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Signal to Noise Ratio Penalty Analysis for Radio over Free Space Optical Systems

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ABSTRACT
Due to ever-increasing demand for capacity and quality in wireless communication links, lead to inspire researchers to innovate new design methodologies and concepts over wireless systems and networks with the ultimate aim of achieving a next-generation network. These researches must ensures data rates similar to those offered by optical fiber systems but at the fraction of its deployment cost. Among the emerging technologies is the new innovative radio on free-space optics system, referred to as Radio over Free Space Optics (RoFSO), which is the main interest of this paper. RoFSO systems have been recognized as a promising wireless interconnecting technology. Such system combines the radio over fiber (RoF) technology comprising heterogeneous wireless services and Fiber Space Optics (FSO) link. In this paper, an analytical time-domain model is presented to analyze the radio over free space optical (RoFSO) systems considering scintillation effect with the log-normal distribution. This analytical model uses a dual-drive Mach-Zehnder modulator (DD-MZM) and photodetector (PD) for optical single sideband (OSSB) signals.

Keywords
Radio over Free Space Optics (RoFSO), Channel Analysis, SNR Penalty

1. INTRODUCTION
The RoFSO system is implemented by simply combining a new-generation FSO system with radio over fiber (RoF) technology. RoF implementation is dependent on availability of installed optical fiber cables. In the absence of fiber infrastructure, the RoFSO systems can be conveniently applied.

RoFSO is a laser driven technology that entails the transmission of information laden optical radiations as the carrier signal through the atmospheric channel. FSO supports the richness of large capacity usage (data, voice, and video) which can effectively make clear last mile access network problem for a foreseeable future. FSO is the potential leading technology as an adjunct to conventional radio frequency (RF) wireless links offering a cost effective, unlicensed spectrum and secure communication. However, this comes at the cost of a number of challenges such as substantial optical signal losses due to the atmospheric absorption and scintillations that require serious considerations [1] [3].

At present, the FSO spectrum band doesn't required regulations and therefore are relatively inexpensive compared to the RF licensed spectrum. This implies that providers can incorporate FSO in their system since the initial set-up cost is lower and the deployment time is shorter.

Recently, free space optical (FSO) systems are actively researched to support future broadband access networks [4]. Especially, FSO systems are on high demand in tactical military communications due to the increasing bandwidth requirements particularly for the transmission of high resolution imagery acquired by tactical sensors. FSO communication technology has been successfully utilized to offer high-speed digital transmission for a variety of applications. It can provide a cost effective alternative to fiber optical systems in last mile applications, enterprise connectivity, metro network extension, fiber backup.

In this paper the SNR penalty due to fiber chromatic dispersion and phase noises from a laser and an RF oscillator using an optical single sideband (OSSB) signal and a direct-detection scheme is calculated [2]. For the analysis of the SNR penalty, the autocorrelation and the PSD function of a received photocurrent are evaluated. The bandwidth of an electrical filter is dealt in the SNR penalty since the phase noises result in an increase of the required bandwidth and the increased bandwidth causes an additional SNR penalty. It is shown that the phase noise from the RF oscillator, rather than that from the laser, is relatively the dominant parameter in a short optical distance . In RoFSO systems, a dual-drive Mach-Zehnder modulator (DD-MZM) has been widely used for high data rate services since it is robust against laser chirp while providing high spectral efficiency [1].

2. ANALYTICAL TIME-DOMAIN MODEL FOR RoFSO SYSTEMS

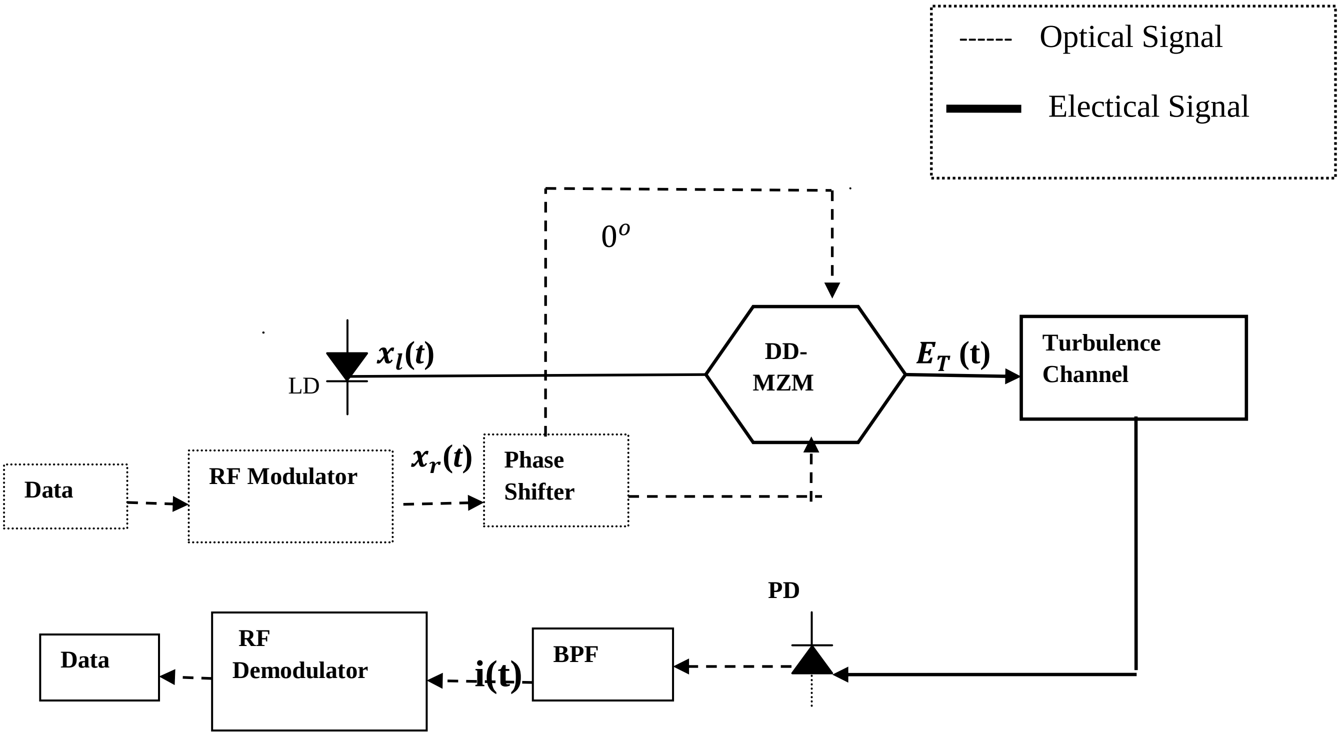

Figure 1: Overall architecture of the radio over FSO system considering of optical transmitter, turbulence channels, and optical receiver [1]

Figure 1 shows the overall architecture of the RoFSO system. A RF signal from the RF modulator is split by a phase shifter. This RF signal is injected directly into the DD-MZM as shown.

The output signal of the DD-MZM is transmitted via atmospheric turbulence channels between telescopes. The received signals are detected by the photodetector (PD), and the photocurrent corresponding to the transmitted RF signal is extracted by the bandpass filter (BPF). Finally, data is extracted by the RF demodulator module. The optical signal, $x_l(t)$ from the laser and the RF signal, $x_r(t)$ from the RF modulator are modeled [1] [2] .

Here, the optical signals $x_l(t)$ from the laser diode (LD) and the RF oscillator signal $x_r(t)$are modeled as

$$x_l(t) = A_0 \exp\ j(w_l t) + \Phi_l(t))$$

$$x_r(t) = V_r \cos\ (w_r t + \Phi_r(t)) \qquad (1)$$

Where A_0 and V_r are the optical carrier amplitudes from the LD and the RF oscillator, w_l and w_r are the angular frequencies of the signals from the LD and the RF oscillator andΦ_l (t) and Φ_r (t) are phase noise processes. After optically modulating RF oscillator signal $x_r(t)$ by $x_l(t)$ with DD-MZM, the output signal of the DD-MZM is expressed as

$$E(0,t) = \frac{A.L_{MZM}}{\sqrt{2}}\{\exp j[w_l t + \gamma\pi + \Phi_l(t) + \alpha\pi\cos\ (w_r t + \Phi_r(t))] + \exp j[w_l t + \Phi_l(t) + \alpha\pi\ \cos(w_r t + \Phi_r(t) + \theta)]\} \qquad (2)$$

Where $\gamma(= V_{dc}/V_\pi)$ and $\alpha(= V_r/\sqrt{2}V_\pi)$ defines a normalized dc and ac values, V_π is the switching voltage of the DD-MZM, L_{MZM} is the insertion loss of the DD-MZM and θ is the phase shift by the phase shifter. Note that the input RF signals into the DD-MZM are $x_r(t)/\sqrt{2}$ and $\tilde{x}_r(t)/\sqrt{2}$ instead of $x_r(t)$ and $\tilde{x}_r(t)$ because the input RF signal is 3-dB attenuated by utilizing the power splitter. By controlling the phase shifter, the output signal can be OSSB or the ODSB signal. Among the two signals, only the OSSB signal will be dealt in my work, as the ODSB signal suffers from fiber chromatic dispersion severely and requires double bandwidth than that of the OSSB signals. For generating the OSSB signal, θ and γ are set to $\pi/2$ and $1/2$ respectively. By using Eqn. (2) and the mentioned conditions, the OSSB signal at the DD-MZM can be modeled as

$$E_{SSB}(0,t) = \begin{bmatrix} \frac{A_0.L_{MZM}}{\sqrt{2}} \exp j(w_l t + \Phi_l t) \\ \left\{\begin{matrix} \sqrt{2}J_0(\alpha\pi)\exp\ (\frac{j\pi}{4}) \\ -2J_1(\alpha\pi)\exp j(w_r t + \Phi_r t) \\ -\exp(-j)\cos(w_r t + \Phi_r t) \end{matrix}\right. \end{bmatrix} \qquad (3)$$

We assume that high order components of Bessel function can be negligible since the value of $\alpha\pi$ in Bessel function is very small due to the fact that $V\pi \gg V_r$in general. The output signal at DD-MZM is transmitted over the SSMF experiencing different group delays due to the fiber chromatic dispersion at a different wavelength. After the transmission of distance L_{fiber} in km SSMF, the signal received at the BS becomes

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$$E_{SSB}(L,t) = \left[\begin{array}{c} A_0.L_{MZM}.L_{add} \\ .10^{\frac{\alpha_{fiber}L_{fiber}}{20}} J_0(\alpha\pi) \\ \left\{ \begin{array}{l} \exp j \begin{bmatrix} w_l t + \Phi_l(t-\tau_0) \\ -\phi_1 + \left(\frac{\pi}{4}\right) \end{bmatrix} - \frac{\sqrt{2}J_1(\alpha\pi)}{J_0(\alpha\pi)} \\ \exp j \begin{bmatrix} w_l t + \Phi_l(t-\tau_+) \\ +w_r t + \Phi_r(t-\tau_+) - \phi_2 \end{bmatrix} \end{array} \right. \end{array} \right] \quad (4)$$

Where L_{add} defines an additional loss in the optical link, α_{fiber} is the SSMF loss, L_{fiber} is the SSMF transmission distance and τ_0 and τ_+ denotes group delays for a center angular frequency of w_l and an upper sideband frequency of $w_l + w_r$. ϕ_1 and ϕ_2 are phase-shift parameter for specific frequencies due to the fiber chromatic dispersion.

Now, we investigate the system performance based on the photocurrent at the PD. BER is a relevant figure of merit to evaluate the system performance. For the evaluation of the BER performance of the RoFSO system, a SNR is utilized because it is simple and good parameter for measuring the system performance by employing the ratio between the signal power and the noise power.

The SNR of the photocurrent is calculated by using an autocorrelation function and a PSD. By using a square-law model, the photocurrent $i(t)$ is represented as

$$i(t) \cong \rho |E_{SSB}(L,t)|^2 \quad (5)$$

By using Eqn. (4), the photocurrent can be written as

$$i(t) \cong \rho \left[\begin{array}{c} A_0.L_{MZM}.L_{add}. \\ 10^{\frac{\alpha_{fiber}L_{fiber}}{20}} J_0(\alpha\pi) \\ \left\{ \begin{array}{l} \exp j \begin{bmatrix} w_l t + \Phi_l(t-\tau_0) \\ -\phi_1 + \left(\frac{\pi}{4}\right) \end{bmatrix} - \frac{\sqrt{2}J_1(\alpha\pi)}{J_0(\alpha\pi)} \\ \exp j \begin{bmatrix} w_l t + \Phi_l(t-\tau_+) \\ +w_r t + \Phi_r(t-\tau_+) - \Phi_2 \end{bmatrix} \end{array} \right. \end{array} \right]^2 \quad (6)$$

Where ρ denotes the responsivity of the PD and $|\cdot|^2$ is the square-law detection. The autocorrelation function $R_I(\tau)$ is obtained as

$$R_I(\tau) = \langle i(t) \cdot i(t+\tau) \rangle \quad (7)$$

$$\frac{R_I(\tau)}{\rho^2.A_1^4} = B^2 + \begin{cases} 2\alpha_0^2 \cos(w_r\tau).e^{-2\gamma_t|\tau|}, |\tau| \le \tau_1 \\ 2\alpha_0^2 \cos(w_r\tau).e^{-2\gamma_l\tau_1 - \gamma_r|\tau|}, \quad |\tau| > \tau_1 \end{cases} \quad (8)$$

Where,

$$A_1 = A_0.L_{MZM}.L_{add}.10^{\frac{\alpha_{fiber}L_{fiber}}{20}} J_0(\alpha\pi) \quad (9)$$

$$\alpha_0 = \frac{\sqrt{2}J_1(\alpha\pi)}{J_0(\alpha\pi)} \quad (10)$$

$$B = 1 + \alpha_0^2 \quad (11)$$

Where $2\gamma_l$ ($= 2\pi\Delta v_l$) and $2\gamma_r$ ($= 2\pi\Delta v_r$) define the angular full linewidth at half maximum (FWHM) of the Lorentzian shape for the laser diode and the RF oscillator, respectively. Δv_l and Δv_r are the linewidths for the laser diode and the RF oscillator, respectively. $2\gamma_t$ is related to the total linewidth for laser diode and RF oscillator. Note that the $2\gamma_t = 2\pi\Delta v_l + \pi\Delta v_r$.$\tau = (\tau_+ - \tau_0)$ is the differential delay due to the fiber chromatic dispersion and is dependent on the wavelength λ_0, the signal frequency f, the fiber chromatic dispersion D, and the optical transmission distance L_{fiber}.

The differential delay due to the fiber chromatic dispersion is given by

$$\tau = D.L_{fiber}.\lambda_0^2.f/c \quad (12)$$

Where, c is the light velocity. The PSD function of the photocurrent is given by the Fourier transform of Eqn. (7). The shot noise term at the PD is omitted here since the noise power can be evaluated by the product of bandwidth and noise density level. The PSD function $S_I(f)$ can be written as

$$S_I(f) = F\langle R_I(\tau) \rangle \quad (13)$$

Where $F\langle\cdot\rangle$ denotes Fourier transform.

Now, by using the autocorrelation function and PSD of the photocurrent we define the ratio p between the total signal power and the required power as

$$p \cong \frac{2}{\pi}\left\{\exp(-2\gamma_t|\tau|)\tan^{-1}\left(\frac{\pi.B_f}{2\gamma_r}\right)\right\} \quad (14)$$

Where, B_f is bandwidth of the electrical filter. From Eqn. (14), the required bandwidth for the p ratio is obtained as

$$B_f = \frac{\gamma_r}{\pi}.\tan\left(\frac{\pi}{2}e^{2\gamma_t\tau}\right)p \quad (15)$$

The required bandwidth increases as more received signal power is needed. Now, we evaluate the SNR ratio considering signal power and noise power.

$$SNR = \frac{Signal\ Power}{Noise\ \ Power} \quad (16)$$

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$$= \frac{2\rho^2 A_1^4 \alpha_0^2}{2B_f.\frac{N_0}{2}} \qquad (17)$$

$$SNR \cong \frac{2\rho^2 A_1^4 \alpha_0^2 p}{N_0.\left(\frac{\gamma_r}{\pi}\right)\tan\left(\frac{\pi.p\exp(-2\gamma_t|\tau|)}{2}\right)} \qquad (18)$$

Note that $2B_f$ is utilized instead of B_f since the received RF signal power is in both real and imaginary parts and noise power must be evaluated in the same manner. If SNR_0 is defined as the reference SNR, the SNR penalty ΔSNR is represented as

$$\Delta SNR = 10\log_{10}\left(\frac{SNR_0}{SNR}\right) \qquad (19)$$

$$= 10\log_{10}\left(\frac{p_0.\gamma_r.\tan\left(\pi.p\frac{\exp(2\gamma_t.\tau)}{2}\right)}{p.\gamma_{ro}.\tan\left(\pi.p_0\frac{\exp(\gamma_{ro}.\tau)}{2}\right)}\right) \qquad (20)$$

For calculating the SNR_0, we set p_0 to 0.5 as a half power bandwidth filter, γ_{ro} to π, which means a 1Hz linewidth of the RF oscillator, and zero laser linewidth. The SNR penalty ΔSNR depends on p, the linewidths, and the differential delay.

3. RESULT

For the evaluation of the performance of the RoFSO system, we evaluate the SNR penalty, which is defined as the ratio between the SNR value and the reference SNR value. The SNR penalty is important and practical in a real system because, generally, the derived SNR value itself is not same as the real SNR value. However, the SNR penalty can show the effect of the specific parameter on the system performance as the value of the parameter is changed [2].

Figure 2 illustrates the results of the SNR Penalty as a function of the Dispersion at three different percentage of the received power ,p (e.g., 0.6, 0.7, 0.9). As shown in Figure 2, following received power percentage increase, the SNR Penalty increases. The effect of *p* is linearly proportional to ΔSNR. ΔSNR increases as *p* becomes large since the increment of the noise power is greater than that of the received signal power as the bandwidth increases. Thus, the bandwidth should be considered carefully for $p > 90\%$, since the SNR penalty increases drastically over the point as shown in result.

ΔSNR also increases as dispersion becomes large, at constant received power percentage.

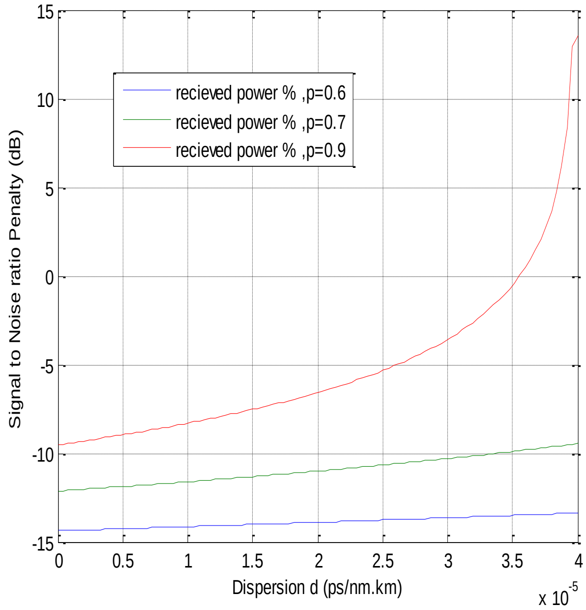
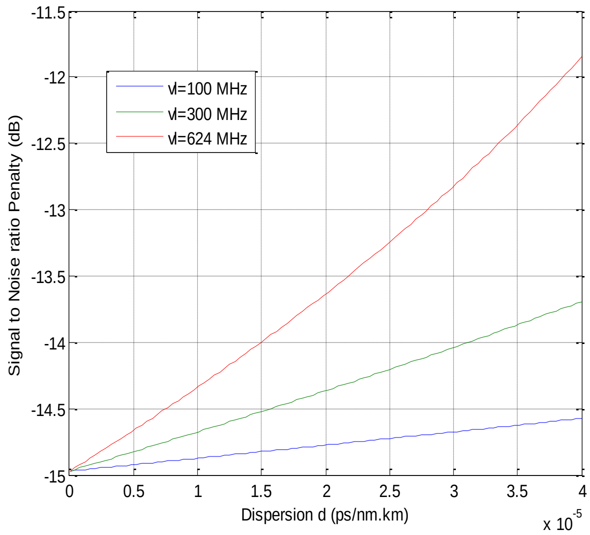


Figure 2. ΔSNR as a function of the dispersion and the percentage of the received power p

Another parameter that affects ΔSNR is the laser linewidth. Figure 3 represents the relationship between the SNR penalty and the Dispersion at three different linewidths for the laser ,vl (100 MHz, 300 MHz, 624 MHz). ΔSNR exponentially increases as the laser linewidth increases. Also, SNR Penalty increases as the dispersion increases by keeping laser linewidth constant.



4. CONCLUSIONS

In this article we present a new innovative broadband wireless communication system based on RoFSO links. We proposed an Analytical time-domain model for Radio over free space optical (RoFSO) systems using a DD-MZM and PD. Also, we drive the SNR penalty due to fiber chromatic dispersion and phase noises from a laser and an RF oscillator using an OSSB signal and a direct-detection scheme . For the analysis of the SNR penalty, the autocorrelation and the PSD function of a received photocurrent are evaluated. We have shown the

MATLAB implementation of analysis of SNR Penalty with respect to dispersion by keeping the other parameters (such as laser linewidth ,v_l and percentage of power received, *p*) constant. The bandwidth of an electrical filter is dealt in the SNR penalty since the phase noises result in an increase of the required bandwidth and the increased bandwidth causes an additional SNR Penalty (ΔSNR).

Figure. 3. ΔSNR as a function of the dispersion and laser linewidth.

5. REFERENCES

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