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Diversity Schemes in Multi-hop Visible Light Communications for 6G Networks

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Abstract

With the fast-emerging trend of deploying Internet-of-things (IoT) in smart homes and cities, next-generation wireless systems (i.e., beyond fifth generation (5G) of wireless mobile communications) are expected to connect a plurality of devices, including machines, sensors, tablets, cameras, etc. To this end, the radio frequency (RF) spectrum would fail to fulfill the demands of such enormous data-heavy wireless applications, as operating at the RF spectrum would largely suffer from data congestion and interference. Based on the potential of Visible Light Communications (VLC) to solve the problem of spectrum scarcity and satisfy the high data-rate requirements of beyond 5G systems, this paper focuses on utilizing VLC for IoT applications in indoor environments by means of adequately routing data among VLC-based nodes. Operating at the unlicensed optical band in the visible light region utilizes simple Light-Emitting-Diodes (LEDs), which is a health-friendly communication method. VLC has the advantages of providing ultra-high bandwidth, robustness to electromagnetic interference, and inherent physical security. VLC, however, suffers from severe short communication ranges and line-of-sight (LoS) constraints. This paper proposes overcoming such challenges by means of adopting a transmit diversity scheme that transmits messages over several paths. In order to reduce the receiver outage probability, the paper proposes multiple combination schemes at the receiver side, namely selection combining, maximal-ratio combining, and threshold combining. The simulation results assess the effectiveness of the proposed diversity schemes in terms of signal-to-noise-ratio and outage probability and illustrate the suitability of deploying VLC for next-generation indoor networks. The results show that that maximal-ratio combining outperforms selection combining and threshold combining by approximately 10% and 40%, respectively.

Keywords: 6G, Visible Light Communication, Diversity, Combination Protocols, Internet-of-things, Indoor applications

1. Introduction

In recent years, affordable technologies have enabled a wide-spread deployment of Internet-of-things (IoT) devices. While efficient deployment of IoT ensures advanced connectivity among different devices,

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systems, or services, the corresponding number of connected devices increases exponentially. The tremendous research efforts devoted to millimeter-wave and terahertz (THz) wireless communications indicate that wide-spread fifth generation (5G) networks will be realized sooner than already thought. Beyond 5G technologies (i.e., sixth generation (6G)) are the key enablers for realizing the full potential of IoT, virtual reality, autonomous driving, and many more new applications that require higher data rates with less latency [1]. While the future generations of mobile communications are expected to support smart vehicles, transport infrastructure, and remote control of heavy machinery, systems would be vulnerable to wireless interference. According to IHS Markit Technology, the number of devices grows by over 12% every year. IHS also forecasts that the total number of devices is expected to exceed 75.44 billion worldwide by 2025 [2], which represents a fivefold increase in less than ten years. The radio frequency (RF) spectrum, therefore, would mostly suffer from data congestion and spectrum scarcity, and would eventually fail to satisfy the data-rate requirements. Moreover, connecting a massive number of devices to the RF spectrum would impose a serious interference problem, which would result in several transmission hurdles. To this end, conventional RF communication, which was once considered a profuse, is now overcrowded and would run out with the increasing demands for wireless data traffic and higher speed wireless communications.

Visible Light Communications (VLC) have emerged as a strong candidate to complement existing technologies, as it has the potential to solve the spectrum scarcity and satisfy the data-rate requirements. VLC provides the advantages of an ultra-wide, unregulated, license-free spectrum. Furthermore, VLC utilizes standard off-the-shelf Light-Emitting-Diodes (LEDs) to transmit data, which ensures having a health-friendly and secure communication method. Moreover, the availability of LEDs at houses, offices, and public places makes VLC an affordable solution to reduce the load of the RF spectrum as well as providing energy-efficient communication systems. Many challenges, however, have to be addressed for this technology to be realized, such as the short communication ranges and the Line-of-Sight (LoS) constraints.

Inspired by the previous literature on conventional RF networks [3] and the hardware constraints of deploying VLC systems, this paper addresses such challenges by means of adopting a transmit diversity scheme, where messages are transmitted over several VLC links. The paper's main contribution is that, in order to reduce the receiver outage probability, it proposes multiple combination schemes at the receiver side, namely selection combining, maximal-ratio combining, and threshold combining. The paper simulation results highlight the effectiveness of the proposed schemes, which illustrates their potent at achieving the ambitions metrics of 6G systems [1].

The paper is organized as follows. Sec. 2 presents the relevant literature review. In sec. 3 and sec. 4, we detail the proposed VLC system model and the diversity algorithms, respectively. Finally, we illustrate the performance gain harvested by the proposed schemes using numerical results in sec. 5, and conclude in sec. 6.

2. State-of-the art

As 5G/6G research is advancing towards universal standards, researches are investigating the reliability of deploying several future services in the high-frequency regime. The services include communication services [4, 5] as well as the integration of sensing [6, 7, 8], imaging [9, 10], and positioning [11, 12]. Transmitting at the THz spectrum would enable such services as it exploits large bandwidths and can fulfill the high data rate demands of future generations of wireless communications. Many challenges, however, need to be addressed related to THz signal generation, signal detection, and transceiver design [13]. Moreover, the security of future systems is a critical issue that needs to be resolved. For these reasons, VLC has a strong potential to complement such futuristic technologies. In the last few years, VLC has proved its capability of achieving high data rates, which makes it a suitable candidate for next-generation wireless systems [14]. The revolutionary efforts of utilizing LEDs for both illumination and communication purposes have encouraged formulating VLC standards for real-time applications. The standards advancements allowed inventing various indoor and outdoor applications. Potential VLC applications include data centers, ad hoc networks, localization, and indoor applications.

The work in [15] leveraged VLC in data centers, where a multi-hop VLC-based system for wireless data centers is proposed to provide a fully-wireless data center network across racks. The proposed system has the potential to reduce the hardware costs since hierarchical switches and inter-rack cables are no longer used. It further simplifies the system as there are no extra center control operations needed. The authors further proposed a greedy routing algorithm that selects the rack with minimum Manhattan distance as the next hop for the transmitted data. The simulation results show that the Manhattan method outperforms the shortest path methods considered in previous works in terms of computational complexity.

In addition to data centers, the recent emergence of VLC together with the advancements in optoelectronic devices including LEDs and Photo-detectors (PDs) led to the exploration of Visible Light Ad Hoc Networks (LANETs). The authors in [16] proposed a routing protocol to overcome the blockage challenges by designing an adaptive system. Particularly, they developed a cross-layer optimized routing protocol that interacts with the Medium Access Control (MAC) layer to maximize the throughput subject to link capacity, maximum queue size, and power budget constraints. The routing protocol uses a distributed algorithm in which the decision is made hop by hop to account for the dynamic nature of LANETs. The results proved that the cross-layer protocol provides up to 124% improvement in throughput compared to other designs.

Moreover, VLC is leveraged for efficient indoor localization. Although WiFi-based indoor localization is known as an alternative to the Global Positioning System (GPS), it suffers from low accuracy. Complex multi-path cancellation techniques are required to improve the systems performance. The motivation behind using VLC instead of Wi-Fi is that there are many more LED luminaires in a building compared to the number of Wi-Fi access points. The higher density allows more accurate triangulation of the mobile device, which leads to higher accuracy. Reference [17] presented the first visible light localization system. Hence, the device performs a receiver side localization by receiving the light beacon from an LED. The PD on a mobile device receives the beacon from several sources. It utilizes the RSS values of received beacon to estimate the distance from the received to the LED source. Based on the distance estimation, the receiver uses trilateration to obtain its location. It is proved that the approach adopted in [17] can achieve a location accuracy of 0.4 meters approximately.

All the previous works considered a multi-hop VLC-system to overcome the short communication range issue. The routing approaches in the above works, however, remain physically impractical to be implemented in real-life VLC applications. This is especially the case because of the hardware constraints imposed by the LOS requirements of VLC transceivers, and the sensitivity of their alignment perturbations. Therefore, this paper proposes an alternative scheme for overcoming VLC deployment challenges through enabling transmit diversity at the transmitter side. We then investigate multiple combination schemes at the receiver side, namely selection combining, maximal-ratio combining, and threshold combining, and assesses their performance via numerical simulations.

3. System Model

This work considers a visible light-based network. Each device in the network is supported by an LED (transmitter) and a PD (receiver). The devices monitor the indoor environment and send the collected data in a multi-hop fashion using a transmission diversity scheme. This section presents the architecture of the considered VLC-based network and highlights the channel link budget.

Operating on the visible light band requires a thorough study and understanding of the channel and the link budget. As a high-frequency technology, visible light cannot penetrate objects, which makes LoS scenarios essential for effective communication. For this reason, light waves are confined within a single room, which helps increasing the security of using light as a wave-carrier. Also, light-wave is limited for short ranges when used for communication, because the wave attenuates, scatters, and reflects before it arrives at the destination. The communication link in VLC-systems is based on the uniform distribution of the location of end-users and is closely related to the transmitter, receiver, and the channel itself, as shown in Fig. 1 [18].

Using the assumptions of a LoS link, we have an optical source with a radiation pattern intensity defined as [19]

$$R(\varphi) = \frac{m+1}{2\pi} P_s \cos^m(\varphi), \text{ for } \varphi \in [\frac{-\pi}{2}, \frac{\pi}{2}], \tag{1}$$

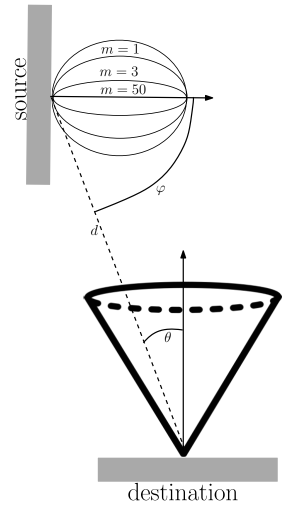

Figure 1. The basic geometry of VLC link including the transmitter and the receiver.

where P_s is the average transmitted power, φ is the irradiance angle, and m is the radiation lobe number, which specifies the directionality of the optical source, e.g., $m = 1$ represents the traditional Lambertian source which is best illustrated in Fig.1. The order of Lambertian emission m defines the radiant intensity that is related to the half-angle $\varphi_{1/2}$ by

$$m = \frac{-1}{\log_2 \cos \varphi_{1/2}}. \tag{2}$$

The DC channel gain in VLC system is given by [19, 18]

$$H = \frac{(m+1)A}{2\pi d^2} \cos^m \varphi T(\theta) G(\theta) \cos\theta, \tag{3}$$

where A is the area of the receiver aperture, d is the euclidean distance between the transmitter and receiver, θ is the angle of incidence, and $0 \le \theta \le FOV$, (i.e., the angle of field of view). $T(\theta), G(\theta)$ are the gain of an optical filter and concentrator, respectively. The received optical power for a single link is, therefore, the channel impulse response of P_s and is expressed as

$$y(t) = x(t) \otimes h(t) + n(t), \tag{4}$$

where $y(t)$ is the received signal, $x(t)$ is the transmitted signal, $h(t)$ is the channel impulse response, $n(t)$ is the total noise, and the notation $\otimes$ denotes the convolution operator. Note that $n(t)$ includes the noise of the channel, shot noise, and thermal noise. The shot and thermal noise variance can be defined as in [20] by

$$\sigma^2_{shot} = 2qB(R_\lambda P_s + I_{bg} I_2), \tag{5}$$

$$\sigma^2_{thermal} = \frac{8\pi K T_k}{G} \eta A I_2 B + \frac{16\pi^2 K T_k \Gamma}{g_m} \eta^2 A^2 I_3 B^3, \tag{6}$$

where q is the charge of the electron, B is the equivalence of bandwidth noise, I_{bg} is the background current, and I_2, I_3 are the defined noise bandwidth factor, and R_λ is the PD responsivity. In (6), the first term represents the feedback-resistor noise, and the second represents the field-effect transistor (FET) channel noise. K is the Boltzmann's constant, T_k is the absolute temperature, G is the open-loop voltage gain, η is the fixed capacitance of PD per unit area, Γ is the FET channel noise factor, and g_m is the FET transconductance.

The quality of the established communication can be assessed using the signal-to-noise ratio (SNR) parameter. For a VLC system, the SNR is expressed as

$$\gamma = \frac{P_s^2}{\sigma_{shot}^2 + \sigma_{thermal}^2}. \tag{7}$$

For indoor VLC-based IoT networks, it is not sufficient to only observe the SNR of the link, as the observation of the outage probability is equally important. The outage probability denotes the probability of having a link rate below the desired rate. In mathematical terms, we define the outage probability as [3]

$$P_{out} = P(\gamma < \gamma_{th}), \tag{8}$$

where γ refers to SNR received value, and γ_{th} is the SNR threshold value. From (8), the probability of outage in terms of SNR can be obtained from the statistical characteristics of the link, i.e., the cumulative distribution function (CDF) of the end-to-end received SNR [21]. For a single link, P_{out} can be expressed as

$$P_{out} = \frac{-1}{r^2}\left((m+1)XL^{m+1}\right)^{\frac{2}{m+3}}\left(\frac{\gamma_{th}}{\bar{\gamma}}\right)^{\frac{-1}{m+3}} + 1 + \frac{L^2}{r^2}, \tag{9}$$

where r is the maximum radius covered by an LED, $X = \frac{1}{2\pi}AR_\lambda T(\theta)G(\theta)$ is a constant, and L is vertical distance between the transmitter and receiver. $\bar{\gamma}$ is the expected value of SNR and is expressed as $\bar{\gamma} = \frac{\rho^2 P_s^2}{nB}$, where ρ is the electrical to optical conversion efficiency. In (9), $\gamma_{th} \in [\frac{\bar{\gamma}((m+1)XL^{m+1})^2}{(r^2+L^2)^{m+3}}, \frac{\bar{\gamma}((m+1)XL^{m+1})^2}{(L^2)^{m+3}}]$. In this paper, we extend the direct link scenario to a multi-hop link. The rationale of such extension is to overcome the short distance coverage in VLC systems. For a multi-hop based decode-and-forward (DF) VLC link, the end-to-end outage probability depends on each link's P_{out}. That is, if an outage occurs at any intermediate hop, the end-to-end link suffers from outage as well. We can express that mathematically by

$$P_{out}^{E2E} = 1 - \prod_{k=1}^{K}(1 - P_{out}^k), \tag{10}$$

where K is the total number of hops, and P_{out}^k is the probability of outage for k-th hop. In the next section, we study and apply the outage probability metric to several diversity schemes, as a means to address the challenges imposed by VLC operation, i.e., to extend the VLC coverage via reducing the overall outage probability.

4. Diversity Algorithms for Visible Light Communication

This section adopts diversity schemes inherited from the theory of conventional wireless communications [3]. In particular, this section proposes utilizing three different diversity algorithms in the context of VLC systems, namely selection combining, maximal-ratio-combining, and threshold combining. The proposed diversity algorithms are implemented as a special case of routing. That is, due to hardware constraints, specifically the field-of-view of the photo-detector, routing in a VLC-based network has a restricted degree of freedom, and therefore, diversity algorithms can compensate for that. The idea of using diversity combining is to send data over several independent VLC multi-hop fading links. Such multiplexing often reduces the effect of fading channels and offers a solution for the LoS constraint. That is, when one path is unavailable due to blockage, the message is transmitted over the remaining paths. The paths are then combined using one of the diversity schemes to get a less noisy version of the received optical signal [3]. Fig. 2 illustrates the proposed system model, which consists of three paths (i.e., A, B, and C) that share the same source and destination points in a VLC-based network. Note that the source, destination, and in-between nodes are represented by a transmitter, receiver, and transceivers, respectively. At the receiver side, the signal monitor selects the path that will derive the best performance. This section overviews three diversity schemes, namely selection combining, threshold combining, and maximal-ratio combining, where sec. 5 evaluates their respective performances.

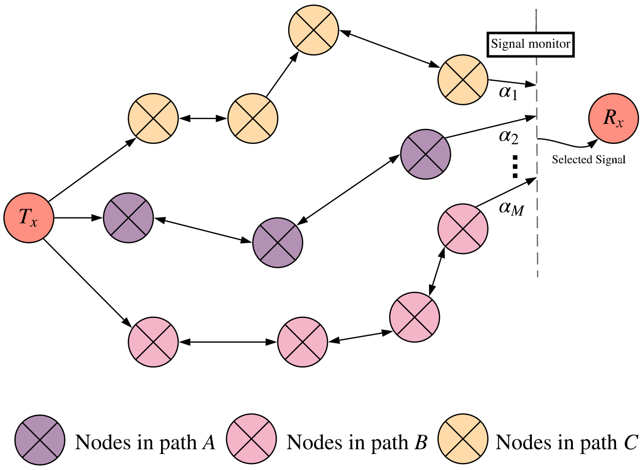

Figure 2. Multi-hop paths in a VLC-based IoT network using diversity combining schemes.

4.1. Selection Combining

In selection combining (SC), the received SNR γ^{SC} is the best SNR of the M different received signals. The resultant output from an SC system can be expressed mathematically in terms of probability of outage as

$$P_{out}^{SC} = P(\gamma^{SC} < \gamma_{th}) = P(max[\gamma_1, \gamma_2, ..., \gamma_M] < \gamma_{th}). \tag{11}$$

In SC, a dedicated receiver on each of the M branches is needed to monitor the signals as illustrated in Fig. 2.

4.2. Threshold Combining

Threshold combining (TC), on the other hand, has a simpler algorithm to improve the system resultant signal γ^{TC}. Threshold combining (TC), on the other hand, has a simpler algorithm to improve the system resultant signal γ^{TC}. In TC, the receiver scans the signal on a sequential order and outputs the first signal that meets the SNR requirement γ_{th}. When a selected branch's signal falls below the required γ_{th}, TC switches to another branch. In other words, it is based on a switch and stay mechanism.

4.3. Maximal-ratio Combining

The third diversity scheme this paper investigates is the maximal-ratio combining scheme. Unlike SC and TC, MRC does not output the superior signal. Instead, it combines the paths in an optimized way. More specifically, MRC outputs the weighted sum of the M branches, that is,

$$\gamma^{MRC} = \frac{1}{N} \frac{\left(\sum_{i=1}^{M} \alpha_i h_{si}\right)^2}{\sum_{i=1}^{M} \alpha_i^2}, \tag{12}$$

where α_i is the weight of branch i, h_{si} is the effective channel of branch i, and N is the noise power of each branch assuming all branches have equal noise power. MRC aims at choosing the branch with the maximum weight to maximize the combiner output γ^{MRC}. By taking the gradient of (12), setting it to zero, and solving for the optimal weights, we get

$$\alpha_i = h_{si}. \tag{13}$$

Table 1. VLC system parameters

Parameter	Value
Detector responsivity	R_λ = 0.54 A/W
Electronic charge	q = 1.602e-19 c
Boltzmanns constant	k = 1.38066e-23
Absolute temperature	T_k = 295 K
Open-loop voltage gain	G = 10
Fixed capacitance	η = 112 pF/cm^2
Background light current	I_{bg} = 5100 μA
Data rate	B = 100 Mbps
Noise bandwidth factor	I_2 = 0.562

Note that the above result (13) can also be derived based on Cauchy-Shwartz inequality. Based on the above discussion, the SNR of the MRC scheme becomes

$$\gamma^{MRC} = \frac{\sum_{i=1}^{M} h_{si}^2}{N} = \sum_{i=1}^{M} \gamma_i. \tag{14}$$

The probability of outage for MRC is, therefore, given by

$$P_{out}^{MRC} = P(\gamma^{MRC} < \gamma_{th}). \tag{15}$$

5. Numerical Results

This section evaluates the performance of the proposed algorithms to assess their merits in multi-hop multi-branch VLC-based systems. We illustrate the performance of all the three diversity schemes in terms of end-to-end outage probability, as a function of the targeted SNR γ_{th}. We evaluate the end-to-end outage probability performance to ensure that the proposed protocols provide a reliable communication link. Recall that the outage probability is defined as the probability that the rate is less than the required rate at the receiver side. Our simulations capture the real-system parameters, including the transmitter power, communication range, number of transceivers, and operating frequency. Table 1 summarizes the parameters used in the simulations.

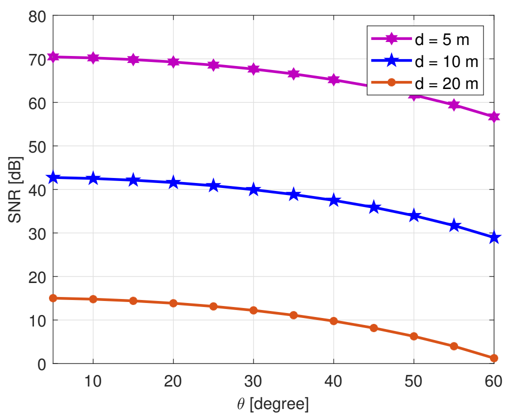

Figure 3. SNR as a function of link distance and incidence angle for a single link using VLC.

First, we show our simulations for a single link. We plot the SNR as a function of the incidence angle θ in Fig. 3. As expected, we can see that the SNR is higher for shorter distances and narrow θ, since the light

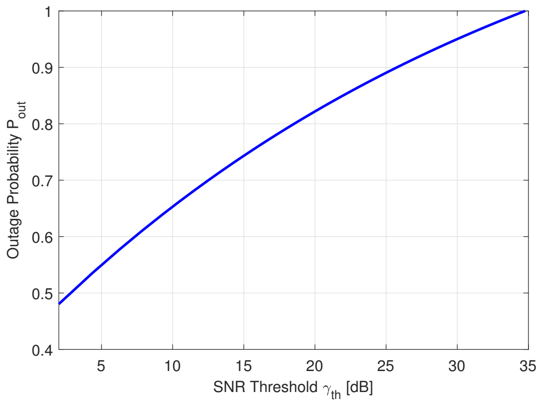

Figure 4. Probability of outage for a single VLC-based link.

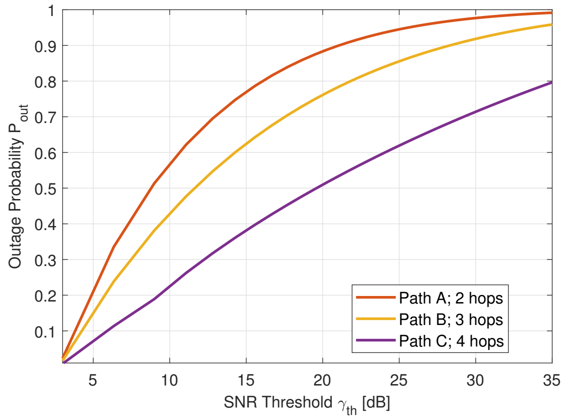

Figure 5. End-to-end probability of outage for three multi-hop links in VLC systems.

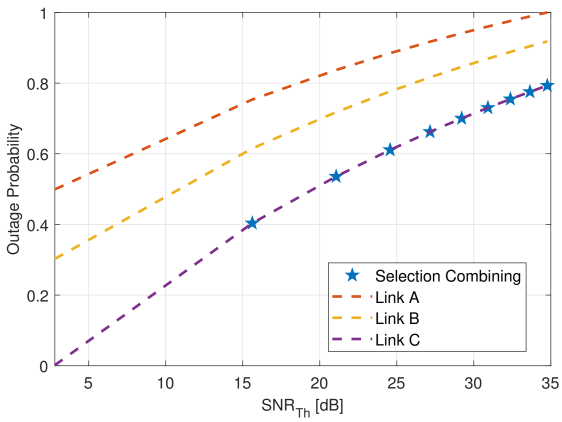

Figure 6. End-to-end probability of outage for three paths using SC scheme in VLC systems.

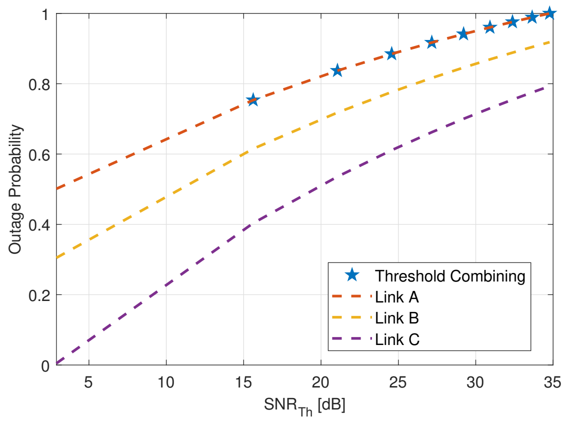

Figure 7. End-to-end probability of outage for three paths using TC scheme in VLC systems.

wave attenuates for long distances, and the transmitted power concentrates with narrow angles. We then simulate the probability of outage for a single link, as shown in Fig. 4, where it is shown that the probability of outage increases proportionally with increasing the target SNR threshold γ_{th}. Finally, we show the effect of outage probability when having multi-hop paths using (10) in Fig. 5. As can be seen, when the number of hops increases in a link/path, the probability of outage decreases. Next, we compare the three diversity schemes in terms of outage portability, where we have three different paths with different performances and select among them using the mentioned diversity schemes. Fig. 6 shows the probability of outage for three different paths using selection combining, where the output of the combiner is the signal with the best SNR, as verified by (4.1). Fig. 7 shows the outage probability for the three paths using threshold combining. As the previous section discusses, as long as the probability of outage is less than the threshold, TC outputs the first signal in sequence and keeps it on hold. The maximal-ratio combiner output is shown in Fig. 8, where the MRC outputs the weighted-sum of the SNRs, thereby resulting in better signal quality. Note that in order to deploy MRC at the receiver side, one must develop a fast and intelligent signal processing unit as well. Finally, we compare the three diversity schemes in Fig. 9. As expected, the MRC has the optimal performance at the cost of increased complexity. Threshold combining is a trivial solution, and the selection combining is the middle ground between the two. Most importantly, the results show that the proposed diversity schemes significantly reduce the outage probability, which is aligned with the ambitious reliability metrics of 5G/6G systems.

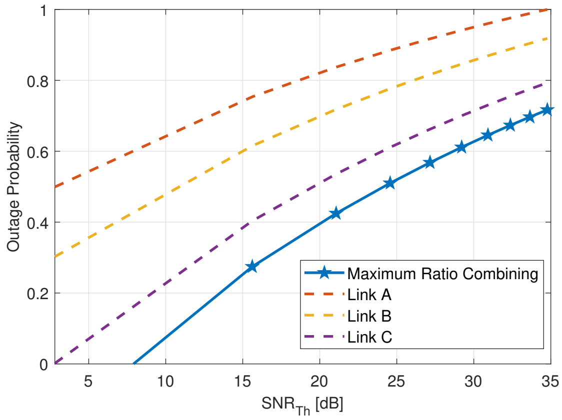

Figure 8. End-to-end probability of outage using MRC scheme in VLC systems.

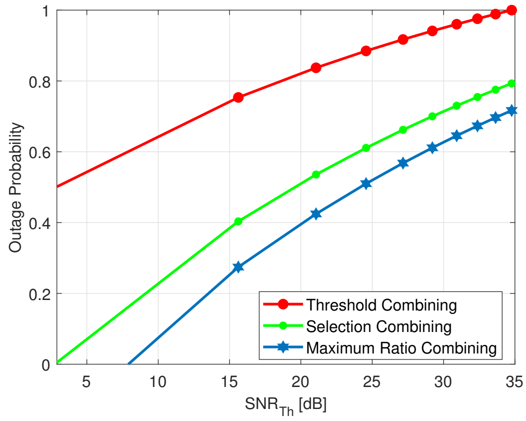

Figure 9. End-to-end probability of outage of three schemes in VLC systems.

6. Conclusion

VLC has emerged as a strong candidate for satisfying Beyond 5G network requirements, by means of solving the RF scarcity problems and accounting for the ambitious high-data-rate demands. To best boost VLC coverage capabilities, this paper considers a multi-hop multi-path VLC-based system and proposes a transmit diversity scheme. The paper then investigates three different receiver combination schemes, namely, selection combining, maximal-ratio combining, and threshold combining. The numerical results of the paper illustrate the effectiveness of the proposed schemes and highlight their suitability for Beyond 5G systems deployment. The proposed selection combining and maximal-ratio combining schemes exhibit a trade-off in their performance and complexity, where the MRC has about a 10% increase in the performance, yet has a higher complexity than SC.

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