Average BER Estimation of Retroreflective Transdermal Optical Wireless Links with Diversity, Attenuation and Spatial Jitter

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***Abstract*— Remarkable recent advances in both medical and optical wireless communication (OWC) fields have paved the way to move to the more bandwidth-effective optical spectrum in order to establish high speed transdermal optical wireless (TOW) communication links between an implanted device and an external one, which is very crucial for a variety of emerging medical applications. However, the development of optical telemetry with medical implants is primarily hindered by skin-induced attenuation and pointing errors effects. In order to combat these dominant impairments, a modulated retro-reflector (MRR) TOW system with diversity is investigated in terms of its total average bit error rate (ABER) performance metric. Thus, taking into account the joint presence of skin-induced path loss along with the stochastic nature of pointing errors due to random misalignments between transmitter and receiver terminals, novel analytical ABER expressions are extracted for various MRR TOW configurations in order to investigate the influence of the diversity technique. Additionally, proper corresponding analytical results are provided which are further validated by Monte Carlo simulations in an attempt to verify the new mathematical expressions and reveal the beneficial impact of diversity method employment on the total ABER performance of a typical MRR TOW system.**

Keywords - Optical Wireless Communication; Medical Implants; Transdermal Optical Wireless Links; Modulated Retro-Reflector; Diversity; Pointing errors; Average Bit Error Rate.

I. INTRODUCTION

Owing to their operation at a high security level with low power consumption, ease of modulation and demodulation, flexibility for deployment and redeployment, electromagnetic interference (EMI) immunity, very large unlicensed available bandwidth and high data rate wireless transmissions, TOW links have drawn particular research attention lately as a viable alternative to their radio frequency (RF) counterparts for varying transdermal communication medical applications, including transdermal communication with cochlear implants for the stimulation of the acoustic nerve, along with cortical neural recording and prostheses, where recording signals from implanted devices (IMDs) are collected and used then from external devices to guide a prosthesis, for instance to actuate artificial limbs, [1]-[8]. Indeed, for such applications, besides the issue of suffering from EMI, traditional RF bio-telemetry cannot simultaneously accommodate both requirements for high data rate transdermal transmissions along with low power consumption, as proved in [9]. The latter, can be achieved however by using optical telemetry via TOW links as reveal findings of [2], [3], [10]-[13]. It should be reinforced here that there are two fundamental TOW link configurations which can be used: the direct link configuration and the modulated retro-reflective (MRR), one. The feasibility of both of them has been experimentally validated in, [2], [3].

Nevertheless, skin is a very complex, multilayered and optically turbid channel composed mainly of epidermis, dermis and hypodermis, [4], [5], [13]. When propagating thus through this layer stack of different components, light signal is highly attenuated due to photon absorption and scattering by elements in the skin, [13]. Even by selecting an optical wavelength between 600nm and 1300nm, i.e. within the "medical optical window" where photon absorption is minimized, this skin-induced attenuation remains a major challenge since only 10% to 30% of incident optical power can be transmitted through skin of typical thickness, i.e. 2mm to 6mm, when transmitter and detector apertures are aligned, while also light can penetrate into tissue as much as several centimeters, [2], [4], [11], [12]. Another concern for TOW development is pointing errors (PEs) stochastic effect due to the relative motion between transmitter and receiver terminals, which results in random irradiance fluctuations and thus, in significant misalignment-induced irradiance fading at the receiver side, [4], [7], [8].

As per author's best knowledge the stochastic detrimental impact of PEs has been just recently introduced and investigated for direct TOW link configurations [7], [8], [14], [15]. Their findings generally reveal that PEs, as such, can degrade the TOW performance more than 10%, considering also the transdermal path loss impact. Under such circumstances authors in [4], [16] extended these works by introducing diversity method for direct TOW link configurations so as to mitigate this joint impact. Indeed, by using diversity technique their findings determined significant total TOW outage performance enhancements. It should be recalled here that diversity, the most of the times, is realized in space, in time or in wavelength and refers to the consideration of multiple copies of propagating information-bearing signals in an attempt to overcome a poor transmission media state and enhance the communication system's availability and performance, [17], [18]. Additionally, to the best of authors' knowledge, contrary to direct TOW links research there are few papers reported on MRR TOW link configurations in the open technical literature. Specifically, in terms of MRR TOW error performance, only instantaneous BER metric has been evaluated in [2], by neglecting however the stochastic nature of PEs and without suggesting any method to improve the total TOW MRR error performance.

Motivated by these facts, in this work we focus on the investigation of spatial diversity (SD) and wavelength diversity (WD) MRR TOW link configurations in an attempt to address the joint influence of PEs stochastic effect along with the skin-induced attenuation deterministic effect, with the ultimate objective of enhancing the ABER performance of a typical TOW link. In this respect, an outage analysis in terms of the more robust ABER metric (than the instantaneous BER) is for the first time performed for MRR TOW links with or without diversity, while novel corresponding analytical mathematical ABER expressions are derived.

II. System And Channel Model

A. Signal Model

The WD MRR TOW system under consideration consists of a composite external laser transmitter which can emit up to M spatially separated laser signals with M different optical wavelengths within the medical optical window towards the internal retro-reflector, which modulates these light signals with On-Off Keying (OOK). Thus, by carrying the same neural data the information-bearing optical signals are reflected back to the out of body receiver side, where they are collected by the proper receiver aperture. By using therefore intensity modulation with direct detection (IM/DD) and optimal combining (OC) technique for signal reception, [17], [18], the received signals are detected and demodulated so as to restore the neural information data. In case of SD MRR TOW configuration the above procedure is simplified by assuming only one external laser transmitter aperture. Thus, in this case the assumed SD system is a MRR TOW single input-multiple output (SIMO) one [18]. Moreover, it becomes evident that when no diversity method is employed the system reduces to a single input-single output (SISO) MRR TOW link. Under these assumptions the statistical channel model is expressed as, [4], [16]:

$$y_m = \eta_m h_m x + n , \qquad (1)$$

where y_m denotes the m-th received optical signal with m=1,2,…M, η_m is the effective photo-current conversion ratio of m-th receiver aperture, h_m represents the m-th total channel state, $x \in \{0,1\}$ is the binary information signal, and n is the additive noise modeled as a zero mean complex Gaussian process with variance σ^2, [4], [14], [16].

Each h_m skin channel state can be expressed as $h_m = h_{T,m} h_{R,m} = h_{T,l,m} h_{R,l,m} h_{p,m}$, where $h_{T,m}$ and $h_{R,m}$ is the m-th channel state for the m-th forward interrogating and backward retro-reflected path, respectively. Additionally, $h_{T,l,m}$ and $h_{R,l,m}$ are the deterministic channel coefficients due to the corresponding transdermal path loss, while $h_{p,m}$ refers to the stochastic process that models the geometric spread owing to the presence of PEs in, [4], [14], [19]. Therefore, $h_{T,m} = h_{T,l,m}$, and $h_{R,m} = h_{R,l,m} h_{p,m}$ while by assuming without loss of generality that $h_{T,l,m} = h_{R,l,m} = h_{l,m}$, the total m-th channel state is obtained as

$$h_m = h_{l,m}^2 h_{p,m} . \qquad (2)$$

The above deterministic attenuation term $h_{l,m}$ is given as [4], [7], [8], [14], [15]

$$h_{l,m} = \exp\left[-\frac{1}{2}\alpha(\lambda_m)\delta_m\right], \qquad (3)$$

where δ_m is the total dermis thickness for the m-th forward or backward path, $\alpha(\lambda_m)$ is the corresponding skin attenuation coefficient with λ_m being the m-th operational wavelength. The wavelength dependent value of $\alpha(\lambda_m)$, depends also on the optical properties of the skin and between 0.4μm and 1.8μm is obtained as [4], [7], [8], [14], [15],

$$\alpha(\lambda_m) = \sum_{i=1}^{8} a_i \exp\left[-\left((\lambda_m - b_i)/c_i\right)^2\right], \qquad (4)$$

where λ_m values are expressed in nm and the values of a_i , b_i and c_i, with i=1,2..,8, are given in Table I in [14].

B. Pointing Errors Model

The probability density function (PDF) for random variable $h_{p,m}$ can be obtained as, [8], [16], [20]

$$f_{h_{p,m}}\left(h_{p,m}\right) = \psi^2 A_{0,m}^{-\psi_m^2} h_{p,m}^{\psi_m^2-1}, \quad 0 \le h_{p,m} \le A_{0,m}, \qquad (5)$$

where $\psi_m = w_{eq,m}/2\sigma_{S,m}$, with $\sigma_{S,m}$ and $w_{eq,m}$ being the PE displacement, i.e. spatial jitter, standard deviation and the equivalent beam radius in the m-th receiver aperture, respectively. Note that any decrease of ψ_m parameter value denote that the corresponding impact of PEs effect is getting stronger, $w_{eq,m} = \left[\sqrt{\pi}\mathrm{erf}(v_m) w_{\delta,m}^2 / 2 v_m \exp(-v_m^2)\right]^{1/2}$, while $A_{0,m} = \mathrm{erf}^2(v_m)$ is the fraction of the collected power at $r_m = 0$ with r_m being the radius of the circular detection m-th aperture, $v_m = \sqrt{\pi} r_m / \sqrt{2}\, w_{\delta,m}$, and $w_{\delta,m}$ represents the m-th beam waist on the receiver plane at propagating distance, δ_m from the implanted MRR, obtained as [7], [8], [16]

$$w_{\delta,m} = \delta_m \tan(\theta_m/2), \tag{6}$$

with θ_m standing for the corresponding divergence angle, [7].

C. *Joint Impact of Path Loss and Pointing Error Effects*

From (2)-(4) and by using standard technique of random variables (RV) transformation, [21], the joint PDF of the random variable h_m is obtained as

$$f_{h_m}(h_m) = \psi^2 A_{0,m}^{-\psi_m^2} h_{l,m}^{-2\psi_m^2} h_m^{\psi_m^2-1}, \quad 0 \le h_m \le A_{0,m} h_{l,m}, \tag{7}$$

Next, by integrating (7) the corresponding cumulative density function (CDF) can be obtained as

$$F_{h_m}(h_m) = \int_0^h f_u(u)\, du = A_{0,m}^{-\psi_m^2} h_{l,m}^{-2\psi_m^2} h_m^{\psi_m^2}, \quad 0 \le h_m \le A_{0,m} h_{l,m}, \tag{8}$$

III. Average Bit Error Rate Estimation

A. *SISO MRR TOW link with IM/DD OOK*

Assuming also equal probabilities of transmitting both bits “0” or “1”, the instantaneous BER for each TOW SISO link can be obtained as a function of h_m as, [18]

$$P_e(h_m) = \frac{1}{2} erfc\left(\eta_m h_m / 2\sqrt{N_{0,m}}\right), \tag{9}$$

where *erfc*(.) is the complementary error function, [22, 06.27.02.0001.01]. By averaging then (9) over h_m and by using [22, 06.27.21.0132.01] the corresponding ABER is obtained as

$$P_{e,av} = \left(2\sqrt{\pi} A_{0,m}^{\psi_m^2}\right)^{-1} h_{l,m}^{-2\psi_m^2} \left(2\sqrt{N_0}/\eta_m\right)^{\psi_m^2} \Gamma\left(\psi_m^2/2\right), \tag{10}$$

where $\Gamma(.)$ is the gamma function [22, 06.05.02.0001.01].

B. *Diversity MRR TOW links with IM/DD OOK*

Considering OC technique for signal reception the ABER for the TOW system with diversity is given as [17]

$$P_{e,av,M} = \int_{\vec{h}} f_{\vec{h}}(\vec{h})\, Q\left(\frac{1}{\sqrt{2MN_0}} \sqrt{\sum_{m=1}^{M} (\eta_m h_m)}\right) d\vec{h}, \tag{11}$$

with $\vec{h} = [h_1, h_2, ..., h_M]$ being the vector of total channel state for each one of the M copies of the signal.

By substituting the accurate approximation of [23] for the Q-function, $Q \approx \left(\exp(-x^2/2) + 3\exp(-2x^2/3)\right)/12$ and by using then (7) and [24, Eq (34)], for each integral of (11) we obtain:

$$P_{e,av,M} = \frac{1}{12} \prod_{m=1}^{M} \frac{\psi_m A_{0,m}\, \Gamma\left(\psi_m^2/2\right)}{2h_{l,m}^2 \left(\mu_m\left(\psi_m^2+2\right)/4M\right)^{\frac{\psi_m^2}{2}}} + \frac{1}{4} \prod_{m=1}^{M} \frac{\psi_m A_{0,m}\, \Gamma\left(\psi_m^2/2\right)}{2h_{l,m}^2 \left(\mu_m\left(\psi_m^2+2\right)/3M\right)^{\frac{\psi_m^2}{2}}}, \tag{12}$$

where μ_m is the average electrical SNR for the m-th TOW MRR path, which after performing the procedure in [14] it is obtained as $\mu_m = \eta_m^2 \psi_m^2 A_{0,m}^2 h_{l,m}^4 \widetilde{P_S} / (\psi_m^2 + 2) N_0$, with $\widetilde{P_S}$ and N_0 being the signal and noise optical power spectral density (PSD), respectively.

IV. Analytical Results

By using (12) the ABER evolution for the described MRR TOW system is investigated over a wide range of average electrical SNR, μ_m, with M = 1 for SISO and M = 2 or 3 for WD or SD system configurations. Without loss of generality we have assumed that for each examined TOW link $\mu_m = \mu_1 = \cdots = \mu_M = \mu$, $\delta_1 = \delta_2 = \cdots = \delta_M = \delta$, $r_1 = r_2 = \cdots = r_M = r = 0.5\text{mm}$, $\sigma_{S,1} = \sigma_{S,2} = \cdots = \sigma_{S,M} = \sigma_S$, $\eta_1 = \eta_2 = \cdots = \eta_M = \eta = 0.8$ and $\theta_1 = \theta_2 = \cdots = \theta_M = \theta = 20°$. Specifically, $\delta \in [5, 8]$mm for each forward or backward dermal link, while $N_0 = \left(1.3\,\text{pA}/\sqrt{\text{Hz}}\right)^2$ and $\widetilde{P_S} = 1\,\mu\text{W/MHz}$. Additionally, each backward link may address varying misalignment-induced fading strengths, ψ_m. Indeed by setting $\sigma_S/r = 3$ to 5 different beam waste values are occurred since, according to (6), $w_{\delta,m}$ depends on propagating distance, δ, provided that θ is constant. Alternatively, by setting $\sigma_S/r = 3$ and $\theta = 20°$ different PEs are occurred by assuming different δ values, e.g. $(\delta, \psi_m) = (6\text{mm}, 1.3)$ and $(\delta, \psi_m) = (5\text{mm}, 1.1)$ for weak or strong PEs, respectively. Moreover, each operational optical wavelength, λ_m, is selected within the medical optical window, i.e. $\lambda_m \in [0.7, 1.8]\mu\text{m}$. Under these assumptions, various analytical results, for realistic cases, are presented below.

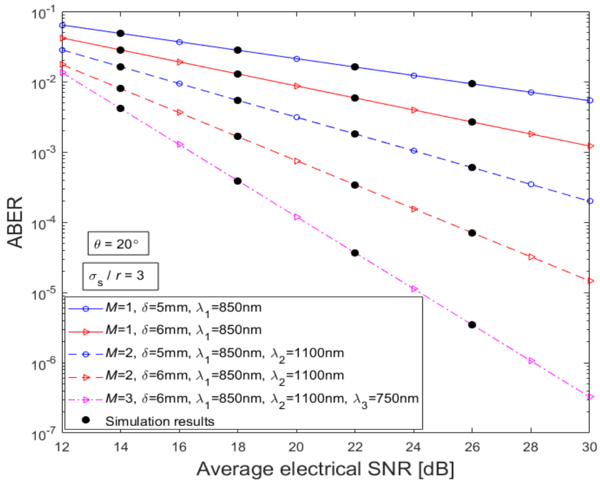

Fig. 1. *Total ABER of the system with WD as a function of μ.*

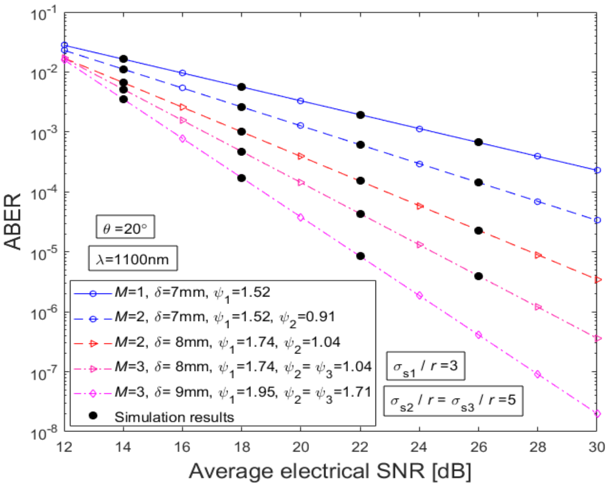

Fig. 2. *Total ABER of the system with SD as a function of μ.*

Figs 1 and 2 illustrate that the use of WD or SD, offers significant MRR TOW ABER performance enhancements, especially for larger number of receiver terminals, weaker PEs which mainly correspond to longer transdermal links (in the order of some millimeters) according to (6), [15], and higher average SNR values. It is also depicted that as average SNR increases the impact of PEs is getting stronger on the total outage performance, which is consistent with findings of [7].

V. Conclusions

In this work a performance analysis in terms of ABER was first presented for MMR TOW links. Additionally, diversity method was first introduced for such MRR links. In this context, novel analytical ABER expressions were derived considering skin-induced attenuation along with the stochastic impact of PEs. Their results mainly demonstrate significant total ABER performance improvements when diversity technique in external space or in wavelength is implemented.

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