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Crosstalk due to optical demultiplexing in subcarrier multiplexed systems

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Abstract We report an in-depth investigation of the inter-modulation crosstalk in subcarrier multiplexing (SCM) systems with optical demultiplexing (ODeMux). Both theoretical derivations and numerical simulations show that the crosstalk in ODeMux systems mainly comes from the nonlinear mixing of the baseband and subcarrier modulations inside the signal channels. Several key parameters are then studied to estimate their effects on the magnitude of the crosstalk. As a result, performance optimization strategies are proposed for ODeMux SCM systems. In order to further enhance the transmission performance of ODeMux SCM systems, we discuss two techniques to suppress the inter-modulation crosstalk and analyze their effectiveness with numerical simulations.

Keywords Subcarrier multiplexing (SCM) · Crosstalk analysis · Optical communications · Optical signal processing · Optical-label switching (OLS) · Passive optical networks (PON)

1 Introduction

Optical subcarrier multiplexing (SCM) technology is widely used in cable television (CATV), optical-label switching (OLS) [1], and WDM passive optical network (WDM-PON) systems [2,3]. Conventional SCM receiver uses electrical filters after the photo-detector (PD) to extract signals. This electrical demultiplexing (EDeMux) scheme is expensive, complicated, and power hungry due to the need of radio-frequency (RF) components. Its performance is also affected by fiber dispersion due to the RF fading effect [1,4,5]. Therefore, EDeMux receiver is not suitable for networks where the cost and power budget is tight or the fiber dispersion is unpredictable, such as in WDM-PON or optical packet switching networks. Optical-demultiplexing (ODeMux) overcomes these drawbacks by putting an optical filter (e.g., fiber Bragg grating) before the PD and eliminates the need of high-speed electronics. The inter-modulation crosstalk plays an important role in limiting the performance of SCM systems, and it has been studied intensively for EDeMux SCM systems [6,7]. However, to the best of our knowledge, it still has not been studied for ODeMux SCM systems with a convincing theoretical model. Most of the previous work [5,8] just simply assumes that the crosstalk is similar to that in EDeMux systems. In this paper, we report an analytical investigation of the inter-modulation crosstalk in ODeMux systems. With both theoretical derivations and numerical simulations, we show that the crosstalk in ODeMux systems is significantly different from that in EDeMux systems. Based on the investigation, we propose strategies for performance optimization of ODeMux SCM systems and discuss two techniques to suppress the inter-modulation crosstalk.

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2 Theoretical analysis

2.1 Analytical model

Figure 1 shows the configuration of a typical SCM system using optical demultiplexing with a fiber Bragg grating. After optical modulation, the optical field of the SCM signal is [6]:

$$E(t) = \cos\left[\frac{\pi}{V_\pi}(S_0(t) + S_1(t)\cos\omega_c t + V_{\text{bias}})\right] \cdot e(t) \quad (1)$$

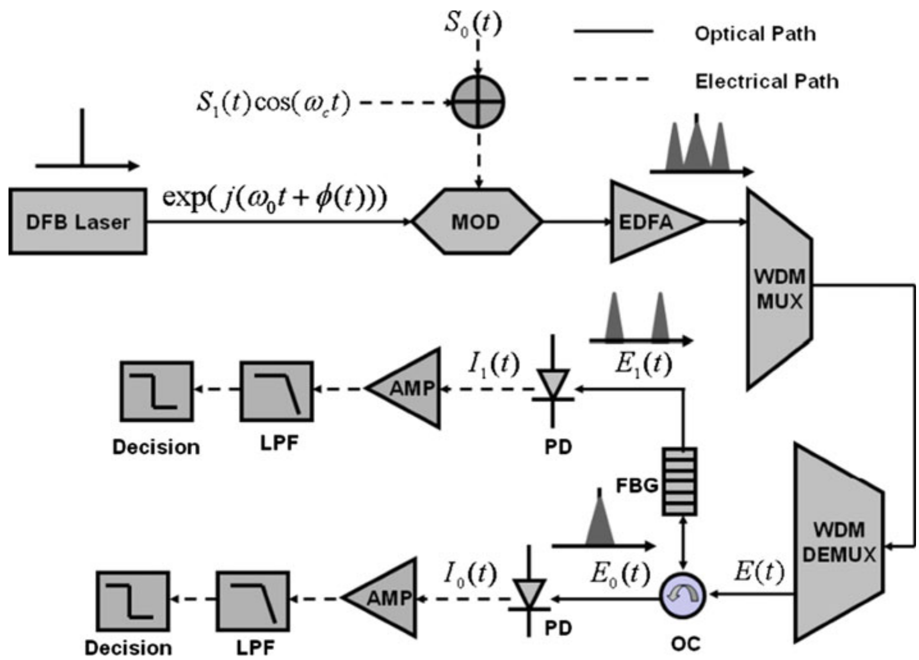

Fig. 1 System architecture of **a** EMux-ODeMux, and **b** OMux-ODeMux SCM systems. *MOD* optical intensity modulator, *EDFA* Erbium-doped fiber amplifier, *FBG* fiber Bragg grating, *OC* optical circulator, *PD* photodiode, *AMP* electrical amplifier, *LPF* low-pass filter

where $S_0(t) \geq 0$ and $S_1(t) \geq 0$ are the electrical signals for baseband and subcarrier, ω_c is the subcarrier angular frequency, V_π is the switching voltage of the optical modulator, V_{bias} is the bias voltage, $e(t) = E_0 \exp(j\omega_0 t + \phi(t))$ is the field of the optical carrier. The signal modulations and bias voltage can be normalized with the switching voltage:

$$\alpha(t) = \frac{\pi}{V_\pi} S_0(t), \quad \beta(t) = \frac{\pi}{V_\pi} S_1(t), \quad \theta = \frac{\pi V_{\text{bias}}}{V_\pi} \tag{2}$$

Then, (1) can be expanded with Bessel functions:

$$\begin{aligned} E(t) = e(t) \Bigg\{ & \cos(\alpha(t)+\theta) \\ & \cdot \left[J_0(\beta(t)) + 2\sum_{n=1}^{\infty} (-1)^n J_{2n}(\beta(t)) \cos(2n\omega_c t) \right] \\ & -2\sin(\alpha(t)+\theta) \\ & \cdot \left[\sum_{n=0}^{\infty} (-1)^n J_{2n+1}(\beta(t)) \cos((2n+1)\omega_c t) \right] \Bigg\} \end{aligned} \tag{3}$$

(3) shows that the field of the optical signal is a summation of baseband and subcarrier harmonics. On each harmonic, the baseband and subcarrier modulations, $\alpha(t)$ and $\beta(t)$, coexist as a mixed term. If we ignore the high-order subcarrier harmonics and assume that they can be removed by WDM filters, (3) reduces to:

$$\begin{aligned} E(t) = e(t)\, & [\cos(\alpha(t)+\theta) \cdot J_0(\beta(t)) - 2\sin(\alpha(t)+\theta) \\ & \cdot J_1(\beta(t)) \cos\omega_c t] \end{aligned} \tag{4}$$

After the optical demultiplexing with a fiber Bragg grating, the field of the optical baseband is:

$$E_0(t) = e(t) J_0(\beta(t)) \cos(\alpha(t)+\theta) \tag{5}$$

while that of the optical subcarrier is:

$$E_1(t) = -2e(t) J_1(\beta(t)) \sin(\alpha(t)+\theta) \cos\omega_c t \tag{6}$$

(5) and (6) can be used to analyze the inter-modulation crosstalk in ODeMux systems. The crosstalk is introduced by nonlinear mixing and is different from that in EDeMux systems. Specifically, the original baseband and subcarrier modulations are mixed and spread to the frequency channels of each other. Numerical simulation is then performed to investigate the crosstalk's impact on system performance.

2.2 Simulation and system optimization

To quantify the crosstalk, we define the eye-opening penalty (EOP) as:

$$\text{EOP} = 10\log_{10}\left(\frac{Best\_Eye\_Opening}{Worst\_Eye\_Opening}\right) \tag{7}$$

The bit rates of $\alpha(t)$ and $\beta(t)$ are 10 Gb/s and 1.25 Gb/s, respectively, both of them use non-return-to-zero (NRZ) encoding with PRBS $2^{31} - 1$ sequence, the subcarrier frequency changes from 14 to 18 GHz with a step of 2 GHz, and the fiber Bragg grating has a 3-dB bandwidth of 10 GHz. Figures 2 and 3 show the simulation results of EOP on recovered baseband and subcarrier signals, with a subcarrier frequency at 14 GHz. We can see that there is a performance

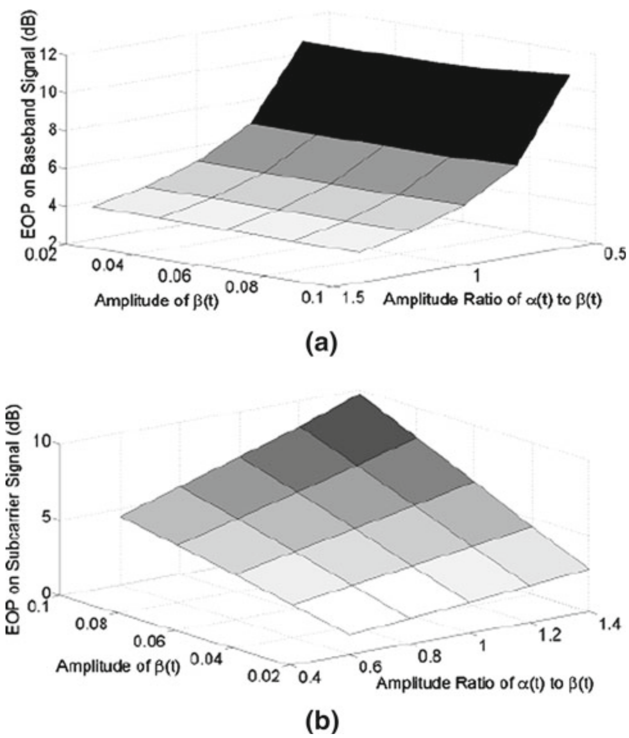

Fig. 2 Simulation results of EOP when V_{bias} is $V_\pi/8$. **a** EOP of baseband signal, $V_{\text{bias}} = \pi/8$, **b** EOP of subcarrier signal. $V_{\text{bias}} = \pi/8$

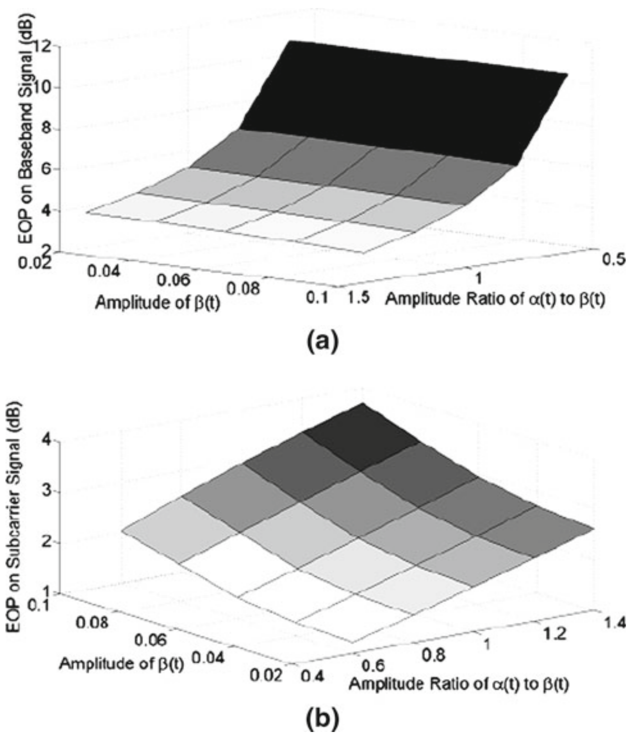

Fig. 3 Simulation results of EOP when V_{bias} is $V_\pi/4$. **a** EOP of baseband signal, $V_{\text{bias}} = \pi/4$, **b** EOP of subcarrier signal. $V_{\text{bias}} = \pi/4$

tradeoff between the baseband and the subcarrier signals. When other conditions are fixed, the EOP on the baseband signal decreases with the amplitude ratio of $\alpha(t)$ to $\beta(t)$, while larger amplitude of $\alpha(t)$ makes the EOP on the subcarrier signal worse. Surprisingly, smaller amplitude of $\beta(t)$ generally brings better system performance. This is due to the fact that smaller amplitude of $\beta(t)$ makes the nonlinear mixing terms smaller in the recovered signals. Higher bias voltage gives better performance for both the baseband and subcarrier signals, because of better linearity on the modulator transfer function. Figure 4 shows the simulated EOP curves and eye diagrams when the amplitude of $\beta(t)$ is 0.02, V_{bias} is $V_\pi/4$, and the subcarrier frequency changes from 14 to 18 GHz. The results show that larger frequency spacing provides better performance. In all, we can summarize the system optimization strategies of ODeMux SCM systems as: (1) limit the amplitude of the signal $\beta(t)$ on the subcarrier channel, (2) apply a high bias voltage toward $V_\pi/2$, and (3) use a large subcarrier frequency when possible. However, using small amplitude limits the signal's tolerance against noise distortions. High bias voltage toward $V_\pi/2$ suppresses the output power from the optical modulator and may generate second-order harmonic if the total voltage is larger than $V_\pi/2$. To further improve the transmission performance of the SCM signal in ODeMux SCM systems, we will discuss two crosstalk suppression techniques in the next section.

3 Crosstalk suppression techniques

In optical SCM systems of optical-label switching or WDM-PON, the baseband signal usually carries high-priority data with less performance margin. Therefore, our crosstalk suppression techniques target for maintaining the performance of baseband and suppressing the inter-modulation crosstalk on the subcarrier channel.

3.1 Manchester coding of baseband signal

Manchester coding the baseband signal presents one possible solution, since the DC-balanced coding scheme suppresses the low-frequency components in the crosstalk on the subcarrier channel and makes it easier for removal with a low-pass filter. We encode the baseband signal with Manchester coding and perform simulation with the worst-case scenario predicted in the analysis in Sect. 2. The subcarrier frequency is 14 GHz, the amplitude of $\beta(t)$ is 0.1, and V_{bias} is $V_\pi/8$. Figure 5 illustrates the comparisons of the eye diagrams and EOP. The NRZ case is the normal case we discussed in Sect. 2, and we plot results from it as a reference.

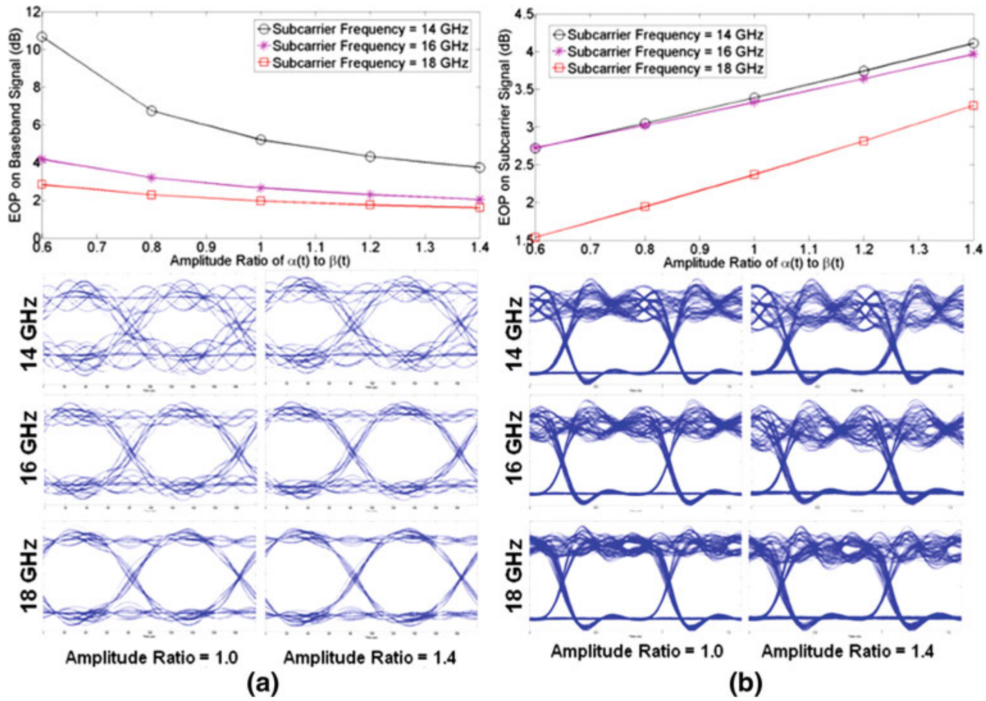

Fig. 4 Simulation results of EOP and eye-diagrams for different subcarrier frequencies. **a** baseband signal. **b** subcarrier signal

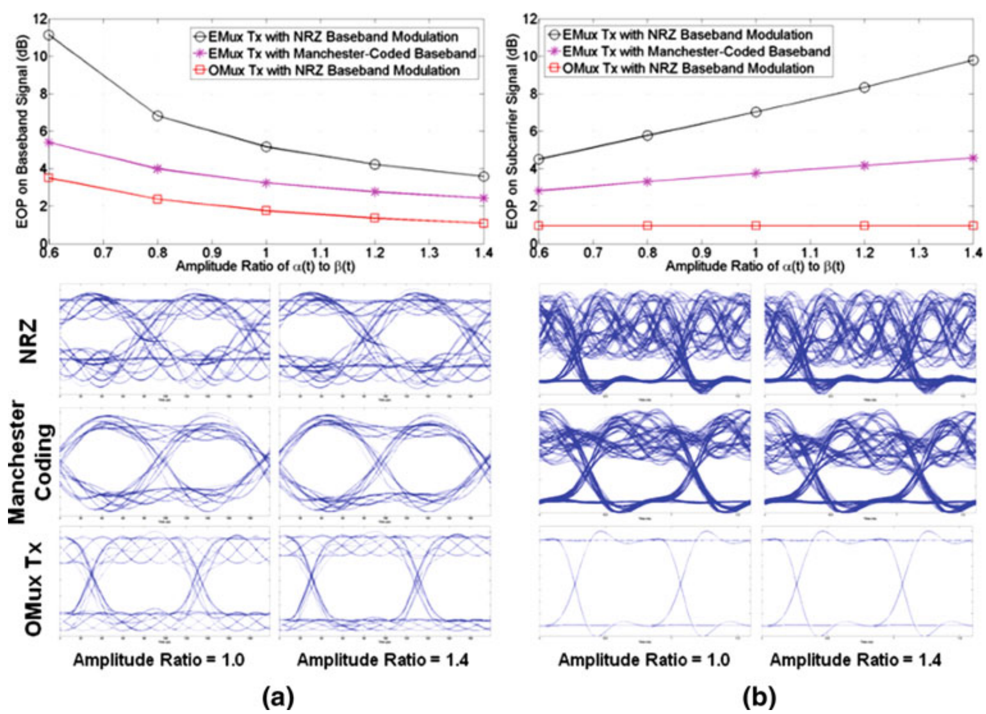

Fig. 5 Simulation results of EOP and eye-diagrams for different crosstalk suppression techniques. **a** baseband signal. **b** subcarrier signal

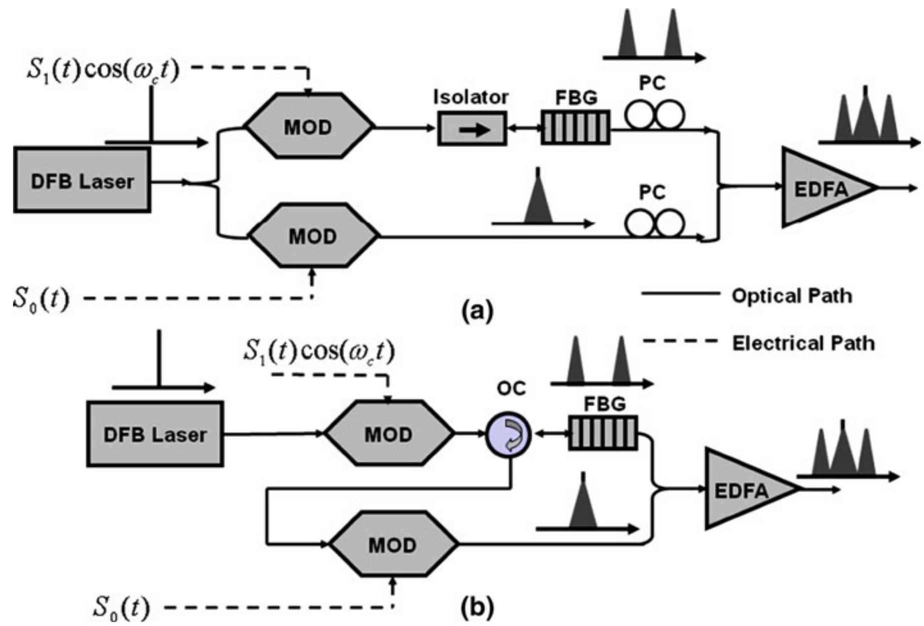

Fig. 6 SCM transmitter configurations using optical multiplexing. **a** split-and-combine scheme, and **b** reflect-and-combine scheme, PC: polarization controller

The Manchester coding can reduce the EOP by more than 4 dB for both the baseband and subcarrier signals. The eye diagrams show that the crosstalk is effectively suppressed on both channels. One major drawback of Manchester coding is that it lowers the spectral efficiency of the baseband signal. To overcome this drawback, more sophisticate DC-balanced coding schemes with higher spectral efficiency, such as 8B/10B can be explored.

3.2 Optical multiplexing in SCM transmitter

Setting up SCM transmitter with an optical multiplexing (OMux) scheme is another option. Figure 6 shows two possible configurations of OMux SCM transmitters [3,9]. Specifically, one optical modulator is dedicated to the subcarrier channel and relieves the inter-modulation crosstalk with the cost of increased transmitter complexity and price. The split-and-combine configuration in Fig. 6a has the best performance because it completely separated the optical modulations of the baseband and subcarrier signals. However, coherent interface may arise when combining the baseband and subcarrier signals optically, since the lights are from the same laser. Therefore, polarization controllers have to be included to put the signals on two orthogonal polarization states, for suppressing the coherent interface. This increases the complexity of the transmitter setup. The reflect-and-combine scheme in Fig. 6b relieves the coherent interface by making the subcarrier signal experience relatively long delay. Figure 5 also shows the simulated EOP and eye diagrams for SCM transmitter setup in Fig. 6b, and the simulation conditions are the same as in Sect. 3.1. The crosstalk on the subcarrier channel is completely removed and there is still crosstalk on the baseband, which is from the residual subcarrier channel modulation on the optical carrier fed to the second modulator. The EOP curves show that the OMux technique achieves the best crosstalk suppression, among the three systems.

4 Conclusion

In this paper, we reported an in-depth investigation of the inter-modulation crosstalk in SCM systems with optical demultiplexing (ODeMux). With both theoretical derivations and numerical simulations, we showed that the crosstalk in ODeMux systems comes from the nonlinear mixing of the baseband and subcarrier modulations. We then studied several key parameters, such as modulation amplitudes, modulator bias, and subcarrier frequency spacing and revealed their effects on the magnitude of the crosstalk. Based on the investigation, we proposed strategies for performance optimization of ODeMux SCM systems. In order to further enhance the transmission performance of ODeMux SCM systems, we discussed two techniques to suppress the inter-modulation crosstalk and demonstrated effective crosstalk suppressions.

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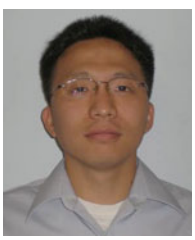
Author Biography



Zuqing Zhu received the B.S. degree from the Department of Electronic Engineering and Information Science, University of Science and Technology of China, in 2001, and the M.S. and PhD degrees from the Department of Electrical and Computer Engineering, University of California, Davis, in 2003 and 2007, respectively. His PhD research was on advanced optical switching technologies for the next-generation optical networks. From July. 2007 to January. 2011, Dr. Zhu worked in the Service Provider Technology Group of Cisco Systems, San Jose, as a senior researcher. In Cisco, he works on research and development of wide-band access routers for hybrid fiber-coaxial (HFC) cable networks and passive optical networks (PON). In January. 2011, Dr. Zhu joined the School of Information Science and Technology in the University of Science and Technology of China, as an Associate Professor. Dr. Zhu has published more than 45 peer-reviewed papers on the journals and conferences of IEEE, IEE, and OSA. Dr. Zhu currently serves as the technical program committee (TPC) member of INFOCOM 2012, ICC 2012, ICT 2011, ICC 2011, ICCCN 2011, etc. Dr. Zhu is also an editorial board member of Elsevier Journal of Optical Switching and Networking (OSN), Springer Telecommunication Systems Journal (TSMJ), Journal of Networks, International Journal of Computer Networks & Communications (IJCNC), Journal of Advances in Network and Communications (ANC), and Journal of Convergence Information Technology (JCIT). Dr. Zhu is a member of IEEE.