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Performance evaluation of transdermal optical wireless communication using spatial diversity techniques

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ABSTRACT

Active medical implants and other contemporary medical applications need a dependable, high-speed communication channel between external and internal transceivers. Optical wireless communications have demonstrated advantages over widely used radio frequency technology in terms of data speeds, bandwidth abundance, and immunity to interference. Regretfully, this advantage implies strict alignment requirements for both sending and receiving ends. This study focuses on the effects of using multiple transmitters or receivers under the influence of pointing error on the transcutaneous link's overall performance measured by the outage probability and outage rate. Spatial diversity techniques have demonstrated their viability in increasing the link's reliability in free space optical communications. This drives the investigation of improvement transdermal communication system by adding numerous transmitters or receivers. Various misalignment severities are used to represent different operating circumstances, and these analyses result in explicit closed-form formulas for the relevant metrics. The findings clearly show the benefits of employing multiple transmitters and receivers on the link's outage performances. A notable improvement in the average signal-to-noise ratio values for the outage probability and outage rate compared to the single input single output setup was achieved. Furthermore, the theoretical conclusions are subsequently confirmed by MATLAB-based Monte-Carlo simulation for several instructive cases.

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1. INTRODUCTION

A highly effective out-body/in-body communication interface is required for modern active medical implants (AMI). AMIs are instruments that diagnose and treat patients simultaneously. They capture bodily impulses and transmit commands to the heart or the nervous system, which includes the brain, spine, ear, eye, and other body parts [1]. Therefore, for these implants to function well in a range of applications, they need to have high data rates and proven reliability. Among these applications are cortical implants at the brain interface, cochlear implants, pacemakers, and retinal implants. For the purpose of meeting the strict requirements of bandwidth abundance, data speeds, and interference immunity, transdermal optical wireless (TOW) communication replaces the conventional and currently employed radio frequency (RF) technology [2]–[4].

The deployment of TOW technology is severely limited by several factors that negatively affect its performance, primarily due to the skin's inherent characteristics and variable nature as a transmission medium. Skin is an intricate organ, multi-layer, highly an-isotropic biological entity with many structural components. All of the skin's structural elements reflect, scatter, and absorb light when it strikes them, which are influenced by various conditions and features [5]. Consequently, there is a large loss of optical signal power, resulting in a spatially expanded power distribution at the receiver, as reported in [6]. When the emitter and detector are aligned, only 10% to 30% of incident optical radiation passes through typical skin thickness (2 to 6 mm), which is why skin-induced attenuation remains a significant issue in TOW communication even with the maximum tissue transmittance (wavelengths between 800 and 1300 nm) [7]–[9]. When one takes into account the pointing errors resulting from inevitable deviations of the transmitter and receiver terminals, which are a major cause for concern in both TOW and wider free space optical (FSO) communication, the availability and performance of TOW transmissions are further compromised [10]–[16].

Despite the advancements in communication, there are still significant research challenges in enhancing communication with implantable medical devices (IMDs). These include power loss, fading caused by misalignment, and the requirement for extremely high data rates at the same time [17]. In summary, an experimental verification of the viability of creating TOW linkages has been conducted in [1], [5], [6], [18].

More specifically, in [9], data rates of up to 16 Mbps were attained with a skin thickness of 4 mm, a bit error rate (BER) of order 10^{-9}, and a 2 mm misalignment between the transmitter and reception terminals, all while using 10 mW of power. A TOW link that uses as little as 1.1 mW to 6.4 mW of power and has a BER of less than 1×10^{-5}, while taking into account a 2 mm misalignment between terminals was demonstrated in [19] can send data at 50 Mbps through 2–6 mm of appropriately thick tissue, but in [6] in vivo experiments on a sheep under anesthesia demonstrated data transmission at 100 Mbps with a BER below 2×10^{-7} and requiring only 2.1 mW of power. Regarding pointing errors (PEs), most works on TOW communications have either written off this effect as insignificant or have used deterministic models to describe it, which are not very appropriate for explaining these kinds of random irradiance fades caused by misalignment [1], [6], [18], [19]. The authors of a recent paper, [13], [14], [16], took into account the random characteristics of a TOW link and created closed-form equations for the average signal-to-noise ratio (SNR) and its outage effectiveness, expressed in terms of the outage probability (OP) metric. As demonstrated in basic terms, PEs can significantly reduce TOW performance by over 10%. Later studies have employed a commonly used model to account for the misalignment's random character caused by the relative movement of the transmitter and receiver terminals in outdoor FSO communication links. This model considers jitter but disregards the non-zero boresight (NZB) displacement, as proposed in [12]. In actuality, Jitter and boresight form the two parts of a PE. Jitter is the random offset of the beam's center at the detector plane, whereas the constant distance between the beam and the center of the detector is called the boresight [20]. In order to obtain better results, it is important to use a more useful and comprehensive PE model called the NZB PE model. This model takes into consideration the impact of NZB errors, beam width, detector size, and various jitters for the elevation and horizontal displacement. It is crucial to consider boresight displacement at the receiver side when employing multiple detector apertures, as each laser can only be precisely positioned with just one receiving aperture. Therefore, there is a natural displacement of boresight that is influenced by the distance between the receiver detectors, which is determined by the specific detector aperture and its alignment point [20]. Diversity technique, with relation to wavelength, time, or space, to enhance a conventional TOW's outage performance in terms of OP criterion has only recently been shown in [15]. Both the misalignment- and attenuation-induced fading effects with NZB, shown by the precise Beckmann distribution [20]–[26]. Essentially, diversity is the process of taking into account several copies of the signals that are being propagated in an effort to strengthen the availability and resilience of the communication link by overcoming subpar transmission media conditions. It is possible to achieve diversity in wavelength, time, or space. A FSO system that takes spatial diversity into account [27], [28] uses several transmitters and/or receivers located at various locations to transmit and receive copies of the same information-bearing signal, which improves error performance. An FSO system uses a single transmitter-receiver pair using time diversity [29]–[31], only re-transmitting the signal at multiple time slots.

Assuming wavelength diversity, an FSO system employs a composite transmitter, which enables simultaneous transmission of multiple copies of the same signal at various wavelengths to multiple receivers [32]. It is evident that through diversity, a single input-single output (SISO) FSO link can be converted into a multiple input-single output (MIMO), single input-multiple output (SIMO), or multiple input-single output (MISO) FSO system that is more error-rate and availability-efficient. Furthermore, as far as the writers are aware, only the most straightforward on-off keying (OOK) modulation combined with intensity modulation/direct detection (IM/DD) forms have been studied in earlier works on TOW communication.

However, these formats are not always sufficiently efficient. Because of its simplicity, OOK is the most popular modulation scheme in the FSO field; nevertheless, when it operates in fading conditions, the detector threshold needs to be evaluated and adopted appropriately based on the fluctuating channel states. Pulse position modulation (PPM), which performs better than OOK in terms of power efficiency, can be used to get around this disadvantage [21], [33]–[35]. Inspired by these facts, a major innovation in this study is the estimation of the OP and outage rate (OR) of SIMO and MISO TOW systems when PEs with zero boresight are combined with skin-induced attenuation. This system may use IM/DD modulation in addition to OOK. It should be noted that earlier published works on frequency division multiplexing (FSO) have addressed the impairments of random atmospheric channels, such as atmospheric turbulence-induced signal fading, by utilizing receiver diversity in terms of SIMO configurations to improve an external, terrestrial FSO communication link's efficiency [10], [11], [26]. Nonetheless, a crucial distinction regarding the transmission medium's composition exists for a TOW link, which is the subject of this study. Biological tissue serves as the transmission medium in this study rather than the atmosphere. The analyzed channel is actually the skin, which is far more complex and varied for the optical signal than the atmosphere is. In summary, while SIMO and MISO techniques with IM/DD have also been explored for outdoor FSO communications, this is the first instance of their application in biomedical and transdermal communication systems using the same method, where the demands for extremely low energy consumption and minimal biological effects must be fully satisfied. Consequently, this study investigated the IM/DD SIMO and MISO TOW designs in order to counteract the adverse impacts of this joint impact. In order to estimate it, new closed-form mathematical expressions are created and an OP and OR analysis are presented. In this context, an OP and OR performance comparison is conducted between SISO, SIMO, and MISO TOW configurations with IMDD/OOK formats in an effort to identify potential significant improvements in outage performance that result from the appropriate selection of SIMO and MISO TOW system configurations. Table 1 presents a comparison between this study and the latest research that is discussed in this work.

Table 1. A comparison between this study and related work

Author[s]	Outcome
Varotsos *et al.* [10]	Developed mathematical formulas to estimate the average bit error rate performance of SIMO FSO links.
Varotsos *et al.* [11]	Provided a performance analysis and closed-form mathematical formulas to calculate the fade probability for FSO communication systems using On-Off keying and reception diversity over gamma-gamma or gamma-modeled atmospheric turbulence channels, accounting for group velocity and pointing errors.
Varotsos *et al.* [26]	Created new approximations of average symbol error probability formulas for SIMO (single-input multiple-output) and SISO configurations.
Tsiftsis *et al.* [27]	Examined the FSO systems' error rate performance for K-distributed atmospheric turbulence channels, talked about the possible benefits of deploying spatial diversity at the transmitter and/or receiver, and provided effective closed-form approximations for the average bit-error rate (BER) of SIMO (single-input multiple-output) FSO systems.
Navidpour *et al.* [28]	investigated the bit error rate (BER) performance of FSO networks with spatial diversity across log-normal atmospheric turbulence fading channels, assuming independent and correlated channels between transmitter and receiver apertures.
Zambrana *et al.* [29]	Presented a novel transmit alternate laser selection mechanism for FSO communication networks and bit-error-rate (BER) asymptotic expressions in closed form are obtained using a gamma-gamma (GG) distribution under pointing error effects.
Nistazakis [30]	Examined a time-diversity technique for highly turbulent free-space optical channels using a negative exponential distribution model, and extracted mathematical expressions in closed form to estimate the outage probability, average bit error rate, and maximum effective bit rate
Rachmani and Arnon [31]	Developed a test bed in the lab to assess how well a wavelength-diversity-based communication system performs with turbulence amplitude.
This study	Introduced IM/DD SIMO and MISO TOW configurations in order to counteract the adverse impacts of skin attenuation and pointing error, in addition to estimating new closed-form mathematical expressions for OP and OR- some of the most important system performance measures in the event of selective combining (SC) at the receiving end. The technique, approach, and findings of this study are not presented in any of the previously listed references

2. METHOD

2.1. System model

The suggested model in the analysis shown in Figure 1 assumes that full skin channel state information (CSI) is available and that a direct transdermal optical wireless link configuration is being used. Additionally, we consider a TOW communications system with IMDD/OOK modulation and selective combining (SC) criterion for various receiver diversity approaches. L optical point sources, or lasers, working at the selected wavelength will send L copies of the identical data under the MISO system. Each of these sources will be engineered to align with a single detector (M = 1) at the receiving end, while in the

SIMO model M direct TOW linkages are used, with only a single iteration of the optical signals going through the skin channel (L = 1).

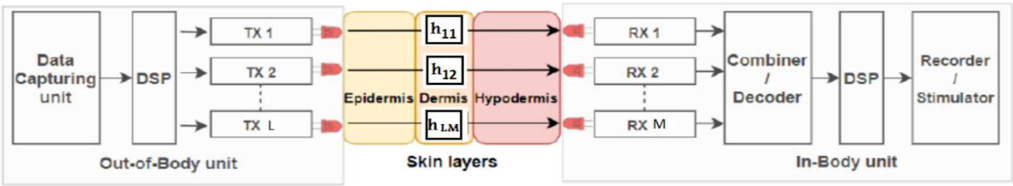

Figure 1. The general proposed system model

Next, the statistical channel model for the studied TOW system is stated as

$$y_{lm}(t) = \eta_{lm}.h_{lm} + n \tag{1}$$

where the zero mean Gaussian process with variance σ_n^2 is denotaed by n, the photodiode's efficiency is represented by η, and its power spectral density, $N_\circ/2,$ is giving in watts/Hz. In addition, the OOK data information signal represented by x ϵ {0,1}.

The skin channel state h is represented by (1) and can be expressed as [15]:

$$h_{lm} = h_{l,lm}\, h_{p,lm} \tag{2}$$

in which h_l is the skin attenuation-related channel coefficient that is predictable due to propagation loss, while the second term h_p is a stochastic process due to misaligned fading.

The deterministic term h_l can be obtained as [13], [15], [16]

$$h_{l,lm} = exp(-0.5\ \alpha(\lambda)\ \delta_m) \tag{3}$$

where δ is a representation of the thickness of the skin and the distance between the transmitter and the recipient. α(λ) represents the skin attenuation coefficient at a working wavelength of λ, which may be computed for λ between 400 and 1800 nm using [14]:

$$\alpha(\lambda) = \sum_{i=1}^{8} a_i \exp(-(\frac{\lambda-b_i}{c_i})^2) \tag{4}$$

in which λ is expressed in nm, and Table 2 provides the values of a_i, b_i and c_i, for i=1,2,….,8.

Table 2. The values of a_i, b_i and c_i [14]

i	a_i	b_i	c_i
1	10	0.35	0.065
2	4.5	0.42	0.25
3	13.48	-1.5	50.12
4	14.7	1442	49.35
5	7.435	1499	75.88
6	48	3322	1033
7	594.1	-183	285.9
8	11.47	-618.5	1054

A statistical explanation of the PRs effect is given by Beckmann's model, which considers the effects of beam width, detector size, and different jitters for movement in both horizontal and vertical directions. The error related to nonzero boresight (NZB) was calculated by [36], which is approximated by [12] when boresight pointing errors are zero to.

$$f_{IP}^{ZB}(i) = \frac{\varphi^2 i^{\varphi^2-1}}{A_\circ^{\varphi^2}}, 0 \leq i \leq A_\circ \tag{5}$$

where the difference between the equivalent beam radius and the standard deviation of the pointing error displacement at the receiver is expressed as $\varphi = w_{eq}/2\sigma_s$. $A_\circ = [\text{erf}\,(v)]^2$ represents the portion of the total power at r = 0, and notation erf (.) is the error function, with $v = \sqrt{\pi}r/\sqrt{2}w_\delta$ and r is the radius of a circular receiving aperture, and $w_\delta = \delta\ \tan(\theta/2)$ is the beam waste (radius estimated at e^{-2}) at δ from the transmitter on the RX plane, with θ denotes the divergence angle of the beam. The equivalent radius of the beam is represented by the following expression $w_{eq}^2 = w_\delta^2\sqrt{\pi}\,\mathrm{erf}(v)\,/2v\exp(-v^2)$. It follows that when a Gaussian beam travels δ in length from the source to a circular detector where the aperture radius is represented by r. One can derive the channel random variable's, h_p, probability density function (PDF) as follows [14].

$$f_{hp}(x) = \frac{\xi}{A_\circ^{\xi}}\, x^{\xi-1}\,, 0 \le x \le A_\circ \tag{6}$$

Similarly, ξ is the square ratio of the pointing error displacement standard deviation at the RX to the corresponding beam radius,w_{eq}, which may be written as $\xi = {\omega^2}_{eq}/4{\sigma_s}^2$, and also shows the sensitivity of the PE (a higher degree of misalignment is indicated by a lower value of ξ) [36]. 0.1 and 2 are the practical values for ξ [16]. Actually, many studies have used the approximation in (6), which is generally acknowledged in the literature [14]–[16] and [37]. In fact, it matches the precise value of h_p, particularly when the ratio $\omega_\delta/a > 6$ is satisfied, yielding a normalized mean squared error (NMSE) below 10^{-3} [12].

2.2. Outage probability

To evaluate the TOL's dependability, an examination of its outage performance was carried out. The possibility that the instantaneous sum of SNR (γ) falls below a specified threshold value (γ_{th}) is known as the outage probability and can be expressed as [13], [38].

$$P_{out} = Prob\ (\gamma \le \gamma_{th}) = \int_0^{\gamma_{th}} f_\gamma\ (\gamma)\ d_{\gamma T} = F_\gamma(\gamma_{th}) \tag{7}$$

where f_γ (γ)and F_γ (γ)are the PDF and the cumulative distribution functions (CDF) of the instantaneous signal-to-noise,γ, respectively. In order to use it as a reference point for analyzing the remaining configurations, a SISO transdermal system's outage performance is then assessed initially, corresponding to SIMO setup using a 1 × M array and MISO system with a L × 1 array.

2.2.1. SISO a 1x1 array TWO system

The SISO configuration's statistical channel model with L = M = 1, can be represented as [13], [38].

$$y = \eta x\, h + n \tag{8}$$

The instantaneous SNR can be defined as [13].

$$\gamma = \frac{\eta^2 \exp(-\alpha(\lambda)\delta) h_p^2 \overline{P_s}}{N_\circ} \tag{9}$$

Subsequently, the average SNR, $\tilde{\gamma}$, takes the form [13].

$$\tilde{\gamma} = \frac{\xi\ A_\circ^2 \eta^2 \exp(-\alpha(\lambda)\delta)\overline{P_s}}{(\xi+2)N_\circ} \tag{10}$$

Using (7), and using some arithmetic, the outage probability can be found as

$$P_{out} = Prob\left(\frac{\eta^2 h_l^2 h_p^2 \bar{P}_s}{N_\circ} \le \gamma_{th}\right) = {F_h}^2\left(\frac{\gamma_{th}\ N_\circ}{\eta^2\ h_l^2 \bar{P}_s}\right) \tag{11}$$

where $\overline{P}_s$ is the average power and F_h^2 is the channel's second-order cumulative distribution. It was demonstrated by [13], that the outage probability P_{out} can be expressed as

$$P_{out} = \frac{1}{(A_\circ\ h_l)^{\xi}}\ \left(\frac{\gamma_{th}\ N_\circ}{\eta^2\ \bar{P}_s}\right)^{\xi/2} \tag{12}$$

Equivalently, this could be written as [13].

$$P_{out}\ (\gamma_{th}) = \left(\frac{\xi}{\xi+2}\ \frac{\gamma_{th}}{\tilde{\gamma}}\right)^{\xi/2} \tag{13}$$

2.2.2. SIMO TOW system with a 1 × m array (receive diversity using SC)

Herein, the evaluation of the outage probability of the SIMO TOW system is based on the fact that one aperture (L = 1) transmits the information signal, while M apertures receive it. The combining scheme is attained according to the selection of the receiver aperture with the optical path that has the highest fading gain (irradiance) [27], [39]. It is obvious in our case, an analogous SISO system model is the SIMO system model, in which the channel irradiance corresponds to the SC scheme, h_{max}, is written as $h_{max} = max_{m=1,2,....M}\, h_m$, while the statistical channel model is represented as

$$y = \eta \frac{1}{M} x\, h_{max} + n \tag{14}$$

Hence, we take into account the division by M to guarantee that the SISO link's receive aperture size is the same as the size of the sum of the receive apertures in M SIMO links [39]. Since only one of M possible receiving apertures is used, the noise variance is obtained by $N_\circ/2M$. Considering that (10), the average SNR can be found using

$$\tilde{\gamma} = \frac{\xi\, A_\circ^2 \eta^2 \exp(-\alpha(\lambda)\delta)\overline{P_s}}{(\xi+2)MN_\circ} \tag{15}$$

Thus, for a SIMO TOW system, the probability of an outage can be written as

$$P_{out} = \left(M \frac{1}{(A_\circ\, h_l)^{\xi}} \left(\frac{\gamma_{th}\, N_\circ}{\eta^2\, \bar{P}_s}\right)^{\xi}/_2\right)^{M} \tag{16}$$

2.2.3. MISO TOW system with a Lx1 array (transmit diversity using laser SC)

Hereafter, we use transmit laser selection to calculate the OP of the previously described model of a transdermal system. Here, one aperture receives the information signal that is delivered through L apertures (i.e., M = 1) using transmit laser selection (TLS). One can view our MISO system model as analogous to the SISO model where the route irradiation correlates to a TLS method in which the choice of the beam axis with a better value of diminishing gain (irradiance) [40], h_{max}, is possible to write as $h_{max} = max_{l=1,2,....L}\, h_l$. In this approach, it is possible to state that the statistical channel model that corresponds to this MISO configuration uses a SISO structure as a guide [38].

$$y = \eta \mathrm{x}\, \mathrm{h_{max}} + \mathrm{n} \tag{17}$$

where the division by L is omitted from (17), because only a single laser is being used at a time. This is necessary in order to keep a steady average optical power transmission level when calculating P_{out} . The CDF of the resulting channel irradiance, h_{max}, may be calculated using order statistics [41]. The CDF, $F_{h_{max}(i)}$, is given by $F_{h_{max}(i)}$ = $[F_h(i)]^L$ and the outage probability can be written as:

$$P_{out} = \left(\frac{1}{(A_\circ\, h_l)^{\xi}} \left(\frac{\gamma_{th}\, N_\circ}{\eta^2\, \bar{P}_s}\right)^{\xi}/_2\right)^{L} \tag{18}$$

2.3. Outage rate

The receiver experiences a deep fade condition when the received instantaneous SNR falls below a specific threshold γ_{th}, making it unable to correctly decode the received bits. Data bits will be transferred by the system at a steady rate of $C_{out} = B\, \log_2(1+\gamma_{th})$ because of the unknown CSI at the sending end, as mentioned by [42], [43] that have probability $(1 - P_{out})$and are successfully understood. Thus, the definition of the average outage rate is:

$$R_{out} = (1 - P_{out})\, B\, \log_2(1+\gamma_{th}) \tag{19}$$

where B is the signal bandwidth.

3. RESULTS AND DISCUSSION

In the following section, we will present performance results based on the OP and OR metrics for both SIMO and MISO TOW arrangements, which could use either OOK modulation format. We will consider the combined effects of pointing errors effect and attenuation caused by the skin over a wide range of average electrical SNR. To achieve this, we will utilize the closed-form expressions derived earlier (12), (15), (18), and (19). The system under investigation may utilize M = 1 to M = 5, L = 1 to L = 5 while the system's operating wavelength is set at λ = 850 nm, TOW links typically have a skin thickness of δ = 9 mm. The assumption is that η = 0.7 for every receiver aperture, *r* = 0.5 mm, θ = 35°, $\overline{P}_s$= 1 mw/MHz, σ =1.4422, α(λ) = 1.8 at λ=850 nm, A = 1 mm² and N_o = $(1.3\text{pA}/\sqrt{Hz})^2$. The degree of pointing error is labeled based on the values found for the parameter ξ, which is calculated as follows: ξ = 0.2 indicates a **severe** PE condition, ξ = 0.5 indicates a **strong** PE state, and ξ = 1 indicates a **moderate** PE state. In all the cases that follow, the appropriate results from Monte Carlo simulations are always shown alongside the numerical results from the closed-form mathematical equations that were previously produced.

Results in Figures 2 and 3 are now acquired for the SIMO TOW with OOK system under examination by using the matching (16) and (19) equations. The OP for SIMO signals is displayed in Figure 2 for a variety of SNR threshold values under various PE situations. It is clear that improved outage is achieved by expanding the TOW system's independent links. As a result, it is safe to say that PE plays a major role in the accomplishment of TOW links. The figure clarifies that the OP is function of PE, whereas the OP enhances as the system affected with strong rather than severe PE. Nevertheless, as the number of receiver apertures increases the OP gets better. At 15 dB and under moderate pointing error, OP using two receivers is around 5.2×10^{-5} and adding another two receivers achieves OP around 4.3×10^{-8}.

Outage rate for SIMO system, with an average SNR of 15dB, subjected to sever and strong PE is depicted in Figure 3. It is emphasized that the OR, for SIMO scheme increases significantly with the number of receivers, despite the stronger PE impact, whereas two values for ξ are chosen. The powerful PE effect causes a decrease in term OR performance even when using severe PE conditions in comparison to the strong case. It evidence that, as the receiver apertures increases more than 4, the OR gain can be ignored.

For the case of MISO TWO system, results for the OP and OR for the same system parameters were presented. The obtained results are shown in Figures 4-6. First, Figure 4 shows the outage probability for a range of normalized SNR values, i.e., the ratio of average SNR to threshold SNR with multiple transmitters. As shown from the figure, deep fading conditions are likely to occur for moderate-severe PE situations even for small values of normalized SNR. The figure also shows that as the number of transmitter units increases the OP will decrease, i.e., the link performance will improve as a consequence of the number of propagation apertures. Under strong PE and at 83 dB the OP is around 17.9×10^{-3} using two transmitters, and around 3×10^{-4} if transmitters number increase to 4.

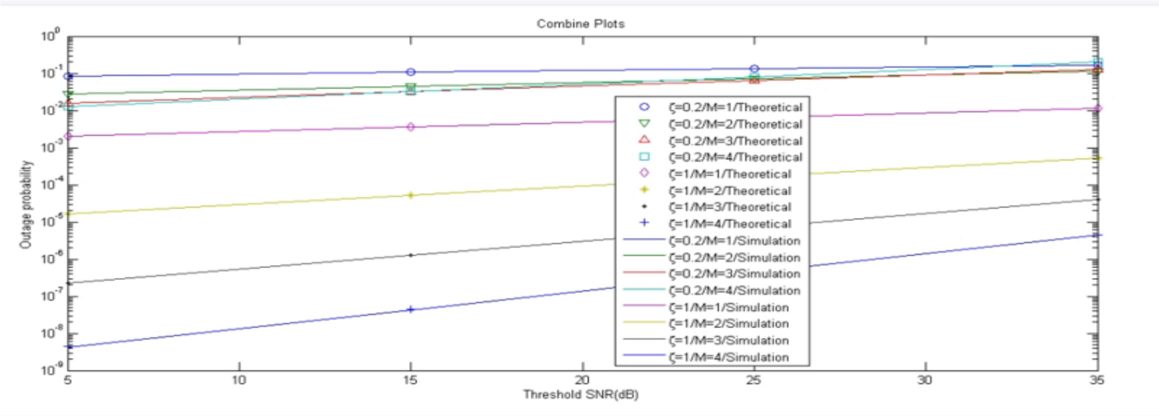

Figure 2. OP for SIMO links vs threshold SNR under multiple PE conditions for different number of receiver apertures

The outage probability for different values of **ξ** is shown as a function of the SNR threshold in Figure 5. In this illustration, the simulation results are represented by the corresponding continuous lines, whereas the analytical results are shown by markers. We also note that, for a given SNR threshold, the outage probability rises with increasing severity of pointing error effects, that is, with decreasing alignment level, **ξ**. Additionally, for a given **ξ**, the outage performance improves as predicted, as transmitters number increases. For example, for a SNR threshold equal 25 dB, L equals 2 and 4 respectively, the OP degrades from 17.6×10^{-3} to 3×10^{-4} when **ξ** is equal 0.2.

Figure 6 depicts the outage rate defined in (19) vs a variety of outage probability with a 15 dB average SNR, and suffering from server PE for various multiple values on L. As clearly seen adding more independent links to the system enhances the outage rate for a certain value of P_{out}. The figure presents comparable behavior as well, but because the PE conditions have changed from severe to strong, the performance is comparatively better. Furthermore, for a given value of **ξ**, the gain value, R_{out}/P_{out}, will increase when there are more transmitters; nevertheless, after the number of transmitters surpasses 4, the amount of gain will be negligible. It's worth mentioning that, using MISO, i.e., using multiple transmitters, scheme can achieve better OP compared with SIMO, i.e., using multiple receivers. At 25 dB, four transmitters/receivers and under severe PE, the OP in SIMO in the range of 10^{-2}, nevertheless in the range of 10^{-4} in MISO case.

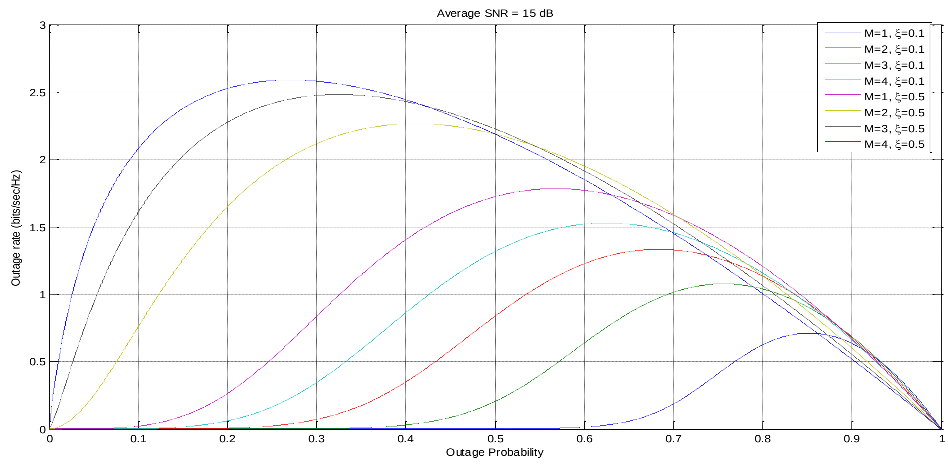

Figure 3. Outage rate for SIMO Links under multiple PE conditions

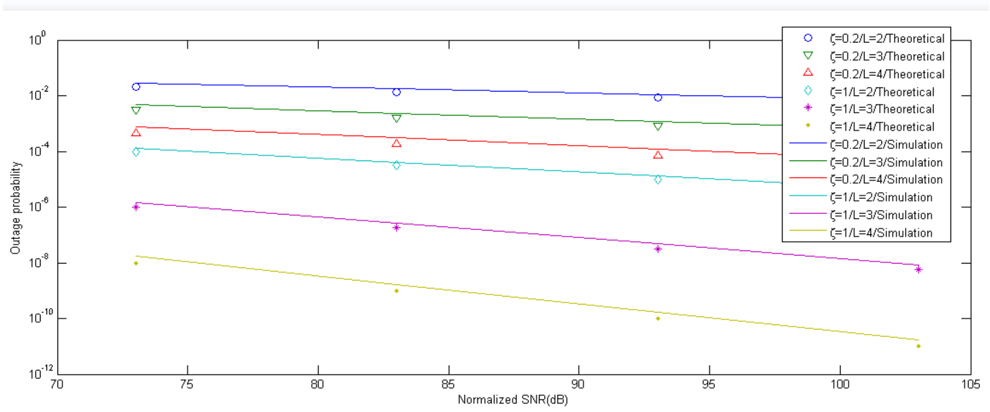

Figure 4. OP for MISO Link vs Normalized SNR under multiple PE conditions for different number of transmit apertures

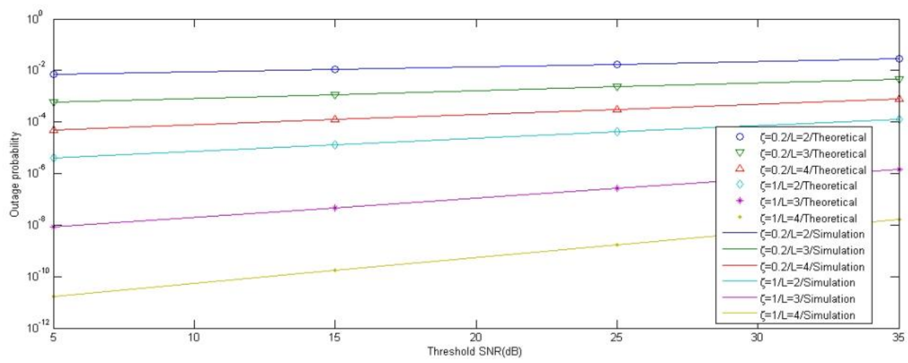

Figure 5. OP for MISO Link vs Threshold SNR under multiple PE conditions considering varying numbers of transmit apertures

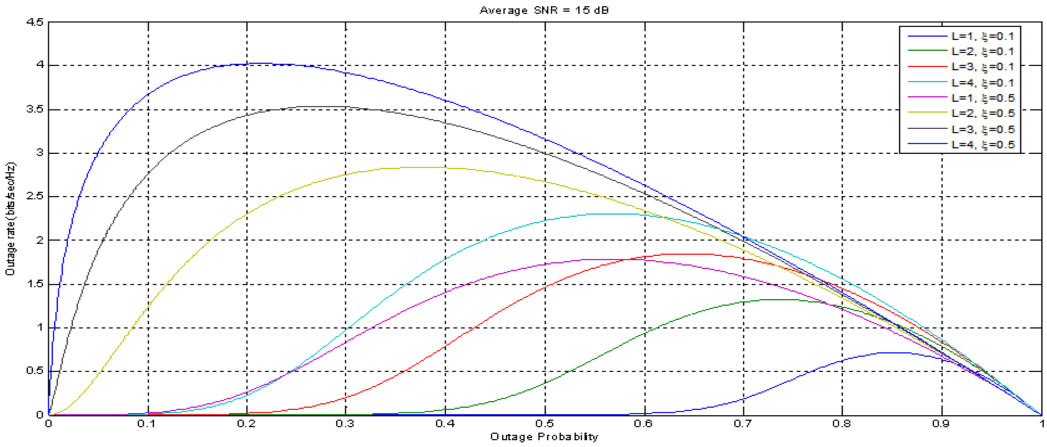

Figure 6. Outage rate for MISO links under multiple PE conditions

Figure 7 compares between SISO, MISO, and SIMO models in terms OP under severe PE conditions. As can be noted, as we move from SISO to MISO or SIMO the OP results get better, with better results in the case of MISO model over SIMO model as we mentioned previously.

These findings are significant since they support the previous findings regarding general communication links like FSO systems and more specific links like TOW systems; where our study suggests using spatial diversity techniques to enhance the TOW links efficiency and performance.

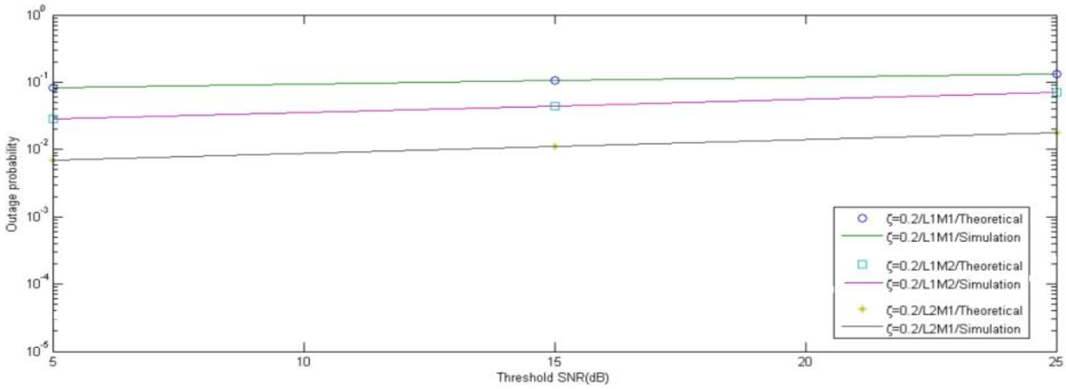

Figure 7. Comparison between SISO, MISO, and SIMO in terms of OP

4. CONCLUSION

In this proposed work, the effects of zero boresight aiming errors and skin-induced attenuation on a TOW communication system's outage performance when its transmitters or receivers are diverse such as SIMO and MISO TWO links using IM/DD with OOK modulation format and SC method at the receivers side has been examined. The main findings of this approach were the generation of new closed-form equations for the TWO system's OP and OR. We provided accurate numerical findings using extracted expressions, which were confirmed by simulations. These results show that using transmitter or receiver diversity can greatly enhance the outage performance of conventional TOW networks. In this case, adding more apertures to the transmitter or receiver will result in higher outage performance improvements. As a result, the suggested analysis is a helpful tool for designing more efficient TOW systems with improved availability and outage performance by overbalancing the key elements that negatively affect TOW development.

The study's field is relatively new and has potential for additional investigation. A wide range of engineering issues can be examined to expand the methodology suggested in this work, including: relying on the work presented to derive a formula for MIMO configuration. This work was limited in using independent identical distributed paths between the transmitter and the receiver, zero boresight PE, and IM/DD with OOK modulation. Future study may generalize the findings of this work to account for independent non-identical distributed pathways between the transmitter and the receiver and the non-zero boresight PE. In addition to examine the benefits of employing different power-efficient modulation techniques to fulfill the medical implants' intended purpose and speed demands.

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