

Experimental Demonstration of Interference Suppression in Radio over Fiber Simultaneously Transmitted with Optical On-Off Keying

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Abstract Radio frequency (RF) and optical on-off keying (OOK) signal can be simultaneously transmitted by using the radio over fiber (RoF) link. In this link, optical OOK signal is a carrier for transmitting the RF signal. However, the OOK modulation interferes with the RF signal at the receiving side. In this paper, biased half-wave rectification is implemented using an analog electronic circuit and demonstrates interference suppression for proof-of-concept. The experiment shows that the proposal improves SNR (signal-to-noise ratio).

Keywords RoF, OOK, IM/DD, Optical Ethernet

1. Introduction

The radio over fiber (RoF) technique enables centralized operation of several small-cell base stations for heterogeneous wireless service, cooperative distributed antenna system, large transmission capacity, reduction of maintenance cost. The typical RoF link employs intensity modulation/direct detection (IM/DD). The IM has two options. Radio frequency (RF) signal directly modulates the laser diode (LD) or externally modulates the light source. The RF signal is detected by a photodetector (PD) after the transmission over optical fiber channel. Meanwhile, the 10 Gbps Ethernet infrastructure is widely used in in-building local area network (LAN). Since the additional installation of the RoF link needs the cost to establish dedicated equipment such as optical light sources and optical fibers, simultaneous transmission of BB signal and RF signal is one of major studies in RoF[1]-[4]. These studies aim at share infrastructure and realize quick and cost effective implementation for independent different types of networks.

Optical On-Off Keying (OOK) modulation for baseband (BB) transmission is employed in 10 Gbps Ethernet PHY layer. In previous papers[1]-[3], the frequency band of RF signal is higher than the main lobe of the OOK spectrum. Since the frequency bands of major cellular systems and Wireless LAN (WLAN) such as Long-Term Evolution (LTE) and WiFi are assigned at lower than 10 GHz, investigation for coexistence of the radio systems with frequency lower than 10 GHz and 10 Gbps optical BB signal is required. Chen et al.[4] investigated simultaneous transmission of 10 Gbps OOK signal and RF signal at 2 GHz. Their scheme uses an unique coding based on 8B10B. Therefore implementing their scheme with existing Ethernet devices which conforms to the current 10 Gbps Ethernet standard employing 64B66B

is difficult. Moreover, their scheme is inflexible for radio frequency.

Previous study[5] has proposed a configuration of RoF link with optical OOK signal. The lightwave is used as a carrier for not only BB transmission, but also RF signal transmission. When the OOK signal has broad bandwidth, and it interferes with the RF signal, an interference suppression scheme using biased half-wave rectification has also proposed[5]. However, its improvement in terms of SNR (signal-to-noise ratio) is shown by only computer simulation with ideal rectification, i.e. neglect of reverse recovery time and nonlinearity of diode. In this paper, an experiment is conducted to assess an interference suppression using electronic circuit. The experiment shows that the proposed scheme improves SNR of receiving RF signal.

2. System Description

Fig. 1 shows the configuration of RoF link with optical OOK signal. A pair of 10 Gbps Ethernet switches is connected by optical fiber links. The transmitted optical stream is re-used as a carrier for intensity modulation for RF signal. The OOK is employed as a modulation format of 10 Gbps Ethernet. The amplitude of RF signal is mapped onto the optical pulse using an external optical modulator (EOM). The proposed system is called as radio over optical OOK (RoOOOK).

At the receiving side, optical signal is divided into two branches using an optical coupler (OC). One branch is led to the OOK demodulator to establish the Ethernet link. The other signal is fed into the optico-to-electric (O/E) converter. Since the obtained photo current is still waveform of pulsed RF signal, the electric band-pass filter (BPF) is used to regenerate the original RF signal and then wireless service is provided.

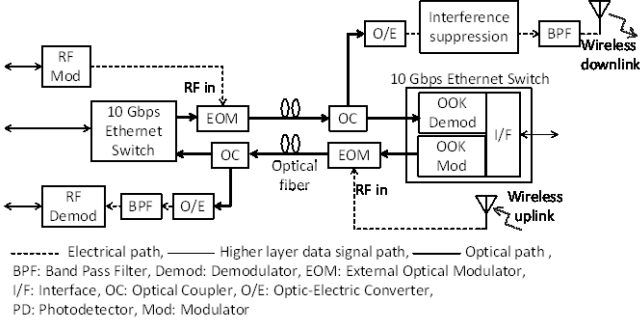


Fig. 1 Radio over Optical OOK (RoOOOK) using 10 Gbps Ethernet.

In the viewpoint of RF signal transmission, it can be considered as the band-pass sampling and regeneration, because the RF signal is sampled by the random pulse sequence. Therefore, the spectrum analysis with stochastic process can be available.

3. Power Spectrum Analysis

Fig. 2 shows the external re-modulation of the OOK signal. Consider $p(t)$ as the rectangular pulse waveform taking 1 or 0 with its duration of $1/f_p$, $s_r(t)$ as the RF signal, B as the amplitude of pulses, and $0 \leq m \leq 1$ as the modulation index. The re-modulated OOK signal is expressed as,

$$v(t) = \{1 + ms_r\}Bp(t). \quad (1)$$

The autocorrelation function of $v(t)$, $R_v(\tau)$, is expressed as,

$$R_v(\tau) = B^2 R_p(\tau) + m^2 B^2 R_p(\tau) R_s(\tau), \quad (2)$$

where τ is the time lag, $R_p(\tau)$ is the autocorrelation function of $p(t)$, and $R_s(\tau)$ is the autocorrelation function of $s_r(t)$. On the basis of Wiener-Khinchin theorem, the Fourier transform of (2), $G_v(f) = \mathcal{F}[R_v(\tau)]$, is the power spectral density (PSD) of the transferred signal. Assuming that the OOK signal is non return-to-zero OOK (NRZ-OOK) bit sequence, any bits are statistically independent, and the probability of occurrence for mark ($p(t) = 1$) is ρ , then

$$G_v(f) = B^2 \rho \delta(f) + B^2 \frac{\rho(1-\rho)}{f_p} \text{sinc}^2\left(\frac{f}{f_p}\right) + m^2 B^2 \rho^2 G_s(f) + m^2 B^2 \frac{\rho(1-\rho)}{f_p} \text{sinc}^2\left(\frac{f}{f_p}\right) * G_s(f), \quad (3)$$

where $G_s(f)$ is the Fourier transform of $R_s(\tau)$ and the operator $*$ means convolution. The first term on the right-hand side of (3) is the DC component. The second term is the OOK component. The third term is the RF signal. The fourth term is the noise caused by the sampling of the RF signal, thus we call this term alias. The peak amplitude of $s_r(t)$ is normalized to 1 and the power of RF signal is considered as a combination of m , B , and S_s which is the power of $G_s(f)$. S_s equals 1/2 when $s_r(t)$ is a sinusoidal wave. Fig. 3 shows an example of PSD.

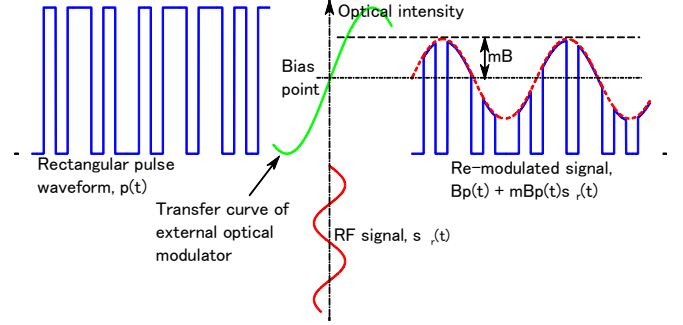


Fig. 2 OOK signal externally re-modulated by RF signal.

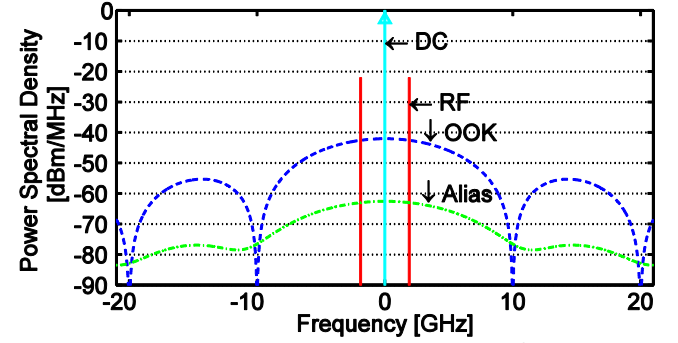


Fig. 3 Power spectral density of RoOOOK ($f_p = 10$ Gbps, $f_r = 1.9$ GHz, $W = 384$ kHz, $B = 0.05$ V, and $m = 0.1$).

Assuming that $G_s(f)$ has a center frequency f_r and the occupied bandwidth W . S is the total power after through BPF,

$$S = \left(\int_{-f_r-W/2}^{-f_r+W/2} + \int_{f_r-W/2}^{f_r+W/2} \right) G_v(f) df. \quad (4)$$

The SNR of the RF signal is expressed as a function of m and ρ ,

$$\gamma(m, \rho) = \frac{m^2 B^2 \rho^2 S_s}{S - m^2 \rho^2 B^2 S_s + N_0 W f_s}, \quad (5)$$

where f_s is the symbol rate of the RF signal, and N_0 is the one-sided power spectral density of the thermal noise. Theoretical EVM is obtained from the relation of average EVM and SNR[6],

$$\text{EVM} \cong 1/\sqrt{\text{SNR}} = 1/\sqrt{\gamma(m, \rho)}, \quad (6)$$

A typical value of ρ is considered as 1/2 because the occurrence for mark ($p(t) = 1$) and space ($p(t) = 0$) are equiprobable. The incident RF power to EOM is related to m ,

$$m = \frac{\sqrt{2} V_{\text{rms}}}{V_{\pi}/2}, \quad (7)$$

where V_{rms} is the root mean square voltage of RF signal and V_{π} is the half-wave voltage of the EOM.

4. Interference Suppression Using Rectification

4.1 Biased half-wave rectification

As shown in Fig. 3, a spectral component of OOK interferes with an RF signal and deteriorates SNR. For RF signal transmission, as shown in Fig. 2, the upper part of re-modulated OOK signal transfers the RF

signal. The under part of re-modulated OOK signal is a pure OOK signal. It does not transfer the RF signal component, however, it contains a wide band frequency spectrum, and interferes with the RF signal. Therefore, to remove the under part of re-modulated OOK signal suppresses the interference. In this section, an interference suppression scheme proposed in previous study[5] is detailed. The proposal outperforms the conventional in terms of EVM.

Biased half-wave rectification can reduce the OOK component. Fig. 4 shows the proposed interference suppression scheme using biased half-wave rectification. The received signal is biased by $(1 - m)B$ and then it is half-wave rectified. The biased half-wave rectified signal is expressed as,

$$\begin{aligned} v_b(t) &= mBp(t) + mBp(t)s_r(t) \\ &= \{1 + m_b s_r(t)\}B_b p(t), \end{aligned} \quad (8)$$

where $m_b = 1$ and $B_b = mB$. Therefore, the biased half-wave rectification is equivalent to make the modulation index of 1. The SNR of the biased half-wave rectified signal is obtained from substituting m_b and B_b for m and B in (5), respectively. Some physical properties of rectifier e.g., reverse recovery time and nonlinearity of diode are ignored in this section.

4.2 Simulation result

Fig. 5 shows a simulation result of PSDs of the conventional and the proposal at $m = 0.1$. The bit rate of OOK signal is 10 Gbps, the pulse amplitude $B = 0.05$ V, the pulse pattern is pseudo random bit sequence (PRBS) of order 31, the RF signal is a sinusoidal wave of frequency 1.9 GHz. This simulation ignores the thermal noise. As a result of the biased half-wave rectification, the amplitude of the OOK signal is m times of the original signal. In this simulation, the biased half-wave rectification suppresses the OOK signal by about 20 dB around 2 GHz. Fig. 6 shows theoretical EVM curves and simulation results of conventional and proposal. Theoretical curves of EVM versus incident RF power to EOM is drawn by Eqs.(6) and (7). Simulation parameters are $\rho = 1/2$, $V_\pi = 5$ V, $W = 384$ kHz, $f_s = 192$ kbaud, and $N_0 = -60$ dBm/MHz. Fig. 6 shows that the biased half-wave rectification improves EVM by about 20 dB. Therefore, the required minimal incident RF power can be reduced by 20 dB compared with the conventional.

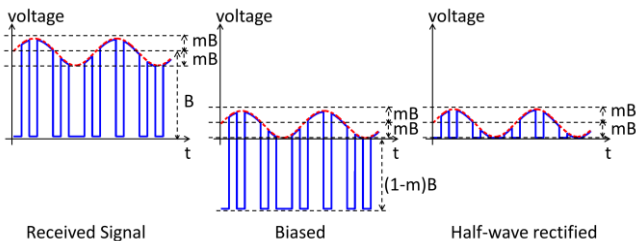


Fig. 4 The waveform of biased half-wave rectified signal.

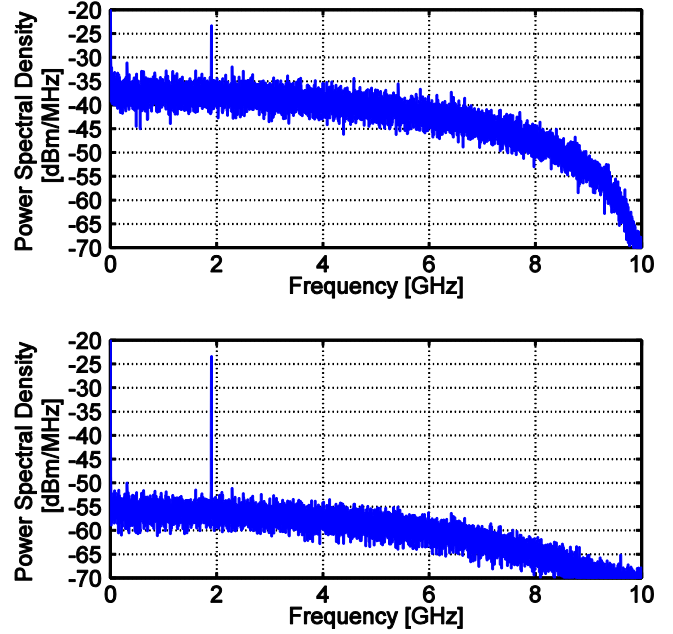


Fig. 5 The power spectral density of conventional RoOOK (top) and biased half-wave rectified RoOOK (bottom) at $m = 0.1$.

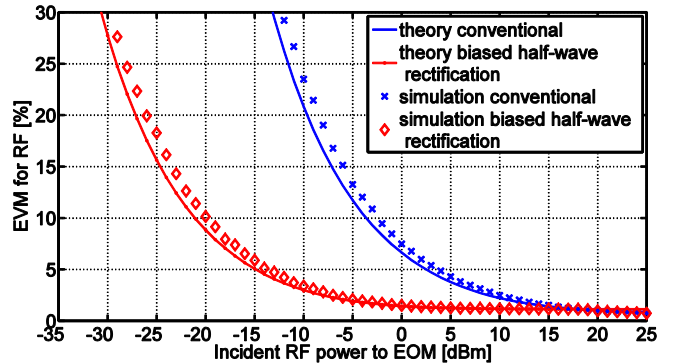


Fig. 6 Relationship between EVM and incident RF power to EOM at $N_0 = -60$ dBm/MHz.

5. Experiment

Fig. 7 shows the experimental setup. The radio CW (continuous wave) is externally modulated using Mach-Zehnder modulator (MZM) driven by BB electric OOK signal of PN14. This signal simultaneously transmitting RoF and OOK is sampled by a sampling oscilloscope with a sampling rate of 1 GSa/s. The carrier frequency of RoF signal was 9.5 MHz, and the bitrate of BB OOK was 50 Mbps. These are downscaled parameters of those in previous study[1], which are 1.9 GHz and 10 Gbps. The average received optical power at photodetector (PD) was about -3 dBm. The modulation index m at PD was about 0.15. Fig. 8 shows an interference suppression circuit composed of electric amplifier, bias tee, and rectifier. Fig. 9 shows a comparison of power spectral densities. The RF power is normalized to 0 dB. The SNR after through the interference suppression circuit is about 8 dB higher than that of the original signal.

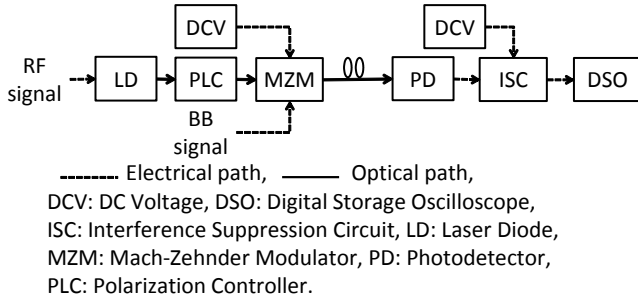


Fig. 7 Experimental setup.

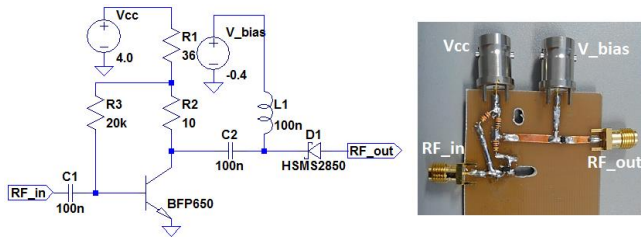


Fig. 8 Interference suppression circuit.

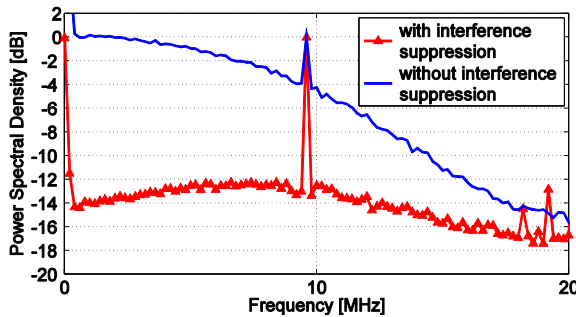


Fig. 9 Comparison of Power spectral density.

6. Conclusion

In this paper, the experiment is conducted to assess an interference suppression using electronic circuit for RoF simultaneously transmitted with optical OOK. At first, RoF link simultaneously transmitting BB OOK is described. The power spectrum analysis shows that the OOK signal interferes with the RF signal. The interference suppression scheme using biased half-wave rectification is detailed. The interference suppression is implemented using an analog electronic circuit, and is demonstrated for proof-of-concept. The experiment shows that the proposed scheme improves SNR of receiving RF signal by about 8 dB.

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