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PROPAGATION CHARACTERISTICS AND SYSTEM PERFORMANCE OF TERAHERTZ–OPTICAL HYBRID COMMUNICATION CHANNELS

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Abstract: This paper investigates the propagation characteristics and system performance of terahertz–optical hybrid communication channels. To meet the increasing demand for high capacity and high reliability in future high-speed wireless communication systems, a hybrid communication model consisting of a terahertz link and an optical wireless link is established. First, the dominant propagation impairments are analyzed, including free-space path loss, molecular absorption, and pointing errors in the terahertz link, as well as atmospheric attenuation, turbulence effects, and pointing errors in the optical wireless link. Then, a hybrid channel model is developed based on an instantaneous signal-to-noise-ratio-based link selection mechanism, and outage probability, bit error rate, and channel capacity are selected as the main performance metrics. Numerical results show that the terahertz and optical wireless links exhibit clear complementarity in terms of propagation impairments. Compared with single-link transmission, the terahertz–optical hybrid communication system can effectively reduce the outage probability and maintain more stable system capacity under different transmission distances and propagation conditions. The results of this work may provide useful guidance for the design of future 6G high-speed wireless backhaul and reliable communication systems in complex environments.

Keywords: Terahertz communication; Optical wireless communication; Hybrid communication channel; System performance

1 INTRODUCTION

With the rapid development of sixth-generation mobile communication systems, space–air–ground integrated networks, and ultra-high-speed wireless backhaul technologies, future communication systems are expected to support higher data rates, larger system capacity, and more reliable link connectivity [1-3]. Terahertz communication, owing to its abundant spectrum resources and ultra-wide bandwidth, has been regarded as a promising candidate for high-speed wireless transmission. Meanwhile, free-space optical communication offers attractive advantages such as high directivity, large transmission capacity, and strong immunity to electromagnetic interference, making it suitable for short-range high-speed links, satellite-to-ground communication, and metropolitan wireless backhaul. However, a single communication link is often unable to simultaneously guarantee high capacity and high reliability under complex propagation conditions. Therefore, hybrid communication that integrates terahertz and optical wireless links has emerged as a promising research direction for future high-speed wireless communication systems.

The propagation characteristics of terahertz communication channels have been extensively investigated in recent years, with particular attention paid to free-space path loss, molecular absorption, atmospheric attenuation, frequency-selective fading, and beam pointing errors [4]. Due to the high carrier frequency of terahertz waves, their propagation is highly sensitive to transmission distance, water-vapor absorption, and transceiver misalignment, which may significantly limit the achievable link distance and stability. On the other hand, free-space optical communication can provide extremely high data transmission capability, but its performance is vulnerable to fog, rain, snow, atmospheric turbulence, and beam jitter. Existing studies indicate that terahertz and optical wireless links exhibit complementary characteristics in terms of propagation impairments and environmental sensitivity. Accordingly, establishing a hybrid terahertz–optical channel model and analyzing its system performance are of great significance for improving the reliability and adaptability of high-speed wireless communication systems [5,6].

In this paper, the propagation characteristics and system performance of terahertz–optical hybrid communication channels are investigated. First, a hybrid communication system consisting of a terahertz link and an optical wireless link is established, and the dominant propagation impairment factors in both links are analyzed. Then, a hybrid channel model is developed by considering the effects of path loss, molecular absorption, atmospheric attenuation, turbulence, and pointing errors on the channel gain and received signal-to-noise ratio. Based on this model, outage probability, bit error rate, and channel capacity are selected as the main performance metrics to compare the terahertz-only, optical-only, and hybrid terahertz–optical links. Through theoretical analysis and numerical simulations, this work aims to reveal the potential advantages of the hybrid communication mechanism in enhancing link reliability, reducing transmission outage risk, and improving system capacity.

2 SYSTEM AND CHANNEL MODEL

In this paper, a typical terahertz–optical hybrid communication system is considered, where a terahertz wireless link and an optical wireless link coexist between the transmitter and the receiver [7,8]. Both links operate under line-of-sight propagation conditions and are employed for high-speed data transmission. The terahertz link provides a large available bandwidth and is suitable for short-range high-speed wireless transmission, while the optical wireless link offers high directivity and large transmission capacity under stable line-of-sight conditions. To improve link reliability in complex propagation environments, the system can select between the terahertz and optical links according to the instantaneous channel state, thereby forming a hybrid communication mechanism.

For the terahertz link, the channel gain is mainly determined by free-space path loss, molecular absorption loss, and pointing error. Due to the high carrier frequency of terahertz waves, severe free-space attenuation occurs during propagation. Meanwhile, atmospheric molecules such as water vapor and oxygen introduce absorption effects within specific frequency ranges, further reducing the received signal power. In addition, terahertz communication usually relies on high-gain narrow-beam antennas to compensate for propagation loss, which makes the link highly sensitive to misalignment between the transmitter and the receiver. Considering these factors, the channel gain of the terahertz link can be expressed as:

$$\mathrm{h}_{\mathrm{THz}}=\mathrm{h}_{\mathrm{pl}}\mathrm{h}_{\mathrm{abs}}\mathrm{h}_{\mathrm{p}} \tag{1}$$

where h_{pl} denotes the free-space path loss component, $\mathrm{h}_{\mathrm{abs}}$ denotes the molecular absorption component, and h_{p} denotes the pointing error component.

For the optical wireless link, a free-space optical communication link is considered in this work. Its channel characteristics are mainly affected by atmospheric attenuation, atmospheric turbulence, and pointing error. Under complex weather conditions such as fog, rain, snow, and aerosols, the optical signal experiences absorption and scattering during propagation, resulting in atmospheric attenuation. Meanwhile, random variations in the atmospheric refractive index induce irradiance fluctuations, leading to random fading of the received optical signal. Moreover, since free-space optical communication also employs narrow-beam transmission, platform vibration or slight transceiver displacement may introduce pointing errors. Accordingly, the channel gain of the optical wireless link can be written as:

$$\mathrm{h}_{\mathrm{FSO}}=\mathrm{h}_{\mathrm{a}}\mathrm{h}_{\mathrm{t}}\mathrm{h}_{\mathrm{p}} \tag{2}$$

where h_{a} represents the atmospheric attenuation component, h_{t} represents the atmospheric turbulence component, and h_{p} represents the pointing error component.

In the hybrid communication system, the terahertz and optical wireless links jointly provide alternative transmission paths. For analytical simplicity, an instantaneous signal-to-noise-ratio-based link selection mechanism is adopted, where the system selects the link with the better channel condition for data transmission. Therefore, the equivalent signal-to-noise ratio of the hybrid link can be expressed as:

$$\gamma_{\mathrm{hybrid}}=\max(\gamma_{\mathrm{THz}},\gamma_{\mathrm{FSO}}) \tag{3}$$

where γ_{THz} and γ_{FSO} denote the instantaneous signal-to-noise ratios of the terahertz and optical wireless links, respectively. This model indicates that the hybrid system can exploit the complementary propagation characteristics of the two links. When one link suffers from severe attenuation or channel degradation, the system can switch to the other link, thereby reducing the outage risk and improving the overall link reliability.

3 PERFORMANCE ANALYSIS

Based on the terahertz–optical hybrid communication channel model established in the previous section, the main performance metrics of the system are further analyzed. To evaluate the reliability and transmission capability of the hybrid link under complex propagation conditions, outage probability, bit error rate, and channel capacity are selected as the key performance metrics. Specifically, outage probability is used to measure the probability that the system fails to satisfy the minimum communication quality requirement, bit error rate reflects the reliability of data transmission, and channel capacity characterizes the achievable information transmission capability of the system. By comparing the terahertz-only link, the optical-only link, and the hybrid terahertz–optical link, the performance advantages of the hybrid communication mechanism can be clearly demonstrated.

First, outage probability is a critical metric for evaluating the reliability of wireless communication systems. When the instantaneous signal-to-noise ratio at the receiver falls below a predefined threshold γ_{th}, the system is considered to be in outage. For the terahertz and optical wireless links, the corresponding outage probabilities can be respectively expressed as:

$$P_{\mathrm{out}}^{\mathrm{THz}}=P(\gamma_{\mathrm{THz}}<\gamma_{\mathrm{th}}) \tag{4}$$

$$P_{\mathrm{out}}^{\mathrm{FSO}}=P(\gamma_{\mathrm{FSO}}<\gamma_{\mathrm{th}}) \tag{5}$$

In the hybrid communication system, since an instantaneous signal-to-noise-ratio-based link selection mechanism is adopted, an outage event occurs only when both the terahertz and optical wireless links have signal-to-noise ratios below the threshold. Therefore, the outage probability of the hybrid link can be given by:

$$P_{\mathrm{out}}^{\mathrm{hybrid}}=P(\gamma_{\mathrm{THz}}<\gamma_{\mathrm{th}},\gamma_{\mathrm{FSO}}<\gamma_{\mathrm{th}}) \tag{6}$$

If the channel states of the two links are assumed to be independent, it can be further written as:

$$P_{\mathrm{out}}^{\mathrm{hybrid}}=P_{\mathrm{out}}^{\mathrm{THz}}P_{\mathrm{out}}^{\mathrm{FSO}} \tag{7}$$

This result indicates that the outage probability of the hybrid system is generally lower than that of either individual link, thereby demonstrating improved link reliability.

Second, bit error rate is used to evaluate the transmission reliability of the system under noise and channel fading. For a given modulation scheme, the average bit error rate is typically related to the received signal-to-noise ratio. Taking binary phase-shift keying as an example, the instantaneous bit error rate can be expressed as:

$$P_\mathrm{b}=Q\left(\sqrt{2\gamma}\right) \tag{8}$$

where $Q(\cdot)$ denotes the Gaussian Q-function and γ is the instantaneous received signal-to-noise ratio. For the hybrid communication system, the equivalent signal-to-noise ratio is determined by γ_hybrid, and therefore its bit error performance can be expressed as:

$$P_\mathrm{b}^\mathrm{hybrid}=Q\left(\sqrt{2\gamma_\mathrm{hybrid}}\right) \tag{9}$$

Since the hybrid system can select the link with better channel conditions for transmission, it can effectively reduce the error risk caused by deep fading or severe atmospheric attenuation. Compared with a terahertz-only link or an optical-only link, the hybrid link is expected to achieve a lower bit error rate, especially in the medium-to-high signal-to-noise ratio region.

Finally, channel capacity characterizes the theoretical transmission capability of the system under given bandwidth and signal-to-noise ratio conditions. According to Shannon's capacity formula, the instantaneous channel capacity of a single link can be expressed as:

$$C=B\log_2(1+\gamma) \tag{10}$$

where B is the system bandwidth and γ is the received signal-to-noise ratio. For the hybrid communication system, the equivalent channel capacity can be written as:

$$C_\mathrm{hybrid}=B\log_2\left(1+\gamma_\mathrm{hybrid}\right) \tag{11}$$

This expression indicates that the capacity of the hybrid system depends not only on the transmit power and system bandwidth, but also on the channel states of both links. When one link suffers from performance degradation due to propagation loss, turbulence, or pointing error, the system can still maintain a relatively high transmission capability by selecting the other link with better channel conditions. Therefore, the terahertz–optical hybrid communication mechanism can improve capacity stability and link availability in complex propagation environments.

4 NUMERICAL RESULTS AND DISCUSSION

To validate the effectiveness of the proposed terahertz–optical hybrid communication model and to further reveal the performance trends under different propagation conditions, numerical evaluations are carried out using representative system parameters. The analysis focuses on propagation loss, outage probability, and average channel capacity, and the performance of the terahertz-only, optical-only, and hybrid links is compared. It should be noted that the following numerical results are mainly intended to illustrate the main performance trends, thereby providing useful insights for subsequent theoretical refinement and experimental investigation, see Table 1.

Table 1 Simulation Parameters

Parameter	Symbol	Value
THz carrier frequency	f_THZ	0.3 THz
Optical carrier wavelength	λ_FSO	1550 nm
Transmission distance range	d	50–500 m
Average transmit SNR range	γ	0–30 dB
Outage threshold	γ_th	5 dB
System bandwidth	B	10 GHz
THz absorption coefficient (clear)	$\alpha_\mathrm{THz,1}$	0.01 dB/m
THz absorption coefficient (high humidity)	$\alpha_\mathrm{THz,2}$	0.04 dB/m
FSO atmospheric attenuation (clear)	$\alpha_\mathrm{FSO,1}$	2 dB/km
FSO atmospheric attenuation (dense fog)	$\alpha_\mathrm{FSO,2}$	80 dB/km
Hybrid mechanism	—	Instantaneous-SNR-based link selection
Link correlation assumption	—	THz and FSO are independent

4.1 Propagation Loss Analysis

As shown in Figure 1, the two links exhibit substantially different propagation-loss behaviors. For the terahertz link, the total attenuation increases rapidly with transmission distance due to the accumulation of free-space path loss, and this effect becomes more pronounced under high-humidity conditions because of the additional molecular absorption loss. In contrast, the optical wireless link experiences relatively low atmospheric attenuation in clear weather, whereas under dense fog the attenuation becomes much more severe and increases almost linearly with distance.

These results indicate that the terahertz link is more sensitive to transmission distance and molecular absorption, while the optical link is more vulnerable to weather variations, particularly fog-induced attenuation. In other words, the dominant degradation mechanisms of the two links are different, which provides the fundamental motivation for combining them in a hybrid communication architecture. For a single-link system, one specific environmental factor may cause a sharp degradation in performance; by contrast, the hybrid system can take advantage of the relative robustness of the other link through a link-selection mechanism, thereby improving the overall communication robustness.

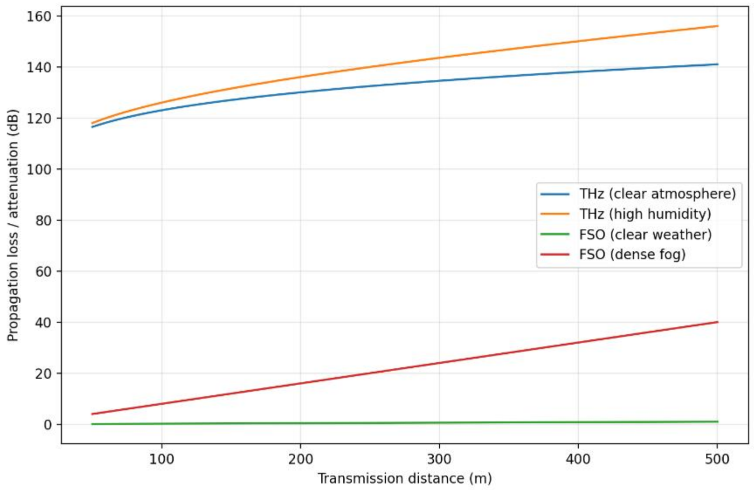

Figure 1 Propagation Characteristics under Representative Conditions

4.2 Outage Probability Analysis

Figure 2 presents the outage probability of the three transmission modes as a function of the average transmit SNR. It can be observed that the outage probabilities of the terahertz-only, optical-only, and hybrid links all decrease with increasing average SNR, while the hybrid link consistently achieves the best reliability. The reduction is particularly evident in the low-to-medium SNR region, indicating that improving the received signal quality can effectively mitigate the adverse effects of propagation loss and random channel fluctuations.

More importantly, the hybrid link always outperforms the individual links in terms of outage probability. Even when the terahertz-only and optical-only links still suffer from relatively high outage due to their own propagation impairments, the hybrid system experiences outage only when both links are simultaneously in poor condition. As a result, its outage performance is significantly improved. From a system-design perspective, this confirms that the instantaneous-SNR-based link-selection strategy is effective in reducing outage risk and enhancing the robustness of the hybrid communication system under complex propagation environments.

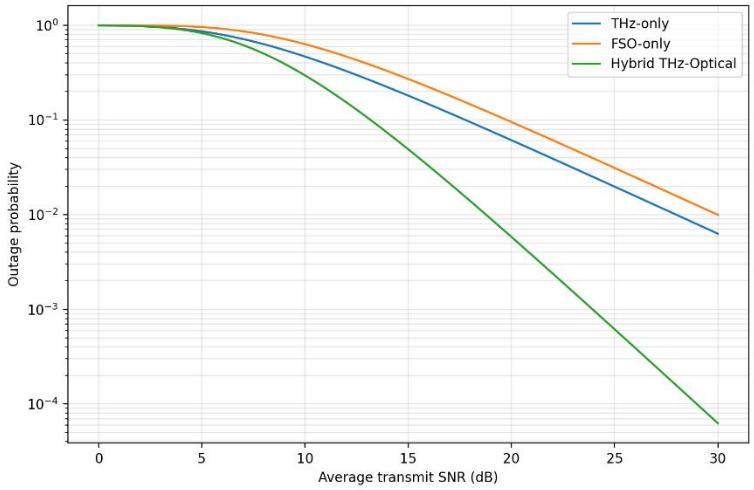

Figure 2 Outage Probability Analysis

4.3 Average Capacity Analysis

Figure 3 shows the variation of the average channel capacity with transmission distance. It is observed that the average capacity of all three links decreases as the distance increases, but the decreasing rates are different. The terahertz link exhibits a higher capacity in the short-distance region because of its relatively high initial SNR and its ability to exploit the large available bandwidth. However, as the distance increases, the joint impact of path loss and molecular absorption causes a more pronounced capacity degradation. In comparison, the optical link starts with a slightly lower capacity at short distances, but its degradation is more gradual, which enables it to provide a more stable transmission capability in the medium-to-long distance region.

It can also be seen that the capacity curve of the hybrid link closely follows the upper envelope of the two individual links. That is, it inherits the high-capacity advantage of the terahertz link at short distances and then benefits from the relatively more stable optical link when the terahertz channel deteriorates at longer distances. Therefore, the hybrid communication system is able to maintain a higher and more stable capacity over the entire distance range. This result further demonstrates that the terahertz–optical hybrid mechanism not only improves link reliability, but also enhances capacity stability and link availability under complex propagation environments and varying transmission distances.

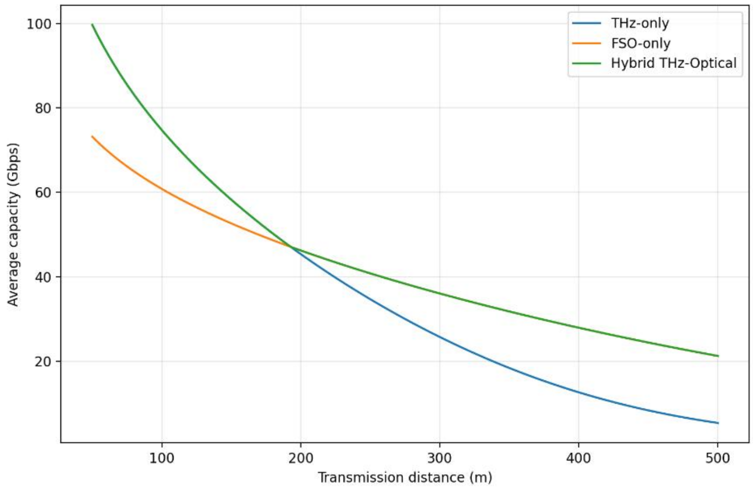

Figure 3 Average Capacity Versus Transmission Distance

4.4 Discussion

From the above numerical results, it is evident that the terahertz and optical links exhibit clear complementarity in their propagation characteristics. The terahertz link is suitable for high-bandwidth, short-range, and high-speed transmission scenarios, but it is sensitive to distance and molecular absorption. The optical link provides strong transmission capability under clear line-of-sight conditions, but its performance is prone to fluctuations under fog, turbulence, and pointing errors. Based on these characteristics, the hybrid communication system can maintain better overall performance by dynamically selecting the more favorable link as the propagation conditions vary. Overall, the hybrid mechanism outperforms the single-link schemes in both outage probability and average capacity, suggesting its strong potential for future high-speed wireless access, inter-building backhaul, and highly reliable communication in complex environments.

5 CONCLUSION

This paper investigated the propagation characteristics and system performance of terahertz–optical hybrid communication channels. A hybrid communication system consisting of a terahertz link and an optical wireless link was first established, and the dominant propagation impairments of both links were analyzed, including free-space path loss, molecular absorption, atmospheric attenuation, turbulence effects, and pointing errors. Based on an instantaneous-SNR-based link selection mechanism, an equivalent hybrid channel model was then developed, and key performance metrics, including outage probability, bit error rate, and channel capacity, were further evaluated.

Numerical results showed that the terahertz and optical wireless links exhibit clear complementarity in terms of propagation characteristics. The terahertz link provides a capacity advantage for short-range high-speed transmission, but it is limited by path loss and molecular absorption. The optical wireless link can maintain stable transmission under clear line-of-sight conditions, while its performance degrades significantly under fog, turbulence, and pointing errors. Compared with single-link transmission, the terahertz–optical hybrid system can reduce the outage probability through link selection and maintain more stable system capacity under different transmission distances and propagation conditions.

Future work may be extended in several directions. More accurate composite channel models can be developed by incorporating rain attenuation, strong turbulence, blockage, hardware impairments, and link correlation into a unified framework. In addition, intelligent switching, resource allocation, and machine-learning-based channel prediction can be introduced to improve the adaptability of hybrid systems in dynamic environments. Experimental platforms and measured channel data are also needed to validate the proposed models and promote the practical deployment of terahertz–optical hybrid communication in 6G high-speed backhaul, space–air–ground integrated networks, and reliable communications under complex environments.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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