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Time and wavelength diversity schemes for transdermal optical wireless links

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ABSTRACT

Transdermal optical wireless communication systems have gained significant research and commercial attention in recent years. While using the skin as a transmission medium, the performance of such a system is influenced by the transdermal channel conditions between the transmitter and receiver. Indeed, for transdermal optical channel links, the performance of a linked communication system can be significantly affected by skin-induced attenuation and pointing errors. Extra attention has been given to diversity techniques to anticipate this. This research examines a conventional transdermal optical wireless system by analyzing the outage probability, an important performance parameter that has not been previously evaluated for such systems using the same method. In an examination of outage probability, both skin-induced attenuation and stochastic spatial jitter, also referred to as pointing error effects, are included. The usefulness of this topic is demonstrated using analytical formulas and results that determine the probability of system outage under various skin channel conditions and varying levels of stochastic pointing faults. Simulation model using Monte-Carlo simulation method was conducted using MATLAB to validate our suggestions. The simulation results showed a good agreement with numerical results, which proved the effectiveness of using wavelength and time diversity schemes to enhance transdermal optical wireless based systems.

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1. INTRODUCTION

Recently, wireless medical applications have been the focus of many researchers in particular active medical implants (AMIs). The main roles of AMIs are to regulate electrically powered devices for medical purposes, such as medicine dispensers, and physiological signals that go to the nervous system, and cardiovascular system. For a variety of health issues, AMIs have been suggested as an effective solution [1]. Optical wireless communications (OWCs) performance has long been recognized as a viable alternative to radio frequency (RF) technology because of its superiority in terms of bandwidth abundance, data rates and interference immunity [2]–[4].

Several alternatives have been imposed to investigate the efficiency and reliability of the transdermal optical wireless (TOW) system [5]–[7]. In fact, many experiments were conducted to show the effectiveness of the TOW system in terms of link speed, transmitter and emitter power, skin thickness, misalignment and bit error rate (BER). Boulogeorgos *et al.* [8] conducted a study of “optical wireless communications for in-body and transdermal biomedical applications" and discussed the core designs of optical-wireless systems for biomedical applications, the main uses, their specifications, the properties of transdermal and in-body optical channels (OCs), and the difficulties they provide in communication system design.

Liu *et al.* [9] conducted an examination regarding data rate, transmitted power, tissue thickness, and the mathematical architecture of a cutaneous wirelessly optically link. Research has shown that transdermal optical links (TOLs) but, they did not consider the influence of pointing errors (PEs), which are likely to have a significant impact on out- to in-body applications. Bit error rate and pointing errors were investigated using deterministic models [10] and [11]. Movement of the transmitter (TX) and receiver (RX) induces this phenomenon, and these models fail to explain its unpredictable behavior. By factoring in the random TOL, Liu *et al.* [10] calculated an average signal-to-noise ratio (SNR) that assesses pointing errors.

The aim of this study is to investigate the influence of time and wavelength diversity in TOW systems affected by pointing errors on the system's outage performance. Specifically, the research focuses on deriving closed-form expressions for outage probability (OP). These expressions consider the distinctive attributes of the transdermal optical channel, the properties of the transceivers, and the extent of pointing errors. The findings from this analysis provide valuable technical insights and mathematical tools essential for the efficient design of transdermal OWC systems.

2. METHOD

2.1. System model

In the analysis presented in Figure 1, proposed model is predicated on the presumption of full skin channel state information (CSI) availability and the utilization of a wireless transdermal optical direct connection setup. Furthermore, we assume a TOW communications system with intensity modulated direct detection and on-off keying modulation (IMDD/OOK), and selective combining (SC) criteria for the different diversity techniques at the receiver. Herein, we take a look at how TOW communication systems can utilize time and wavelength diversity. Assuming that the transmitter sends out M transmissions of the same information signal at the same receiver, each at a little distinct point in time for time diversity approach [12]. However, in a time diversity, each copy that propagates addresses a different set of channel characteristics because the transmitter is sending out M copies of the same signal at M different times and the channel characteristics change at random. Thus, M separate virtual propagation pathways (or receivers) are considered. Each of the M copies really arrives at the receiver and waits in the system's buffer until all of the copies have been received. Information is transmitted M times, each time within the same path but with different channel settings; the resulting signal at the receiver's buffer is a product of these M signals [12], [13]. Lastly, wavelength diversity works by having a composite transmitter deliver M optical wavelength replicas of the same information signal to M recipients [14].

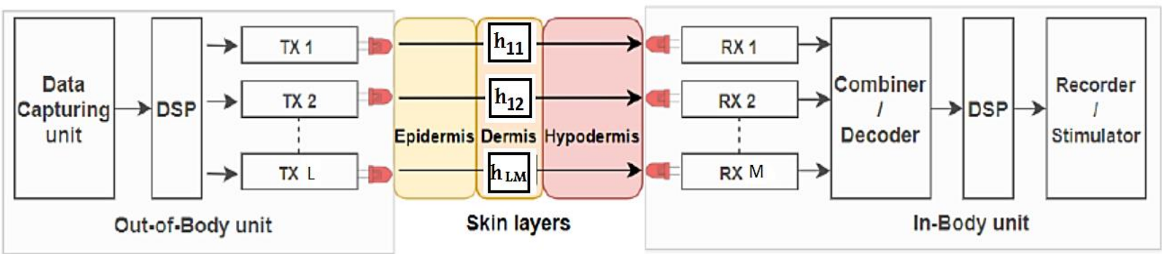

Figure 1. General proposed system model

Next, for the examined TOW system, the statistical channel model is expressed as (1).

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

where n is the zero mean Gaussian process with variance σ_n^2, η is the photodiode's efficiency, and power spectral density $N_o/2$ is expressed in watts/Hz. Additionally, $x\epsilon\{0,1\}$ represents the OOK data information signal.

In (1), h is the skin channel state and can be written as [15].

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

in which h_l is the deterministic channel coefficient resulting from propagation loss (skin attenuation), while the second term h_p is a stochastic process due to misaligned fading.

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

The deterministic term h_l can be obtained as [15]–[17].

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

where α(λ) is the skin attenuation coefficient at an operating wavelength λ in "nm". The skin thickness is donated by the parameter δ, which is equivalent to the communication distance between the transmitter and the receiver. The term α(λ) is a representation of the skin attenuation coefficient that may be assessed for λ=400 nm to λ=1,800 nm using [18],

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

where λ is stated in nm, and the values of a_i, b_i, and c_i, with $i = 1,2,\ldots,8$, are provided in Table 1.

Table 1. The a_i, b_i and c_i values [18]

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

Beckmann's model provides a statistical description of the PRs effect that considers the impact of beam width, detector size, varied jitters for horizontal and vertical movement, and the nonzero boresight (NZB) error was derived by Boluda-Ruiz *et al.* [19], which is approximated by Farid and Hranilovic [20] when boresight pointing errors are zero to (5).

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

where $\varphi = w_{eq}/2\sigma_s$ is the proportion of the receiver's equivalent beam radius to the receiver's standard deviation of the pointing error displacement. $A_\circ = [\mathrm{erf}\,(v)]^2$ is the percentage of the power gathered at $r = 0$, and notation erf (.) is the error function, with $v = \sqrt{\pi} r/\sqrt{2} w_\delta$ and r represent the circular receiving aperture's radius, and $w_\delta = \delta\ \tan(\frac{\theta}{2})$ is the beam waste of the RX plane, with a computed radius of e^{-2} at distance δ from the transmitter, with θ represents the beam's divergence angle. The equivalent beam radius can be expressed as $w_{eq}^2 = w_\delta^2 \sqrt{\pi}\,\mathrm{erf}(v)\ /2v\exp(-v^2)$.

Hence, when a Gaussian beam propagates through distance δ from the transmitter to a circular detector with aperture radius r. The probability density function (PDF) for the channel random variable h_p can be obtained as [18],

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

Likewise, ξ is the equivalent beam radius squared ratio of the w_{eq}, and the displacement standard deviation of the pointing error at the RX, which can be expressed as $\xi = {\omega^2}_{eq}/4{\sigma_s}^2$, and also represents the PE's sensitivity (a lower value of ξ indicates a more severe misalignment condition) [19]. Practical values for ξ fall between 0.1 and 2 [15]. In fact, the approximation in (6) is well accepted in the literature and has been utilized in a number of researches [15], [16], [18], and [21]. As stated in [20], it truly agrees with the precise value of h_p particularly when the ratio $\omega_\delta/a > 6$ is satisfied. This results in a normalized mean squared error (NMSE) of less than 10^{-3}.

2.2. Outage probability

In order to assess how reliable the TOL is, an analysis of its outage performance was conducted. The outage probability is the probability that the instantaneous sum of SNR (γ) drops below a given threshold value (γ_{th}) and can be expressed as [17], [22],

$$P_{out} = Prob(\gamma \leq \gamma_{th}) = \int_0^{\gamma_{th}} f_\gamma(\gamma) d_{\gamma_T} = F_\gamma(\gamma_{th}) \quad (7)$$

where the instantaneous signal-to-noise ratio, γ, PDF and the cumulative distribution functions (CDF) are represented by the variables $f_\gamma(\gamma)$ and $F_\gamma(\gamma)$, respectively.

The definition of the instantaneous SNR is [17],

$$\gamma = \frac{\eta^2 exp(-\alpha(\lambda)\delta)\, h_p^2 \bar{P}_s}{N_\circ} \quad (8)$$

Next, the average SNR, $\tilde{\gamma}$, has the form [17],

$$\tilde{\gamma} = \frac{\xi\, A_\circ^2 \eta^2 \exp(-\alpha(\lambda)\delta)\bar{P}_s}{(\xi+2)N_\circ} \quad (9)$$

Using (7), and going through some mathematical manipulation, the outage probability can be found as (10).

$$P_{out} = Prob\left(\frac{\eta^2 h_l^2\, h_p^2 \bar{P}_s}{N_\circ} \leq \gamma_{th}\right) = F_h^2\left(\frac{\gamma_{th}\, N_\circ}{\eta^2\, h_l^2\, \bar{P}_s}\right) \quad (10)$$

where $\overline{P}_s$ is the average power and F_h^2 is second order cumulative distribution of the channel. It was shown by Trevlakis *et al.* [17], that the outage probability P_{out} can be written as (11).

$$P_{out} = \frac{1}{(A_\circ\, h_l)^\xi} \left(\frac{\gamma_{th}\, N_\circ}{\eta^2\, \bar{P}_s}\right)^{\xi/2} \quad (11)$$

Equivalently, this could be written as (12) [17].

$$P_{out}(\gamma_{th}) = \left(\frac{\xi}{\xi+2} \frac{\gamma_{th}}{\tilde{\gamma}}\right)^{\xi/2} \quad (12)$$

2.3. Outage probability for time diversity scheme

Simulating the TOW link's time diversity technique requires only one sender and several recipients, just like any other communication system. The reason for this is that M identical copies of the signal are being sent by the transmitter at M distinct times. The copy of every signal that is received by the receiver is stored in the receiver's memory [13].

In this case, the signal processing operation is implemented using M signals, which have all been transmitted from the transmitter and have spread throughout the same channel, however with slightly distinct periods of time. The laser beam in transdermal links follows a rectilinear path as it travels through the skin, which acts as an additive white Gaussian noise (AWGN) channel. We assume memoryless, static ergodic and independent and i.i.d. intensity fast fading channel. In addition, we presume OOK modulation with a binary input and a continuous output using IMDD. In addition, we assume that the CSI is shared between the sender and the receiver.

As mentioned above, TOW link can be modeled as a communication system with a single transmitter and an arbitrary number of receivers (M in this case), and we use this assumption to simulate the time diversity feature of the TOW link, which involves sending out M copies of each part of the signal. Therefore, the statistical channel model is [14], [23],

$$y_m = \eta x\, h_m + n, m = 1, \ldots.. M \quad (13)$$

with y_m represents the copy of each signal at the receiver, η is the receiver's effective photo-current conversion ratio, h_m is the normalized instantaneous irradiance that reaches the receiver, the modulated signal, x, has values of “0” or “1”, and the AWGN, n, has zero mean and $N_o/2$ variance. Additionally, the assessment of the outage probability for each of the M transmitted signal copies is provided in (11). Considering that each signal copy has an independent outage probability [14], then the outage probability for the entire temporal diversity transdermal link is equal to the outage probability for all M copies of the provided data. It is mathematically expressible by (14),

$$P_{out} = \prod_{m=1}^{M} P_{out,m} = \prod_{m=1}^{M} Pr(\gamma \le \gamma_{th}) = \prod_{m=1}^{M} F_{\gamma}(\gamma_{th}) \tag{14}$$

The definition of the instantaneous SNR is [17].

$$\gamma = \frac{\eta^2 \exp(-\alpha(\lambda)\delta)\, h_p^2 \bar{P}_s}{N_o} \tag{15}$$

By substituting (8) into (14) as follows, one can obtain the closed form expression for the transdermal link's total outage probability with time diversity.

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

2.4. Outage probability for wavelength diversity scheme

TOW system that incorporates wavelength diversity is a communication system with a composite transmitter that broadcasts a signal at many operational wavelengths simultaneously to multiple receivers, each of which is tuned to pick up the signal at a single wavelength [14]. The explanation behind this is as follows; assume that M transmitters at M distinct wavelengths send the signal concurrently in a TOW system consists of M trans-receivers. If each receiver "recognizes" just its own wavelength, then the m^{th} copy of the signal (where $m = 1, \dots, M$) will only be picked up by the m-th receiver. Optical receivers are limited in the wavelength range within which they can function well, therefore the m^{th} signal in the m^{th} receiver can only have come from the m^{th} transmitter that broadcasts at the m^{th} wavelength. Since each transmitter can only communicate with a single receiver, the wavelength diversity scheme for a TOW link can be understood as a composite transmitter communicating with M receivers, one at each end of a spectrum of wavelengths [24].

In light of the foregoing, let us think about the m^{th} laser beam as it travels horizontally through a channel containing AWGN. We assume a memoryless, stationary, ergodic channel including binary input and continuous output, IMDD with OOK modulation, CSI at both the transmitter and the receiver, and i.i.d. intensity rapid fading statistics [14]. The statistical channel model has an expression provided by [23], [25],

$$Y_m = \eta_m x\, h_m + n, m = 1, \dots, M \tag{17}$$

where y_m represents each M receiver's output signal, η_m is each receiver's effective photocurrent conversion ratio, h_m is the received normalized irradiance in every receiver, x is the signal that has been modulated, accepting the binary values "0" or "1", and n depicts the AWGN with a zero mean and a variance of $N_o/2$. As was previously discussed, the outage probability occurring for each of the M copies of the broadcast signal is expressed in (11). Due to the fact that not all combined channel gains have a PDF that converges to a closed-form expression, particularly when there are a large number of links, the OP in a multi-receiver system is treated in a different method in this study as it presented by [21].

Assuming that each communication line will operate independently from other lines as long as the necessary distance between the receivers is maintained, the likelihood of a deep fade is reduced to the product of the probabilities of each individual outage. In the context of i.i.d. links, OP might be expressed as (18).

$$P_{out,M} = P_{out,link\ 1}\, P_{out,link\ 2} \cdots P_{out,link\ M} \tag{18}$$

3. RESULTS AND DISCUSSION

Numerical results are presented using novel closed form expressions derived in the previous chapter for the system metrics. In order to confirm the accuracy of the numerical results, the results of a Monte Carlo simulation are additionally provided. A good agreement was concluded between the numerical and the simulated results. The system under examination has the option to utilize M=1 to M=5, L=1 to L=5 TOW links, with an average skin thickness of $\delta = 9$ mm. The system’s operational wavelength remains constant at

$\lambda = 850$ nm. For each receiver aperture, it is assumed that $\eta = 0.7$, $r = 0.5$ mm, $\theta = 35°$, $\overline{P}_s = 1$ mw/MHz, $\sigma = 1.4422$, $\alpha(\lambda) = 1.8$ at $\lambda = 850$ nm, $A = 1$ mm² and $N_o = (1.3\ \text{pA}/\sqrt{\text{Hz}})^2$. Pointing error severity is labeled in accordance with the values obtained for the parameter ξ, which is computed as $\xi = 0.2$, implies severe PE state, $\xi = 0.5$, implies strong PE state, $\xi = 1$, implies moderate PE state.

The OP can be estimated for a TOW system with wavelength and time diversity using the expressions obtained in (16) and (18). Here numerical results for the achieved OP of a time- or wavelength-diversity TOW system were presented and their change for several system factors that could impact the TOW system's efficiency was checked. It is assumed that M, the time diversity parameter, can take on the values 1, 2, 3, and 4 with a single increment. Expression (16) is used to calculate the outage probability of a time diversity TOW link. Considering severe and moderate PE conditions, the OP for various links (M=1,2,3 and 4) is shown in Figure 2. The OP enhancement when going from M=1 to M=2,3 and 4 for multiple SNR threshold values, under moderate PE are summarized in Table 2. For instance, choosing to deploy three independent receive apertures under severe PE results in 2.34×10^{-3} OP enhancement when operating at 25 dB SNR.

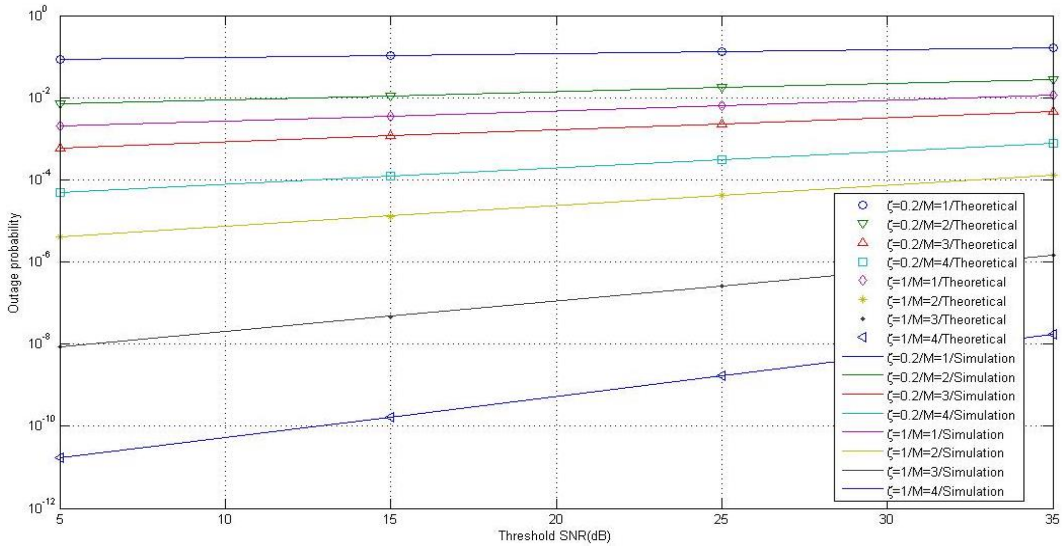

Figure 2. OP with time diversity vs threshold SNR for various values of the time diversity parameter M

Table 2. OP enhancement for M=1,2,3 and 4 under ξ=1

SNR	15 dB	25 dB	35 dB
M=1	0.1054	0.1327	0.1671
M=2	1.305×10^{-5}	4.11×10^{-5}	1.303×10^{-4}
M=3	4.714×10^{-8}	2.64×10^{-7}	1.485×10^{-6}
M=4	1.698×10^{-10}	1.7×10^{-9}	1.698×10^{-8}

Furthermore, it is obvious that as the effect of pointing errors becomes more severe, i.e. as the value of ξ decreases, the outage probability gets worse, for a fixed threshold SNR. At 25 dB, the OP under severs PE 2.34×10^{-3} compared with 2.64×10^{-7} under moderate PE using the same number of receiver apertures (M=3). The OP is rewritten in terms of normalized SNR for validation purposes, as illustrated in Figure 3. It is clear that the existence of a stronger time diversity scheme, i.e. regardless of the PE degree, greater values of M result in significantly better availability results for the TOW links.

In the following numerical results, the OP, P_{out}, is displayed as a function of skin thickness for the above-mentioned values of M as shown in Figure 4. As discussed previously, as skin thickness increases, link availability decreases. Moreover, an improvement in OP when moving from M=1 arrangement to M=2, 3, and 4.

Figure 5 demonstrates the outage probability for various values of M as a function of the operating wavelength and fixed value of jitter standard deviation, σ. The smallest value of OP will occur at λ= 1,200, which represents the optimal transmission wavelength. The results emphasize that using multiple links will improve link availability.

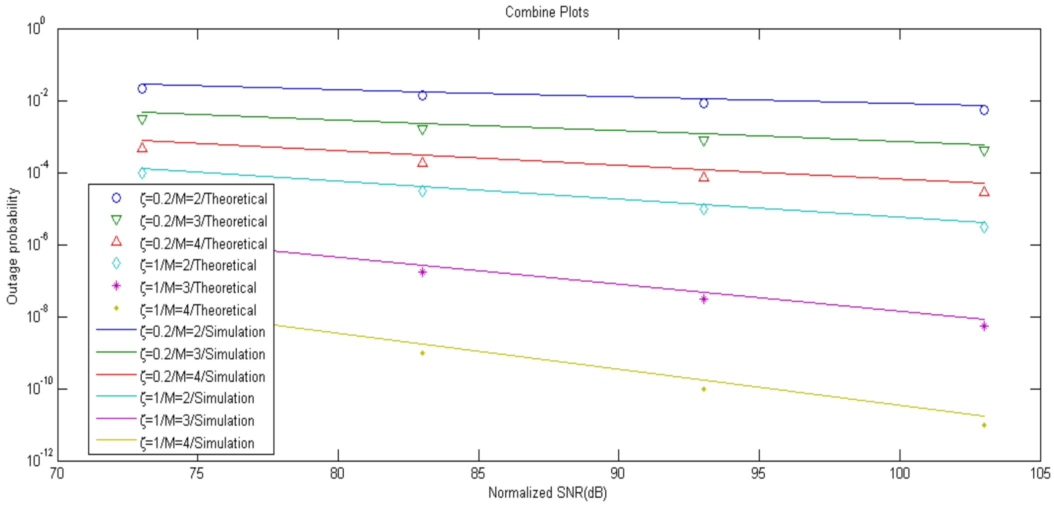

Figure 3. OP with time diversity vs normalized SNR for a range of time variety parameter M values

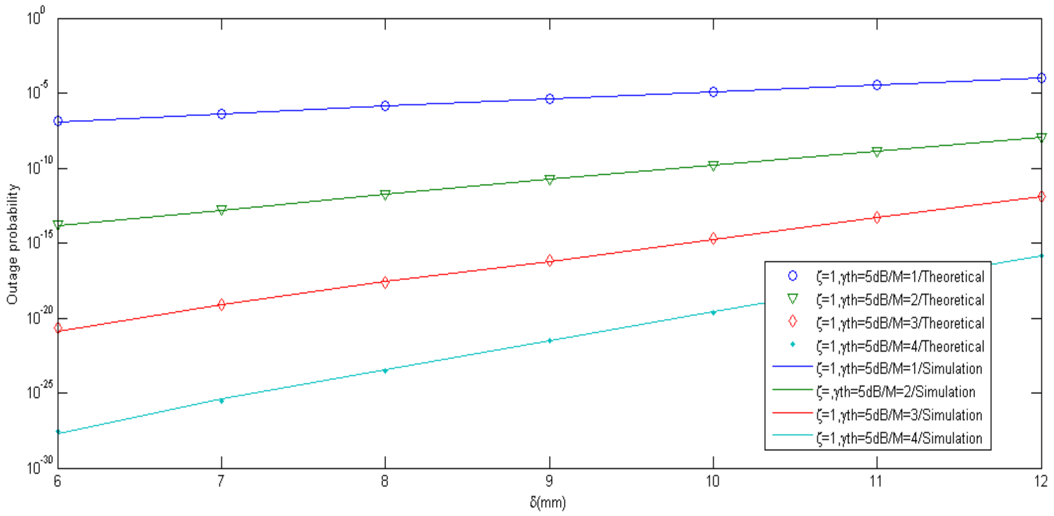

Figure 4. OP with time diversity vs skin thickness for various values of the time diversity parameter M

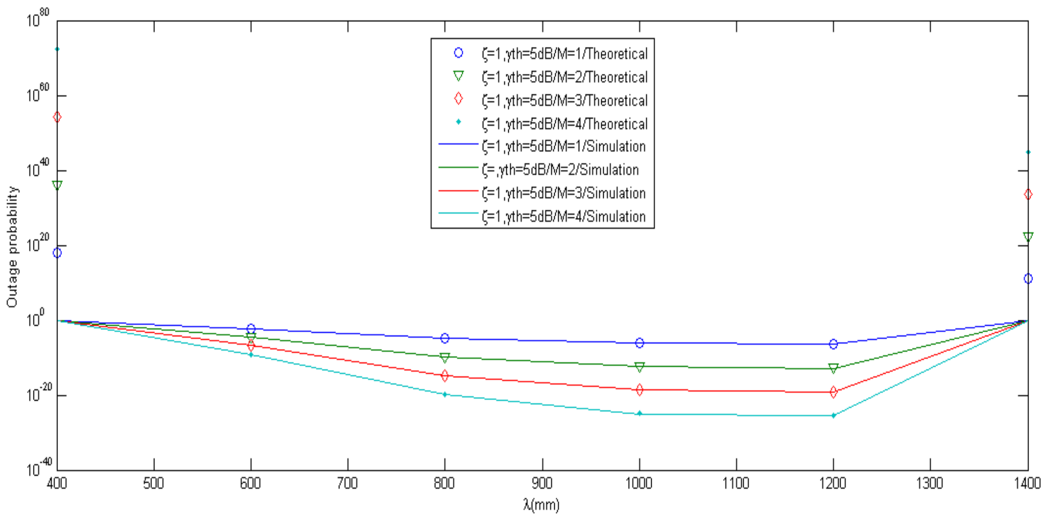

Figure 5. OP with time diversity vs wavelength for a range of time variety parameter M values

For the case of the wavelength diversity scheme, results for the OP for the same system parameters were presented. These parameters include the various channels' M numbers, λ_m, $(m = 1, \dots, M)$. The obtained results are shown in Figures 6 and 7. First, the outage probability versus the skin thickness as visualized in Figure 6 was estimated. For specific instantaneous SNR threshold ($\gamma_{th} = 1$) and under moderate PE, initially significant OP decrements as skin thickness decreased was obtained. Either way, using wavelength diversity results in notable improvements in outage performance.

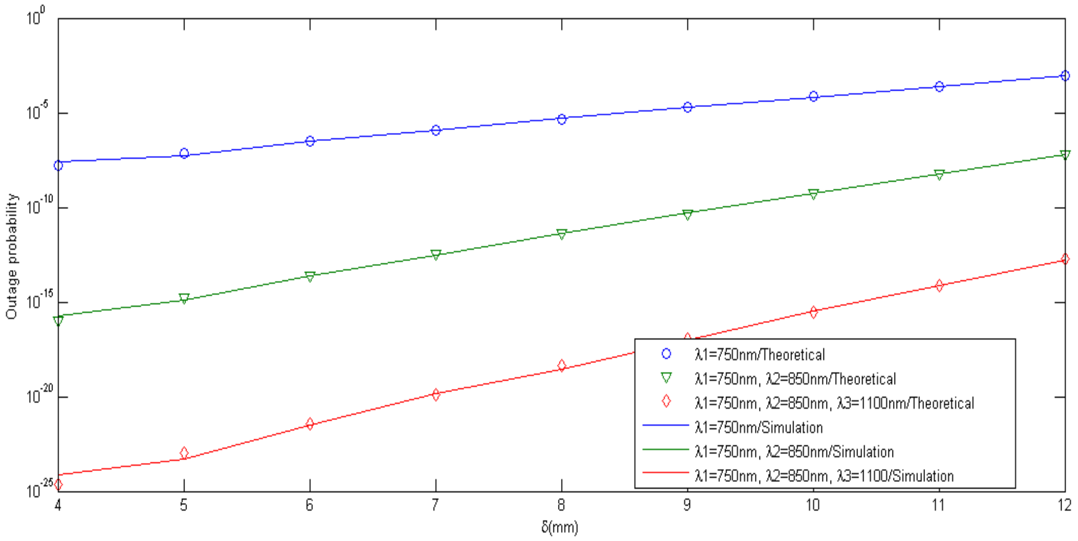

Figure 6. OP vs skin thickness with wavelength diversity

The outage probability (OP) is then estimated as a function of ξ using (18). Figure 7 displays the acquired results and shows that using wavelength diversity can greatly reduce the outage probability of a typical TOW link, particularly when more wavelengths are used. Additionally, lower SNR threshold levels and weaker pointing error can considerably reduce the TOW link's outage probability and enhance system performance. A comparison between this study and the state-of-the-art research mentioned in this work is shown in Table 3.

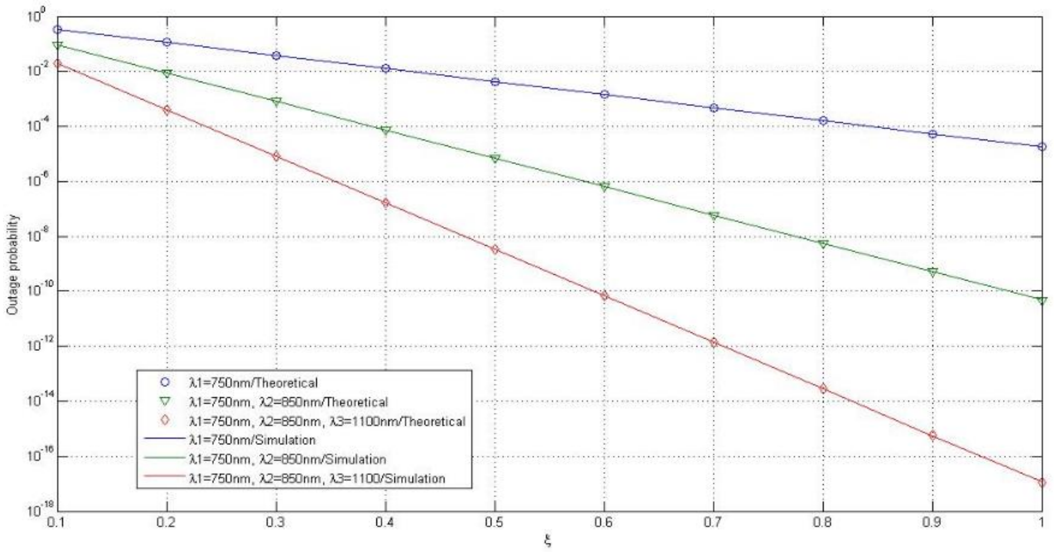

Figure 7. OP vs ξ with wavelength diversity

Table 3. A Comparison between this study and related work

Author [s]	Outcome
Varotsos *et al.* [12]	Provided an effectiveness evaluation of On-Off keying free space optical (FSO) communication systems while accounting for pointing defects and established closed-form computations for estimating the fade possibility.
Nistazakis [13]	A closed-form mathematical expression for the calculation of the interruption possibility, the typical bit error rate, and the absolute maximum operational bit rate is derived from the investigation of a time-diversity system for space-free optical components networks in severe turbulent circumstances modelled with the adverse exponential variance.
Nistazakis and Tombras [14]	According to inadequate to robust turbulent atmospheric circumstances modelled by the gamma-gamma shipment, obtained closed-form computations for determining the structure's feasible probability of failure and common bit error rate, taking into account the utilization of time and wavelength diversity in wireless optical communications networks.
Varotsos *et al.* [16]	Derived new closed form mathematical formulas for the outage probability of the entire TOW system under the influence of NZB pointing errors that use various diversity configurations in space, time, or wavelength.
Trevlakis *et al.* [17]	Obtained a closed-form expression for the optical wireless transdermal link's outage probability that accounts for the physical limitations of the in-body device, the transmitter-receiver misalignment, the channel particularities, and the optical unit characteristics.
Rachmani and Arnon [24]	Proposed using a lab test bed to assess how well a wavelength-diversity-based communication system performs in relation to turbulence amplitude.
This study	Evaluated the transdermal optical wireless communications system's performance when time or wavelength diversity techniques are used. Moreover, closed-form expressions for estimating the outage probability—one of the crucial system performance metrics—for the case of selective combining at the receiver's end. The approach, methodology and results of this research work lakes in any of the references mentioned above.

4. CONCLUSION

In recent years, the TOW communication systems have emerged as a focal point of both research and commercial interest. This heightened attention can be attributed to their potential applications in various fields, ranging from healthcare to consumer electronics. However, the unique characteristic of utilizing the skin as a transmission medium poses challenges to the performance of such systems. The efficacy of the TOW system is intricately linked to the transdermal channel's conditions between the transmitter and receiver. Specifically, factors such as pointing errors and skin-induced attenuation play pivotal roles in determining the overall performance of the communication system. These challenges underscore the importance of investigating and understanding the underlying mechanisms governing the behavior of TOW systems, as well as developing strategies to mitigate the adverse effects of channel impairments.

The effectiveness of transdermal optical wireless communication systems that employ either wavelength or temporal diversity approaches is assessed in this study. We estimated the outage probability using closed-form equations for the selective combining scenario at the receiver, which is an important performance parameter. We examined the behavior of the TOW system under different parameter settings using these equations. According to the results, the link's performance metrics are improved by both temporal and wavelength diversity. The maximum effective bit rate must be lowered with temporal diversity, and system complexity and expense are increased with wavelength diversity due to the requirement for an individual transceiver for each wavelength. This was highlighted analytically and numerically for specific insightful cases. Additionally, the system was configured to examine the added benefit of time and wavelength diversity strategies on the overall performance. There was a noticeable improvement over the first post. Finally, it is also demonstrated that the severity of PE has a significant impact on the outage probability.

REFERENCES

[1] Y. Gil, N. Rotter, and S. Arnon, "Feasibility of retroreflective transdermal optical wireless communication," *Applied Optics*, vol. 51, no. 18, pp. 4232–4239, Jun. 2012, doi: 10.1364/AO.51.004232.

[2] A. Apostolos and Boulogeorgos, "Low-cost cognitive radios against spectrum scarcity," *Journal Of Networking and Internet Architecture*, no. 1, pp. 2–5, 2018.

[3] A.-A. A. Boulogeorgos, "Interference mitigation techniques in modern," Ph.D. dissertation, Telecommunications Department, Aristotle University of Thessaloniki, 2016.

[4] D. K. Borah, A. C. Boucouvalas, C. C. Davis, S. Hranilovic, and K. Yiannopoulos, "A review of communication-oriented optical wireless systems," *Eurasip Journal on Wireless Communications and Networking*, vol. 2012, no. 1, Mar. 2012, doi: 10.1186/1687-1499-2012-91.

[5] D. M. Ackermann, B. Smith, K. L. Kilgore, and P. H. Peckham, "Design of a high speed transcutaneous optical telemetry link," in *Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings*, Aug. 2006, pp. 2932–2935. doi: 10.1109/IEMBS.2006.260398.

[6] D. M. Ackermann, B. Smith, X. F. Wang, K. L. Kilgore, and P. H. Peckham, "Designing the optical interface of a transcutaneous optical telemetry link," *IEEE Transactions on Biomedical Engineering*, vol. 55, no. 4, pp. 1365–1373, Apr. 2008, doi: 10.1109/TBME.2007.913411.

[7] J. L. Abita and W. Schneider, "Transdermal Optical Communications," *Johns Hopkins Apl Technical Digest*, vol. 25, no. 3, pp. 261–267, 2004.

[8] A. A. A. Boulogeorgos, S. E. Trevlakis, and N. D. Chatzidiamantis, "Optical wireless communications for in-body and transdermal biomedical applications," *IEEE Communications Magazine*, vol. 59, no. 1, pp. 119–125, 2021, doi: 10.1109/MCOM.001.2000280.

[9] T. Liu, J. Anders, and M. Ortmanns, "System level model for transcutaneous optical telemetric link," in *Proceedings - IEEE International Symposium on Circuits and Systems*, May 2013, pp. 865–868. doi: 10.1109/ISCAS.2013.6571984.

[10] T. Liu, U. Bihr, S. M. Anis, and M. Ortmanns, "Optical transcutaneous link for low power, high data rate telemetry," in *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, Aug. 2012, pp. 3535–3538. doi: 10.1109/EMBC.2012.6346729.

[11] T. Liu, U. Bihr, J. Becker, J. Anders, and M. Ortmanns, "In vivo verification of a 100 Mbps transcutaneous optical telemetric link," in *IEEE 2014 Biomedical Circuits and Systems Conference, BioCAS 2014 - Proceedings*, Oct. 2014, pp. 580–583. doi: 10.1109/BioCAS.2014.6981792.

[12] G. K. Varotsos, H. E. Nistazakis, C. K. Volos, and G. S. Tombras, "FSO links with diversity pointing errors and temporal broadening of the pulses over weak to strong atmospheric turbulence channels," *Optik*, vol. 127, no. 6, pp. 3402–3409, Mar. 2016, doi: 10.1016/j.ijleo.2015.12.060.

[13] H. E. Nistazakis, "A time-diversity scheme for wireless optical links over exponentially modeled turbulence channels," *Optik*, vol. 124, no. 13, pp. 1386–1391, Jul. 2013, doi: 10.1016/j.ijleo.2012.03.065.

[14] H. E. Nistazakis and G. S. Tombras, "On the use of wavelength and time diversity in optical wireless communication systems over gamma-gamma turbulence channels," *Optics and Laser Technology*, vol. 44, no. 7, pp. 2088–2094, Oct. 2012, doi: 10.1016/j.optlastec.2012.03.021.

[15] S. E. Trevlakis, A. A. A. Boulogeorgos, and G. K. Karagiannidis, "On the impact of misalignment fading in transdermal optical wireless communications," in *2018 7th International Conference on Modern Circuits and Systems Technologies, MOCAST 2018*, May 2018, pp. 1–4. doi: 10.1109/MOCAST.2018.8376613.

[16] G. K. Varotsos, H. E. Nistazakis, G. S. Tombras, K. Aidinis, F. Jaber, and K. K. Mujeeb Rahman, "On the use of diversity in transdermal optical wireless links with nonzero boresight pointing errors for outage performance estimation," *2019 8th International Conference on Modern Circuits and Systems Technologies (MOCAST)*, Thessaloniki, Greece, 2019, pp. 1-4, doi: 10.1109/MOCAST.2019.8741807.

[17] S. E. Trevlakis, A. Boulogcorgos Alexandros-Apostolos, and G. K. Karagiannidis, "Outage Performance of Transdermal Optical Wireless Links in the Presence of Pointing Errors," in *IEEE Workshop on Signal Processing Advances in Wireless Communications, SPAWC*, Jun. 2018, vol. 2018-June. doi: 10.1109/SPAWC.2018.8445766.

[18] S. E. Trevlakis, A. A. A. Boulogeorgos, and G. K. Karagiannidis, "Signal Quality Assessment for Transdermal Optical Wireless Communications under Pointing Errors †," *Technologies*, vol. 6, no. 4, p. 109, Nov. 2018, doi: 10.3390/technologies6040109.

[19] R. Boluda-Ruiz, A. García-Zambrana, B. Castillo-Vázquez, and C. Castillo-Vázquez, "Impact of nonzero boresight pointing error on ergodic capacity of MIMO FSO communication systems," *Optics Express*, vol. 24, no. 4, p. 3513, Feb. 2016, doi: 10.1364/oe.24.003513.

[20] A. A. Farid and S. Hranilovic, "Outage capacity optimization for free-space optical links with pointing errors," *Journal of Lightwave Technology*, vol. 25, no. 7, pp. 1702–1710, Jul. 2007, doi: 10.1109/JLT.2007.899174.

[21] S. E. Trevlakis, A.-A. A. Boulogeorgos, P. C. Sofotasios, S. Muhaidat, and G. K. Karagiannidis, "Optical wireless cochlear implants," *Biomedical Optics Express*, vol. 10, no. 2, p. 707, Jan. 2019, doi: 10.1364/boe.10.000707.

[22] A. García-Zambrana, C. Castillo-Vázquez, and B. Castillo-Vázquez, "Outage performance of MIMO FSO links over strong turbulence and misalignment fading channels," *Optics Express*, vol. 19, no. 14, p. 13480, Jun. 2011, doi: 10.1364/oe.19.013480.

[23] T. A. Tsiftsis, H. G. Sandalidis, G. K. Karagiannidis, and M. Uysal, "Optical wireless links with spatial diversity over strong atmospheric turbulence channels," *IEEE Transactions on Wireless Communications*, vol. 8, no. 2, pp. 951–957, Feb. 2009, doi: 10.1109/TWC.2009.071318.

[24] R. Rachmani and S. Arnon, "Wavelength diversity in turbulence channels for sensor networks," in *2010 IEEE 26th Convention of Electrical and Electronics Engineers in Israel, IEEEI 2010*, Nov. 2010, pp. 915–918. doi: 10.1109/EEEI.2010.5661946.

[25] H. E. Nistazakis, V. D. Assimakopoulos, and G. S. Tombras, "Performance estimation of free space optical links over negative exponential atmospheric turbulence channels," *Optik*, vol. 122, no. 24, pp. 2191–2194, Dec. 2011, doi: 10.1016/j.ijleo.2011.01.013.

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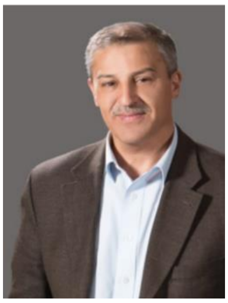

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