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Performance evaluation of radio over fiber link simultaneously transmitted with 10 Gbps on-off keying signal

Yuya Kaneko[a)], Takeshi Higashino, and Minoru Okada

Graduate School of Information Science, Nara Institute of Science and Technology, 8916–5 Takayama-cho, Ikoma-shi, Nara 630–0192, Japan

a) *kaneko.yuya.kr2@is.naist.jp*

Abstract: Analog type radio over fiber (RoF) link transports radio frequency (RF) signal composed of different kind of frequency. Although previous papers have reported the transmitting multiple frequency signals using single wavelength without overlapping in electrical frequency domain, this paper assumes seriously contaminated channel for transmitting RF signal so that RF signal locates center frequency in main lobe of baseband (BB) signal. Specifically, this paper proposes RF signal transmission with 10 Gbps optical BB signal. Since RF signal is superimposed onto the optical BB signal, no additional light source is required. In addition, RF signal is naturally bandpass-sampled by random nonuniform sequence, therefore stochastic analysis is required. This paper derives error vector magnitude (EVM) of digitally modulated RF signal when the signal is simply regenerated by using bandpass filter. It is shown that theoretical analysis agrees with experimental results.

Keywords: radio over fiber, on-off keying, optical Ethernet, nonuniform sampling, error vector magnitude

Classification: Optical systems

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1 Introduction

The radio over fiber (RoF) offers small base stations, centralized operation for heterogeneous wireless service, cooperative distributed antenna system, and large transmission capacity. The modulation and detection scheme employed in analog type RoF link is the intensity modulation/direct detection (IM/DD). In the IM/DD link, radio frequency (RF) signal directly modulates the laser diode (LD) or externally modulates the optical carrier. The RF signal is detected using a photodetector (PD) after the transmission over optical fiber channel. Meanwhile, optical on-off keying (OOK) modulation for baseband (BB) transmission is employed in 10 Gbps Ethernet PHY layer. The 10 Gbps Ethernet is widely spread in in-building local area network (LAN). Since additional installation of the RoF link into building requires dedicated devices such as light sources and optical fibers, simultaneous transmission of BB signal and RF signal is one of notable studies in RoF [1, 2, 3, 4, 5, 6, 7, 8, 9]. It enables independent different types of network to share communication infrastructure.

In previous papers [1, 2, 3], center frequency of RF signal is higher than the main lobe of the BB spectrum. Since the frequency channels of current cellular system and WiFi are mainly assigned at lower than 10 GHz, this paper assumes seriously contaminated channel for transmitting RF signal so that RF signal locates center frequency in main lobe of baseband signal. Chen et al. [9] employed specific channel coding based on 8B10B for encoding BB signal to make spectral notches. However, their scheme does not ensure compatibility with existing Ethernet, because current 10 Gbps Ethernet standard employs the 64B66B. In addition to channel coding, their scheme is inflexible for frequency allocation.

This paper proposes a new configuration of RF signal transmission with 10 Gbps optical BB signal. Since RF signal is superimposed onto the optical BB signal, no additional light source is required. In addition, RF signal is naturally bandpass-sampled by random nonuniform sequence, therefore stochastic analysis is required. Previous papers [10, 11] have derived power spectrum of random nonuniform samples and signal to noise power ratio (SNR), however, experimental investigation have not conducted. This paper derives error vector magnitude (EVM) of digitally modulated RF signal when the signal is simply regenerated by using bandpass filter. It is shown that theoretical analysis agrees with experimental results. In addition, proposal achieves low EVM of less than 5% even though center frequency of RF signal is varied between 1 to 3 GHz.

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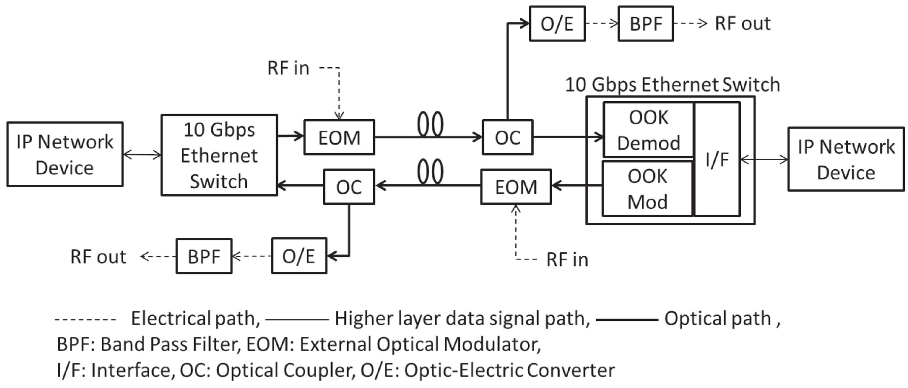

Fig. 1. Radio over optical OOK (RoOOOK) using 10 Gbps Ethernet.

The rest of this paper is organized as follows. Section 2 describes the configuration of proposal. Sections 3 and 4 show the theoretical analysis and experiment. Section 5 concludes this paper.

2 System description

Fig. 1 shows the configuration of radio over optical OOK (RoOOOK). A pair of 10 Gbps Ethernet switches is connected by optical fibers. The optical signal transmitted from one of switches is led to an external optical modulator (EOM). The modulation scheme of Ethernet is OOK. The amplitude of RF signal is superimposed onto the optical intensity.

At the receiving side, optical signal is divided into two branches using optical coupler (OC). One is led to the OOK demodulator in the Ethernet switch. The other is led to the optic-to-electric (O/E) converter for detecting the RF signal. The electric band-pass filter (BPF) followed by O/E converter suppresses the wide band BB signal spectrum and pass through the desired RF signal component.

3 Theoretical analysis

Fig. 2 illustrates the process of external re-modulation at EOM as shown in Fig. 1. Let us suppose that $\Pi(t)$ is the rectangular function, $T_p = 1/f_p$ is the duration of a pulse, $s_r(t)$ is the RF signal, B is the amplitude of pulses, and $0 \leq m \leq 1$ is the optical modulation index. The re-modulated OOK signal can be represented by,

$$v(t) = \{1 + ms_r(t)\}B \sum_{k=-\infty}^{\infty} b_k \Pi\left(\frac{t}{T_p} - k\right) = \{1 + ms_r(t)\}Bp(t), \tag{1}$$

where $b_k \in 0, 1$ is the bit stream, and $p(t) = \sum_{k=-\infty}^{\infty} b_k \Pi(t/T_p - k)$ is the optical OOK signal waveform. When the Mach-Zehnder intensity modulator (MZM) is employed as EOM, the optical modulation index m is defined as

$$m = \frac{\sqrt{2}V_{\mathrm{rms}}}{V_\pi/2}, \tag{2}$$

where V_{rms} is the root mean square voltage of incident RF signal and V_π is the half-wave voltage of MZM. Assuming that $v(t)$ is wide-sense stationarity and real function, the autocorrelation function of $v(t)$, $R_v(\tau) = E[v(t)v(t-\tau)]$, is expressed as,

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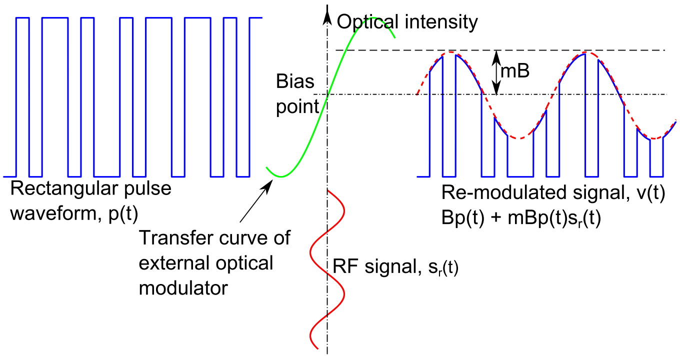

Fig. 2. OOK signal externally re-modulated by RF signal.

$$R_v(\tau) = B^2E[p(t)p(t-\tau)] + mB^2E[p(t)p(t-\tau)s_r(t-\tau)] + mB^2E[p(t-\tau)p(t)s_r(t)] + m^2B^2E[p(t)s_r(t)p(t-\tau)s_r(t-\tau)], \tag{3}$$

where τ is the time lag, $E[\cdot]$ is the expectation operator. When $p(t)$ and $s_r(t)$ are statistically independent,

$$R_v(\tau) = B^2R_p(\tau) + mB^2R_p(\tau)E[s_r(t-\tau)] + mB^2R_p(\tau)E[s_r(t)] + m^2B^2R_p(\tau)R_s(\tau), \tag{4}$$

where $R_p(\tau)$ and $R_s(\tau)$ are the autocorrelation function of $p(t)$ and $s_r(t)$, respectively. Generally, $E[s_r(t)] = 0$, then the autocorrelation function of $v(t)$ can be simplified to

$$R_v(\tau) = B^2R_p(\tau) + m^2B^2R_p(\tau)R_s(\tau). \tag{5}$$

If bit generation of b_k is statistically independent, and the probability of occurrence for mark ($b_k = 1$) is ρ, then $R_p(\tau) = \rho^2 + \rho(1-\rho)\Lambda(f_p\tau)$, where $\Lambda(x)$ is the triangular function,

$$\Lambda(x) = \begin{cases} 1-|x| & (|x| \le 1) \\ 0 & (|x| > 1) \end{cases}. \tag{6}$$

A value of ρ is 0.5 when the mark ($p(t) = 1$) and space ($p(t) = 0$) are equiprobable occurrence. The Fourier transform of Eq. (5), $G_v(f) = \mathcal{F}[R_v(\tau)]$, or the power spectral density (PSD) of $v(t)$, is expressed as,

$$G_v(f) = B^2\left\{\rho^2\delta(f) + \frac{\rho(1-\rho)}{f_p}\,\mathrm{sinc}^2\left(\frac{f}{f_p}\right) + m^2\rho^2G_s(f) + m^2\frac{\rho(1-\rho)}{f_p}\,\mathrm{sinc}^2\left(\frac{f}{f_p}\right) * G_s(f)\right\}, \tag{7}$$

where $G_s(f)$ is the Fourier transform of $R_s(\tau)$, and $*$ denotes the convolution operator. In the right-hand side of Eq. (7), the first, second, third, and fourth terms respectively correspond to the DC component, the power spectrum of the OOK signal, the RF signal, and the noise caused by the sampling. The fourth term is referred to as “alias” component in the following, because it includes the original signal.

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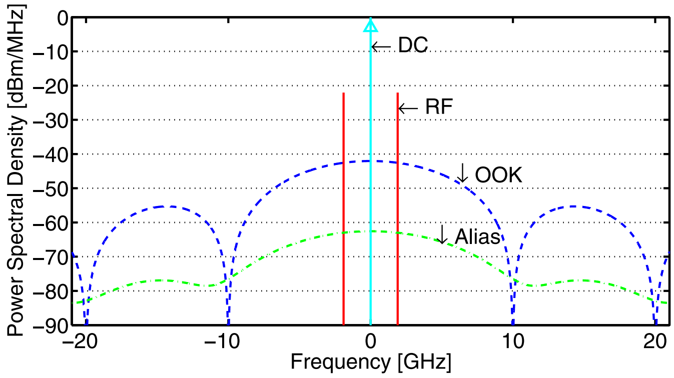

Fig. 3. Power spectral density ($f_p = 10$ Gbps, $f_r = 1.9$ GHz, $W = 384$ kHz, $B = 0.05$ V, and $m = 0.1$).

RF signal power at the output of the BPF depends on m, B, and $S_s = E[|s_r(t)|^2]$. Fig. 3 shows a power spectral density (PSD) when $f_p = 10$ Gbps, $f_r = 1.9$ GHz, $W = 384$ kHz, $B = 0.05$ V, and $m = 0.1$. The main lobe of the OOK signal spreads over DC to 10 GHz and interferes with the RF signal. Although the alias component also has wide bandwidth, its power density is much less than that of the OOK signal. Therefore, the OOK signal is the dominant interference for the RF signal.

Denoting that the center frequency and occupied bandwidth of $G_s(f)$ are f_r and W, respectively. Assuming that BPF is designed to pass all the RF signal component and suppress all the unwanted signal components outside of the RF signal spectrum. The signal power after passing through BPF, S is,

$$S = B^2\rho(1-\rho)S_p + m^2B^2\rho^2S_s + m^2B^2\rho(1-\rho)S_a, \tag{8}$$

where

$$S_p = \frac{2}{f_p}\int_{f_r-W/2}^{f_r+W/2} \mathrm{sinc}^2\left(\frac{f}{f_p}\right)\mathrm{d}f, \tag{9}$$

is the OOK signal, and

$$S_a = 2\frac{2}{f_p}\int_{f_r-W/2}^{f_r+W/2} \mathrm{sinc}^2\left(\frac{f}{f_p}\right) * G_s(f)\mathrm{d}f, \tag{10}$$

is the alias component.

The SNR of the RF signal can be represented by,

$$\gamma = \frac{m^2B^2\rho^2S_s}{B^2\rho(1-\rho)(S_p + m^2S_a) + N_0W}\frac{W}{f_s}, \tag{11}$$

where f_s is the symbol rate of the RF signal, and N_0 is the one-sided power density of the thermal noise. Assuming that the thermal noise is negligible compared to the alias, that is, $B^2\rho(1-\rho)(S_p + m^2S_a) \gg N_0W$,

$$\gamma \simeq \frac{m^2\rho S_s}{(1-\rho)(S_p + m^2S_a)}\frac{W}{f_s}. \tag{12}$$

This implies that SNR is independent of B in case of high SNR. In that case the SNR is determined by the modulation index m.

Supposing that $W \ll f_p$, $G_s(f)$ is simplified to $G_s(f) \simeq \delta(f - f_r)/2 + \delta(f + f_r)/2$. Substituting this approximation to Eq. (10),

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Table I. Specification of the equipments.

XFP spec.	
PHY Std.	10GBASE-ER
Tx. power	0 dBm
Rx. sensitivity	−16 dBm
RF spec.	
Carrier freq. f_r	1.9 GHz
Bit rate	384 kbps
Modulation	$\pi/4$ QPSK
LPF	root Nyquist, $\alpha = 0.5$
Optical system spec.	
λ	1550 nm
fiber	SMF
V_π	5 V

$$S_a = \frac{1}{2f_p}\int_{-f_r-W/2}^{-f_r+W/2}\left\{\mathrm{sinc}^2\left(\frac{f+f_r}{f_p}\right)+\mathrm{sinc}^2\left(\frac{f-f_r}{f_p}\right)\right\}\mathrm{d}f + \frac{1}{2f_p}\int_{f_r-W/2}^{f_r+W/2}\left\{\mathrm{sinc}^2\left(\frac{f-f_r}{f_p}\right)+\mathrm{sinc}^2\left(\frac{f+f_r}{f_p}\right)\right\}\mathrm{d}f = \int_{-\frac{W}{2f_p}}^{\frac{W}{2f_p}}\left\{\mathrm{sinc}^2\,\xi+\mathrm{sinc}^2\left(\xi+\frac{2f_r}{f_p}\right)\right\}\mathrm{d}\xi. \tag{13}$$

According to mean-value theorem, there exists x satisfying the following equation,

$$S_a = \frac{W}{f_p}\left\{\mathrm{sinc}^2\,x+\mathrm{sinc}^2\left(x+\frac{2f_r}{f_p}\right)\right\}\quad\left(-\frac{W}{2f_p}\le x\le\frac{W}{2f_p}\right). \tag{14}$$

x is approximately equal to 0 when $W \ll f_p$, then,

$$S_a \simeq \frac{W}{f_p}\left\{1+\mathrm{sinc}^2\left(\frac{2f_r}{f_p}\right)\right\}. \tag{15}$$

If $f_r \ll f_p$ then $\mathrm{sinc}^2(2f_r/f_p) \simeq 1$ and $S_a \simeq 2W/f_p$. The same approach can be applied to S_p, then $S_p \simeq 2W/f_p$. Eq. (11) is simplified to

$$\gamma \simeq \frac{m^2B^2\rho^2S_s}{B^2\rho(1-\rho)(1+m^2)(2W/f_p)+N_0W}\,\frac{W}{f_s}. \tag{16}$$

Eq. (12) can be rewritten by,

$$\gamma = \frac{m^2\rho f_pS_s}{2(1-\rho)(1+m^2)f_s}. \tag{17}$$

In the digital modulation, relationship between EVM and SNR over AWGN (additive white Gaussian noise) channel is given by [12], EVM $\simeq 1/\sqrt{\gamma}$.

4 Experiment

Table I shows the specification of the experimental setup. Fig. 4 shows the experimental setup. Two types of setup have prepared. The left side shows reference system for the IM/DD RoF with external modulation (EM) using

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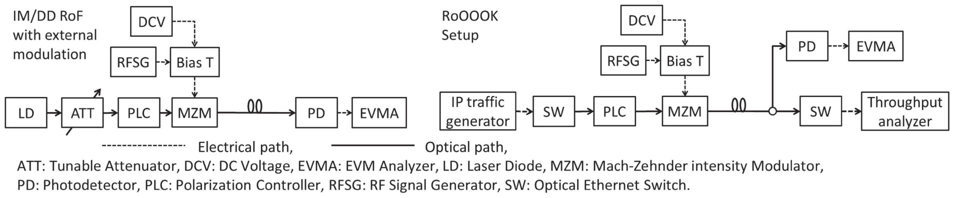

Fig. 4. Experimental setup.

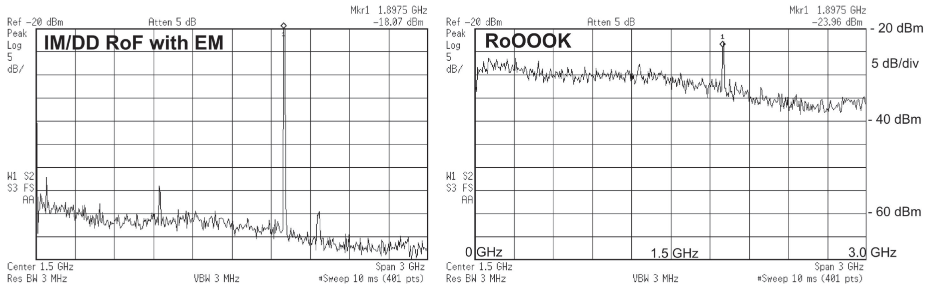

Fig. 5. Power spectral density of IM-DD RoF with external modulation (left) and RoOOOK (right), RBW = 3 MHz, RLV = −20 dBm, RF in = 0 dBm.

continuous wave (CW) light source. The right side shows proposed. The optical signal from Ethernet switch is led to the MZM after controlling its polarization by polarization controller (PLC). The DC-biased RF signal is led to MZM to modulate the light. At the receiving side, the received optical signal is divided into two branches. One is led to the Ethernet receiver and the other is led to the photo detector (PD). The photo current is then analyzed to evaluate the degradation of modulation. IP traffic generator connected with Ethernet link using category 5e cable. UDP (user datagram protocol) load of 800 Mbps continuously sent. The throughput was measured by analyzer at the receiver side. Since the average optical power emitted from the LD is higher than that of the Ethernet switch. A tunable attenuator adjusted the optical power to be equal to the peak value of light from Ethernet switch. Total optical power loss between switches including connector loss, fiber loss, insertion loss of MZM, and splitting loss was 11 dB.

Fig. 5 shows the measured PSDs for both setups at the output of PD in Fig. 4. The RF signal power in proposal is less than the reference by 6 dB. It is caused by the 3 dB difference of the average incident optical power to EOM. This 3 dB difference is caused by equiprobable occurrence of mark and space. The BB spectrum interferes with the RF signal. It corresponds to the analysis shown in Eq. (7) and Fig. 3.

Fig. 6 shows a comparison between the theory and the experiment in EVM. The cyan dashed line (theory approx.) and magenta solid line (theory) correspond to the EVM calculated by Eqs. (11) and (17), respectively. The theoretical curves agree with the experimental results. The EVM can be improved by increasing the incident RF power. Fig. 6 also measured throughput of IP traffic. It is found that the maximum allowable incident RF power not to be outage the Ethernet link is 6 dBm. The required EVM was 12.5% in this experiment, because the personal handy phone system (PHS) was employed as an RF standard. As shown in Fig. 6, the

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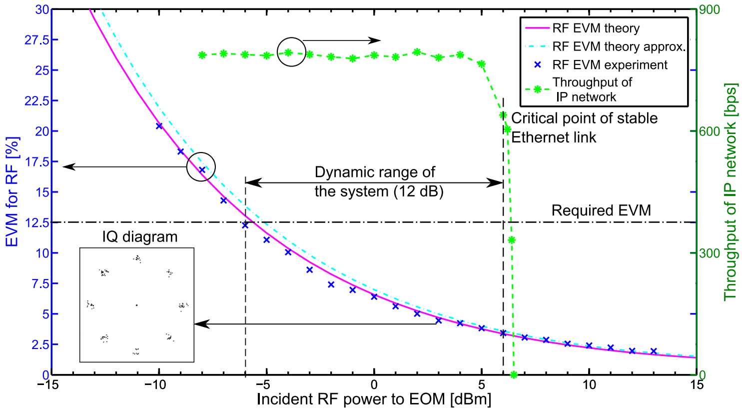

Fig. 6. Relationship between RF EVM, throughput of IP traffic, and incident RF power to EOM.

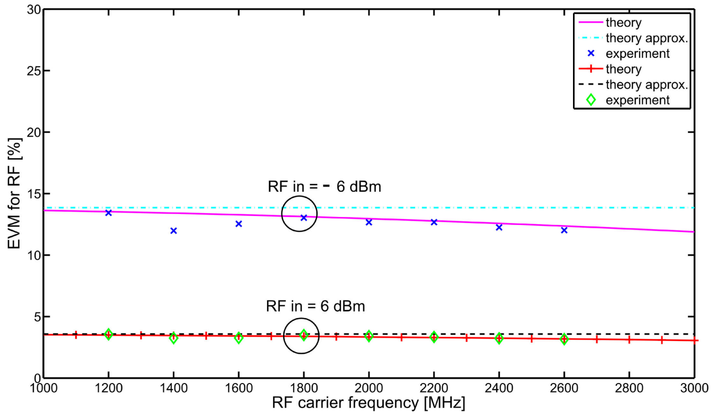

Fig. 7. Relationship between EVM and carrier frequency of RF signal.

minimum value of RF power to achieve required EVM is −6 dBm. As a result, the input RF signal power to EOM should be ranged from −6 dBm to 6 dBm.

Fig. 7 shows the relationship between EVM and carrier frequency of RF signal. Theoretical curves agree with the experimental results. The EVM slightly depends on frequencies in the range between 1 GHz and 3 GHz. The maximum allowable incident RF power also slightly depends on frequencies. Therefore, it is found that proposal enables the carrier frequency to be flexibly allocated compared to previous method [9].

5 Conclusion

This paper proposed a new RoF link and investigated coexistence for optical BB signal and RF signal when the frequency of RF signal is within the main lobe of BB spectrum. Theoretical analysis has been compared with the experiment and it corresponded with each other. The external re-modulation of Ethernet signal with high power RF results in service outage for 10 Gbps Ethernet link, however, both signals can coexist and share a single fiber channel with the dynamic range of 12 dB. Proposed link can be easily established without light source and fiber-optics in current Ethernet.

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