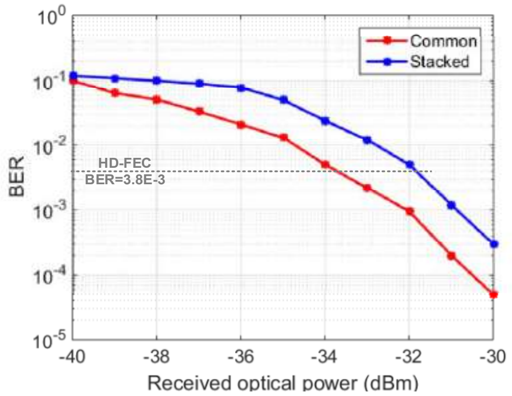

Fig. 8. BER versus optical received power of OOK.

For wireless access network, the power penalty here is 4 ~ 5 dB at HD-FEC threshold. This is because that there is less power allocated to OFDM signals, which also fits the performance analysis of Fig. 7. To improve the QoT of wireless access networks, more power should be allocated to the analog signals. Since the main idea here is suggesting to use PON to load the wireless services while holding the fixed broadband services, QoT requirements of PON is comparatively higher than wireless access network. Otherwise, the parameters can also be adjusted to meet the QoT of wireless access network. Besides, the transmission performance of the envelope of the stacked modulation is also comparable with the purely analog wireless access network, which can also reduce the capacity requirement compared to eCPRI.

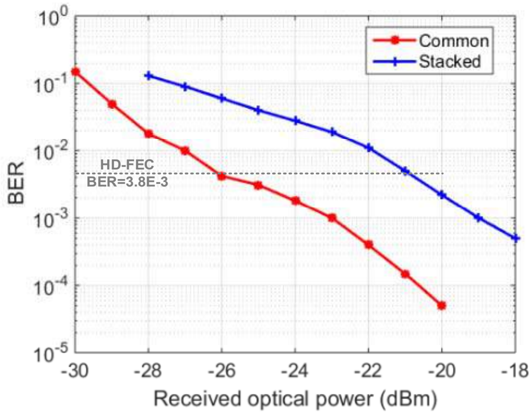

Fig. 9. BER versus optical received power of OFDM.

IV. Conclusions

We propose a stacked modulation mechanism to realize the transmission convergence of fixed broadband and wireless access. The solution is applicable for both upstream and downstream transmission. As an integrated solution, it stacks the analog multicarrier signals on top of the digital signals. This scheme is also compatible with the existing transceivers in wireless and optical access networks. It offers several benefits, such as significantly reduced system cost and enhanced spectrum efficiency, while according to our simulation results the sensitivity penalty for the 10Gbps/λ PON is only 1~2 dB after optimization for broadband services. If the QoT of wireless access is higher, the performance of wireless access can also be improved by increasing the power ratio of wireless signals in stacked modulation.

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