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CHANNEL CAPACITY OPTIMIZATION AND PERFORMANCE ANALYSIS OF FIBER-WIRELESS CONVERGED COMMUNICATION SYSTEMS

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Abstract: With the increasing demand for high data rates, large capacity, and flexible access in 5G and 6G communication networks, fiber-wireless converged communication systems have become an important technical direction for future broadband access and mobile fronthaul networks. This paper investigates channel capacity optimization and performance analysis of fiber-wireless converged communication systems. First, an end-to-end system model consisting of cascaded optical fiber and wireless links is established, and the channel capacity expression is derived based on the equivalent signal-to-noise ratio. Then, the impacts of key factors, including fiber length, wireless transmission distance, transmit power, bandwidth, and modulation format, on system capacity are analyzed. Based on this model, a simplified capacity optimization strategy is proposed by identifying the bottleneck link and adaptively adjusting transmission resources to improve the end-to-end system performance. Simulation results show that, compared with the fixed resource allocation scheme, the proposed adaptive allocation strategy achieves higher channel capacity and effective throughput, while improving the bit error performance to some extent. These results demonstrate that bottleneck-link identification and optimized resource allocation are effective methods for enhancing the performance of fiber-wireless converged communication systems.

Keywords: Fiber-wireless converged communication systems; Channel capacity optimization; End-to-end channel model; Adaptive resource allocation

1 INTRODUCTION

With the continuous evolution of fifth-generation mobile communication technologies and the rapid development of sixth-generation communication systems, future networks are expected to support higher data rates, larger transmission capacity, lower latency, and massive connectivity[1-3]. Although conventional wireless communication systems provide flexible deployment and mobile access, their capacity improvement is increasingly constrained by limited spectrum resources, path loss, and wireless channel fading[4]. In contrast, optical fiber communication offers large bandwidth, low transmission loss, and high reliability, making it a promising solution for high-speed data transport. Therefore, integrating optical fiber communication with wireless communication has become an important research direction for future broadband access, mobile fronthaul, and 6G-oriented networks[5].

In recent years, extensive research has been conducted on fiber-wireless converged communication systems, mainly focusing on radio-over-fiber transmission, millimeter-wave over fiber, optical fronthaul networks, dynamic resource allocation, and system performance optimization[6]. Existing studies have demonstrated that fiber-wireless convergence can effectively combine the high-capacity transmission capability of optical fiber links with the flexible coverage of wireless links, thereby improving overall network performance. However, in practical systems, the end-to-end channel capacity is not determined by a single link, but is jointly affected by fiber attenuation, optoelectronic conversion noise, wireless transmission distance, path loss, transmit power, and bandwidth allocation. Therefore, establishing an appropriate end-to-end channel model and further analyzing and optimizing the system capacity remain important research issues in this field[7-8].

This paper investigates channel capacity optimization and performance analysis of fiber-wireless converged communication systems. First, a typical cascaded fiber-wireless system model is established, and the expressions of the end-to-end equivalent signal-to-noise ratio and channel capacity are derived. Then, the impacts of fiber length, wireless transmission distance, transmit power, bandwidth, and modulation format on system capacity are analyzed. Furthermore, a simplified capacity optimization strategy is proposed, in which the capacity bottleneck between the optical fiber link and the wireless link is identified and the transmission resources are adaptively adjusted. Finally, simulation results are used to compare the system performance before and after optimization in terms of channel capacity, bit error rate, and throughput, thereby verifying the effectiveness of the proposed strategy.

2 SYSTEM MODEL AND CHANNEL CAPACITY ANALYSIS

This section establishes the basic model of the fiber-wireless converged communication system and analyzes its end-to-end channel capacity. The considered system consists of a cascaded optical fiber link and wireless link. The signal is first transmitted through the optical fiber link and then delivered to the user terminal through the wireless link. Since the

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end-to-end transmission performance is jointly affected by both links, a unified system model is required to evaluate the impact of different system parameters on channel capacity.

2.1 System Architecture

A typical fiber-wireless converged communication system is considered in this paper. The system mainly consists of a transmitter, an optical fiber link, an optoelectronic conversion unit, a wireless link, and a receiver. At the transmitter, the input signal is modulated and processed before being converted from an electrical signal into an optical signal. The optical signal is then transmitted through the optical fiber link. At the remote access node, the received optical signal is converted back into an electrical signal and then transmitted to the user terminal through the wireless link. Finally, the receiver demodulates and detects the received wireless signal to recover the transmitted data.

The system architecture can be represented as: transmitter → Optical Fiber Link → Optical-to-Electrical Conversion → Wireless Link→ Receiver. In this architecture, the optical fiber link provides high-capacity, low-loss, and reliable data transmission, while the wireless link offers flexible access and coverage. The integration of these two links can effectively improve the overall transmission capability of the communication system. However, the optical fiber link may suffer from attenuation, dispersion, and optoelectronic conversion noise, while the wireless link is affected by path loss, multipath fading, and thermal noise. Therefore, the end-to-end channel capacity is not determined by a single link, but jointly constrained by both the optical fiber and wireless links.

2.2 End-to-End Channel Model

For analytical simplicity, the fiber-wireless converged communication system is modeled as a two-stage cascaded system. The optical fiber link and the wireless link are treated as two subchannels, whose signal-to-noise ratios are denoted by $\gamma_f$and γ_w, respectively. Specifically, $\gamma_f$represents the SNR of the optical fiber link, which is mainly affected by fiber attenuation, optoelectronic conversion noise, and transmission bandwidth. Meanwhile, $\gamma_w$represents the SNR of the wireless link, which is mainly determined by wireless transmission distance, path loss, channel fading, and noise power.

The received power of the optical fiber link can be expressed as:

$$P_{r,f}=P_{t,f}e^{-\alpha L_f} \tag{1}$$

where $P_{t,f}$is the transmit power of the optical fiber link, $P_{r,f}$is the received power of the optical fiber link, $\alpha$is the fiber attenuation coefficient, and $L_f$is the fiber length. Accordingly, the SNR of the optical fiber link is given by:

$$\gamma_f=\frac{P_{r,f}}{N_f B_f} \tag{2}$$

where $N_f$denotes the noise power spectral density of the optical fiber link and $B_f$denotes the bandwidth of the optical fiber link.

The received power of the wireless link can be written as:

$$P_{r,w}=P_{t,w}G_tG_rd^{-\eta}\,|\,\mathrm{h}_w\,|\,^2 \tag{3}$$

where $P_{t,w}$is the transmit power of the wireless link, $G_t$and $G_r$are the transmit and receive antenna gains, respectively, $d$is the wireless transmission distance, $\eta$is the path-loss exponent, and $\mathrm{h}_w$is the wireless channel fading coefficient. The SNR of the wireless link is then expressed as:

$$\gamma_w=\frac{P_{r,w}}{N_w B_w} \tag{4}$$

where $N_w$is the noise power spectral density of the wireless link and $B_w$is the wireless bandwidth.

Since the optical fiber link and the wireless link are cascaded, the end-to-end equivalent SNR can be formulated as:

$$\gamma_{eq}=\left(\frac{1}{\gamma_f}+\frac{1}{\gamma_w}\right)^{-1} \tag{5}$$

This expression indicates that the end-to-end SNR will be significantly limited when either the optical fiber link or the wireless link has a low SNR. Therefore, the performance optimization of a fiber-wireless converged communication system should jointly consider the conditions of both links.

Based on Shannon's channel capacity theorem, the end-to-end channel capacity of the system can be expressed as:

$$C_{e2e}=B\log\boxed{f0}_2(1+\gamma_{eq}) \tag{6}$$

where $C_{e2e}$is the end-to-end channel capacity, $B$is the effective system bandwidth, and $\gamma_{eq}$is the end-to-end equivalent SNR.

2.3 Capacity Influencing Factors

According to the above model, the channel capacity of a fiber-wireless converged communication system is jointly affected by optical fiber parameters, wireless channel parameters, and system resource allocation. First, fiber length is an important factor affecting system capacity. As the fiber length increases, the optical signal experiences greater attenuation during transmission, which reduces the received optical power and the SNR of the fiber link, eventually leading to a decrease in end-to-end channel capacity.

Second, wireless transmission distance also has a significant impact on system capacity. As the wireless distance increases, path loss becomes more severe, resulting in reduced received signal power and lower wireless-link SNR. In particular, for millimeter-wave or higher-frequency communication scenarios, wireless path loss becomes more pronounced. Therefore, the wireless link is often more likely to become the capacity bottleneck of the end-to-end system.

In addition, transmit power and system bandwidth are key factors determining channel capacity. Increasing transmit power can improve the received SNR and thus enhance channel capacity to some extent; however, the capacity gain gradually becomes saturated as the transmit power continues to increase. Increasing bandwidth can improve the theoretical transmission capacity, but it also increases the noise power. Therefore, bandwidth allocation should be properly designed according to the link conditions. The modulation format also affects the practical throughput and bit error performance of the system. Higher-order modulation can improve spectral efficiency, but it requires better channel quality.

In summary, the channel capacity of a fiber-wireless converged communication system is determined by multiple factors. To improve the end-to-end capacity, transmission resources should be properly allocated between the optical fiber link and the wireless link, and suitable optimization strategies should be adopted according to the dominant capacity bottleneck.

3 CAPACITY OPTIMIZATION STRATEGY

In a fiber-wireless converged communication system, the end-to-end channel capacity is jointly affected by the optical fiber link and the wireless link. When either link experiences poor channel conditions, the overall transmission capability of the system will be limited. Therefore, the key to capacity optimization is to identify the dominant bottleneck link and allocate transmission resources according to the link conditions. Based on the system model established in the previous section, this section formulates the capacity optimization objective and presents a simplified adaptive capacity optimization strategy.

3.1 Optimization Objective

The objective of this paper is to improve the end-to-end channel capacity of the fiber-wireless converged communication system under limited transmission resources. According to the end-to-end capacity model, the system capacity can be expressed as:

$$C_{e2e}=B\log_2(1+\gamma_{eq}) \tag{7}$$

where C_{e2e} is the end-to-end channel capacity, B is the effective system bandwidth, and γ_{eq} is the end-to-end equivalent SNR. Since the equivalent SNR is jointly determined by the fiber-link SNR γ_f and the wireless-link SNR γ_w, improving system capacity requires the conditions of both links to be considered.

In practical systems, transmit power and bandwidth resources are usually limited. Therefore, the capacity optimization problem in this paper is simplified as maximizing the end-to-end channel capacity under a total power constraint, which can be written as:

$$\max C_{e2e}=B\log_2(1+\gamma_{eq}) \tag{8}$$

subject to:

$$P_f+P_w\le P_{total} \tag{9}$$

where P_f represents the transmission power allocated to the optical fiber link, P_w represents the transmission power allocated to the wireless link, and P_{total} denotes the total available transmission power of the system. This constraint indicates that the sum of the power used by the optical fiber link and the wireless link should not exceed the maximum allowable system power.

If the minimum quality-of-service requirement is further considered, a capacity constraint can be introduced as:

$$C_{e2e}\ge C_{min} \tag{10}$$

where C_{min} denotes the minimum channel capacity required by the system. This constraint ensures that the system not only pursues capacity maximization during optimization, but also satisfies the basic transmission requirement.

Therefore, the capacity optimization problem can be formulated as:

$$\begin{aligned} \max \quad & C_{e2e}=B\log_2(1+\gamma_{eq}) \\ s.t. \quad & P_f+P_w\le P_{total} \\ & C_{e2e}\ge C_{min} \end{aligned} \tag{11}$$

This optimization objective indicates that this paper does not aim to develop a complex multi-variable global optimization framework. Instead, it focuses on improving the end-to-end channel capacity through bottleneck-link identification and adaptive resource adjustment under limited transmission resources.

3.2 Simplified Optimization Procedure

Since the fiber-wireless converged communication system consists of cascaded optical fiber and wireless links, its end-to-end performance is generally limited by the weaker link. Therefore, this paper proposes a simplified capacity optimization strategy based on bottleneck-link identification. The key idea is to first calculate the capacities of the optical fiber link and the wireless link, then identify the current capacity bottleneck, and finally allocate more transmission resources to the bottleneck link to improve the overall end-to-end capacity.

The capacities of the optical fiber link and the wireless link can be expressed as:

$$C_f=B_f\log\boxed{f()}_2(1+\gamma_f) \tag{12}$$

$$C_w=B_w\log\boxed{f()}_2(1+\gamma_w) \tag{13}$$

where C_f denotes the capacity of the optical fiber link, C_w denotes the capacity of the wireless link, and B_f and B_w are the bandwidths of the optical fiber link and the wireless link, respectively. By comparing C_f and C_w, the dominant capacity bottleneck of the current system can be identified.

When $C_f<C_w$, the capacity of the optical fiber link is lower than that of the wireless link, indicating that the optical fiber link becomes the system bottleneck. In this case, the system should prioritize improving the fiber-link conditions, such as increasing the power allocated to the optical fiber link, improving optoelectronic conversion efficiency, or reducing fiber transmission loss. Conversely, when $C_w<C_f$, the wireless link becomes the system bottleneck. In this case, wireless -link conditions should be preferentially improved, for example by increasing wireless transmit power, enhancing antenna gain, or adjusting wireless resource allocation.

For simplicity, this paper mainly considers adaptive adjustment of power resources. The basic procedure is summarized as follows:

Step 1: Initialize system parameters, including total transmit power, fiber length, wireless distance, bandwidth, and noise power.
Step 2: Calculate the SNR and capacity of the optical fiber link.
Step 3: Calculate the SNR and capacity of the wireless link.
Step 4: Compare the capacities of the two links and identify the bottleneck link.
Step 5: Allocate more transmit power to the bottleneck link under the total power constraint.
Step 6: Recalculate the end-to-end equivalent SNR and channel capacity.
Step 7: Compare the optimized capacity with the fixed-allocation scheme.

This method does not require a complicated iterative solution process. It is easy to implement and can intuitively reflect the influence of the bottleneck link on the end-to-end capacity of the fiber-wireless converged system. By preferentially optimizing the bottleneck link, the system can achieve higher end-to-end capacity under limited transmission resources.

Overall, the proposed simplified optimization strategy mainly includes three key steps: link capacity calculation, bottleneck-link identification, and adaptive resource adjustment. Although the strategy has a simple structure, it provides a clear basis for subsequent performance simulations and can also serve as a foundation for more advanced optimization methods, such as water-filling algorithms, convex optimization, and intelligent resource allocation.

4 PERFORMANCE EVALUATION AND DISCUSSION

This section evaluates the performance of the proposed capacity optimization strategy for the fiber-wireless converged communication system through numerical simulations. The evaluation mainly focuses on end-to-end channel capacity, fiber length, wireless transmission distance, bit error rate, and effective throughput. To highlight the effectiveness of the proposed strategy, the adaptive capacity optimization scheme is compared with a conventional fixed resource allocation scheme. In the fixed allocation scheme, the total transmit power is equally divided between the optical fiber link and the wireless link. In contrast, the proposed adaptive scheme identifies the capacity bottleneck according to the link conditions and allocates more resources to the bottleneck link.

4.1 Simulation Setup

A typical cascaded fiber-wireless communication system is considered in the simulation. The signal is first transmitted through the optical fiber link and then delivered to the user terminal through the wireless link. The effective system bandwidth is set to 1 GHz, the fiber attenuation coefficient is set to 0.2 dB/km, and a simplified path-loss model is adopted for the wireless link. The main simulation parameters are listed in Table 1.

Table 1 Simulation Setup

Parameter	Symbol	Value
Effective bandwidth	B	1 GHz
Fiber length	L_f	5–50 km
Fiber attenuation coefficient	α	0.2 dB/km
Wireless transmission distance	d	5–100 m
Carrier frequency	f_c	28 GHz
Path-loss exponent	η	2.7
Total transmit power	P_{total}	0–30 dBm
Noise power spectral density	N_0	(-174) dBm/Hz
Antenna gain	G_tG_r	25 dB
Modulation formats	—	QPSK, 16-QAM, 64-QAM
Baseline scheme	—	Fixed allocation

Parameter	Symbol	Value
Proposed scheme	—	Adaptive allocation

For comparison, two resource allocation schemes are considered, as summarized in Table 2.

Table 2 Comparison of Resource Allocation Schemes

Scheme	Resource Allocation Principle	Description
Fixed allocation	Equal power allocation	The total power is equally allocated to the optical fiber and wireless links.
Proposed adaptive allocation	Bottleneck-aware allocation	The bottleneck link is identified according to link capacity, and more power is allocated to that link.

As shown in Tables 1 and 2, the simulation does not aim to include excessive system-level parameters. Instead, it focuses on several key factors that directly affect the end-to-end capacity, including transmit power, fiber length, wireless transmission distance, and modulation format. This setting can more clearly reveal the impact of the capacity bottleneck on the overall performance of the fiber-wireless converged system.

4.2 Capacity Performance

Figure 1 shows the simulated end-to-end channel capacity as a function of the total transmit power. It can be observed that the channel capacity of both schemes increases as the total transmit power increases. This is because a higher transmit power improves the received SNR, thereby increasing the end-to-end channel capacity.

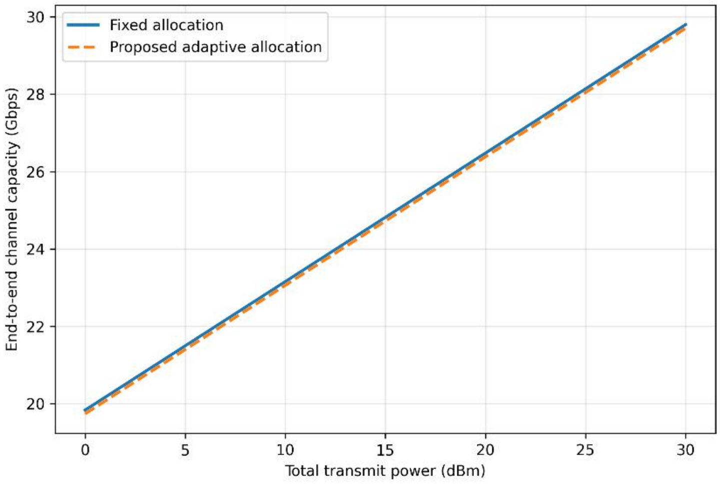

Figure 1 End-to-End Channel Capacity Versus Total Transmit Power

As shown in Figure 1, the proposed adaptive allocation scheme outperforms the fixed allocation scheme over the entire power range. This indicates that simply allocating the same amount of power to the two links cannot achieve the best end-to-end performance in a cascaded fiber-wireless system. When one link becomes the capacity bottleneck, allocating excessive resources to the non-bottleneck link contributes little to the overall capacity improvement. By contrast, the proposed adaptive scheme adjusts the resource allocation according to the link conditions, allowing more power to be assigned to the bottleneck link and thus achieving a higher end-to-end capacity.

In addition, the capacity growth gradually slows down as the transmit power further increases. This trend is consistent with the logarithmic relationship in Shannon's capacity formula, where the capacity gain becomes less significant at high SNR levels. Therefore, in practical systems, increasing transmit power alone is not the most efficient way to improve capacity; appropriate resource allocation is also essential.

4.3 Impact of Fiber Length and Wireless Distance

To further analyze the influence of different link parameters on system capacity, the effects of fiber length and wireless transmission distance are investigated separately.

Figure 2 illustrates the impact of fiber length on the system capacity. As the fiber length increases from 5 km to 50 km, the end-to-end capacity gradually decreases. This is because the optical signal experiences attenuation during fiber transmission. A longer fiber length leads to lower received optical power and reduced fiber-link SNR, which eventually decreases the end-to-end capacity.

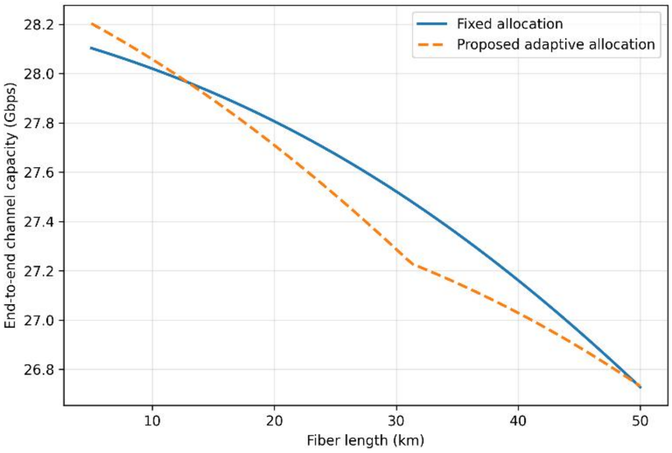

Figure 2 Impact of Fiber Length on End-to-End Channel Capacity

It can also be observed from Figure 2 that the adaptive allocation scheme consistently achieves higher capacity than the fixed allocation scheme under different fiber lengths. This indicates that when the fiber-link quality deteriorates due to increased transmission distance, adjusting resource allocation can partially compensate for the capacity loss caused by fiber attenuation. In particular, for longer fiber transmission scenarios, the fixed allocation scheme cannot adapt to link-state variations, while the proposed adaptive scheme provides better robustness.

Figure 3 presents the effect of wireless transmission distance on the system capacity. As the wireless distance increases, the end-to-end channel capacity decreases significantly. Compared with fiber length, wireless distance has a more pronounced impact on capacity because the wireless link is strongly affected by path loss, and the received signal power decreases rapidly with distance.

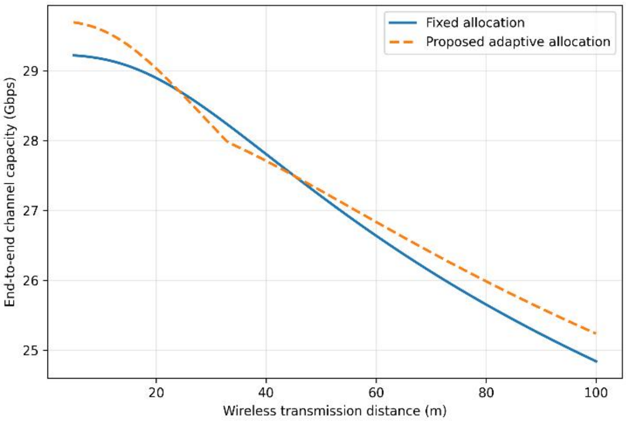

Figure 3 Impact of Wireless Transmission Distance on End-to-End Channel Capacity

As shown in Figure 3, both schemes maintain relatively high channel capacity in short-distance wireless transmission scenarios. However, as the wireless distance increases, the capacity decreases more rapidly. In this case, the wireless link is more likely to become the dominant bottleneck of the end-to-end system. By allocating more resources to the wireless bottleneck link, the proposed adaptive scheme can improve the system capacity to some extent. Therefore, the wireless-link condition plays a critical role in determining the end-to-end capacity of fiber-wireless converged communication systems, especially in millimeter-wave or high-frequency wireless access scenarios.

The main trends observed from the effects of fiber length and wireless distance are summarized in Table 3.

Table 3 Effects of Key Parameters on System Capacity

Factor	Variation Trend	Impact on Capacity	Main Reason
Fiber length	Increases	Decreases	Fiber attenuation increases and received optical power decreases.
Wireless distance	Increases	Significantly decreases	Path loss increases and received wireless power decreases.
Transmit power	Increases	Gradually increases	Received SNR is improved.
High transmit power region	Continues increasing	Capacity gain becomes saturated	Capacity follows a logarithmic relationship with SNR.
Adaptive allocation	Enabled	Capacity improves	Resources are preferentially allocated to the bottleneck link.

4.4 BER and Throughput Analysis

In addition to channel capacity, bit error rate and throughput are also important metrics for evaluating communication system performance. Channel capacity reflects the theoretical transmission capability of the system, while BER and throughput further indicate transmission reliability and practical data delivery performance.

Figure 4 shows the BER performance under different modulation formats as a function of SNR. It can be seen that the BER of all modulation formats decreases significantly as the SNR increases. This is because a higher SNR improves the received signal quality and reduces the probability of detection errors.

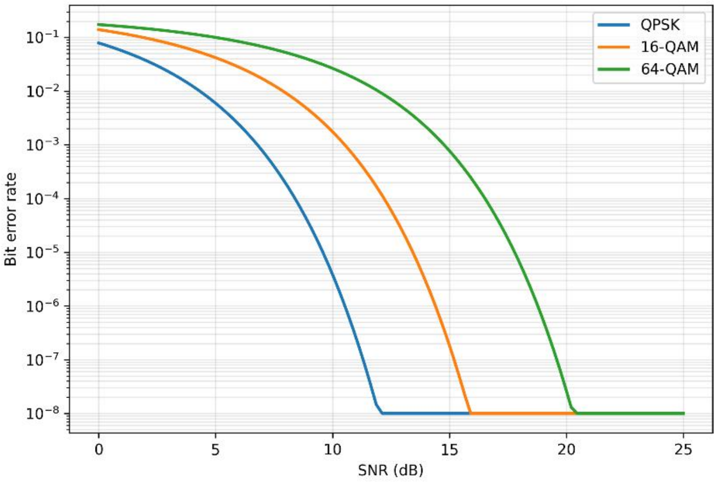

Figure 4 BER Performance under Different Modulation Formats

As shown in Figure 4, QPSK achieves the lowest BER under the same SNR condition, followed by 16-QAM and 64-QAM. This is because higher-order modulation provides higher spectral efficiency, but the distance between constellation points becomes smaller, making the signal more sensitive to noise and channel fading. For fiber-wireless converged communication systems, higher-order modulation can be adopted to improve throughput when the end-to-end channel quality is good. However, under poor link conditions or long wireless transmission distances, lower-order modulation is more suitable for ensuring transmission reliability.

Figure 5 further compares the effective throughput of the fixed allocation scheme and the proposed adaptive allocation scheme. The effective throughput can be expressed as

$$T=C_{e2e}(1-BER) \tag{14}$$

where Tdenotes the effective throughput, C_{e2e}denotes the end-to-end channel capacity, and BERdenotes the bit error rate.

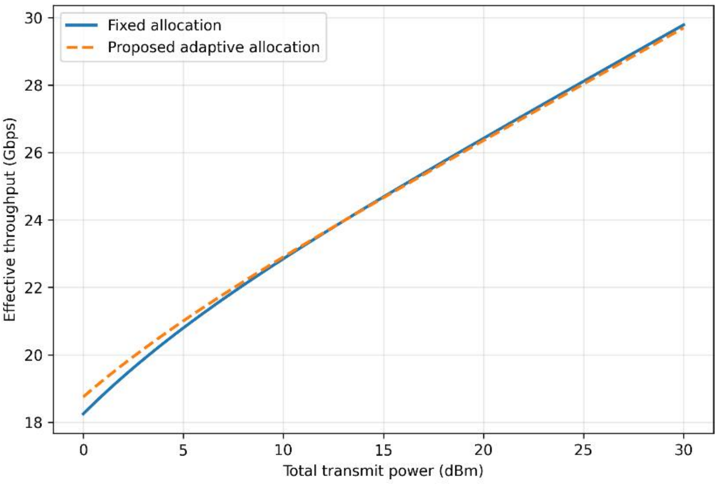

Figure 5 Effective Throughput Comparison under Different Resource Allocation Schemes

As shown in Figure 5, the effective throughput of both schemes increases with the total transmit power. This is because higher transmit power not only improves channel capacity but also reduces BER, thereby increasing the practically achievable throughput. Compared with the fixed allocation scheme, the proposed adaptive allocation scheme achieves higher throughput over the entire power range. This indicates that the proposed strategy improves not only the theoretical capacity but also the practical transmission capability of the system.

Based on the results in Figures 1–5, it can be concluded that the performance of a fiber-wireless converged communication system is jointly determined by the optical fiber link and the wireless link. Among the considered parameters, wireless transmission distance and bottleneck-link conditions have particularly significant effects on end-to-end performance. The proposed adaptive capacity optimization strategy can adjust resource allocation according to link conditions, thereby achieving better performance than the fixed resource allocation scheme in terms of channel capacity, BER, and throughput.

5 CONCLUSION

This paper investigated channel capacity optimization and performance analysis for fiber-wireless converged communication systems. First, an end-to-end system model consisting of cascaded optical fiber and wireless links was established, and the channel capacity expression was derived based on the equivalent signal-to-noise ratio. Then, the impacts of key factors, including fiber length, wireless transmission distance, transmit power, bandwidth, and modulation format, were analyzed. Based on this model, a simplified capacity optimization strategy was proposed by identifying the bottleneck link and adaptively adjusting the transmission resources to improve the end-to-end system performance.

Simulation results showed that the proposed adaptive allocation strategy achieves higher end-to-end channel capacity and effective throughput than the fixed resource allocation scheme, while also improving the bit error performance to some extent. The results further indicated that the system capacity decreases as the fiber length and wireless transmission distance increase, and the wireless distance has a more significant impact on the end-to-end performance. Therefore, bottleneck-link identification and adaptive resource allocation are essential for improving the performance of fiber-wireless converged communication systems.

Future work may be extended in several directions. More accurate optical fiber channel models can be introduced by considering dispersion, nonlinear effects, and optoelectronic conversion impairments. The proposed strategy can also be extended to MIMO-OFDM, millimeter-wave, and terahertz communication scenarios. In addition, machine learning or intelligent optimization algorithms may be employed to enable more efficient dynamic resource allocation. Further studies can also investigate capacity optimization, energy efficiency, and fairness in multi-user fiber-wireless converged networks.

COMPETING INTERESTS

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

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