

Scintillation Mitigation based on Time Diversity by Subcarrier Time Interleaved DFT-s-OFDM in Satellite Optical Transmission System

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ABSTRACT

Satellite optical communication (SOC) offers high bandwidth and data rates, while coherent detection enables high-capacity optical links. However, atmospheric turbulence causes severe intensity fluctuations and deep fading, degrading link reliability. In this paper, we propose subcarrier time-interleaved DFT-s-OFDM, a novel diversity scheme that achieves time diversity without sacrificing spectral efficiency. By redistributing frequency-domain subcarriers across multiple temporal positions, different components of each DFT-s-OFDM symbol experience independent or weakly correlated turbulence conditions. The dispersed subcarriers are equalized and recombined at the receiver to recover the original symbol while averaging fading effects. Numerical simulations and a 25-Gbps 16-QAM coherent DFT-s-OFDM PoC experiment demonstrate significant performance improvements over conventional coherent OFDM, particularly under strong turbulence, without bandwidth expansion.

Keywords: Satellite Communication, Free-Space Optical Communication, Orthogonal Frequency Division Multiplexing, Coherent Detection

1. INTRODUCTION

Satellite optical communication (SOC) has emerged as a promising technology for next-generation satellite networks, offering significantly larger bandwidth and higher data rates than conventional radio-frequency (RF) communication systems. Recent demonstrations of high-capacity optical links, including TBIRD¹ and EDRS,² have further highlighted the potential of optical communication for future space networks. In particular, coherent optical communication provides advantages such as high spectral efficiency, support for advanced modulation formats, and robust digital signal processing, making it attractive for high-capacity SOC systems.^{3,4}

However, ground-to-satellite optical links are strongly affected by atmospheric turbulence. Random fluctuations in the refractive index of the atmosphere cause scintillation and intensity fluctuations, resulting in time-varying channel fading. These effects can lead to severe power fluctuations at the receiver and substantially degrade the reliability of high-capacity optical links.⁵ As the required data rate increases, mitigating such channel impairments becomes increasingly important. Various techniques have therefore been investigated to improve the robustness of optical links against turbulence. Among them, diversity techniques are particularly effective because they allow transmitted information to experience multiple statistically different channel realizations.^{6–9} Spatial diversity, for example, can exploit multiple beams or apertures, while time diversity transmits information over different temporal channel realizations. However, conventional time-diversity schemes generally require repeated transmission of the same information, resulting in reduced spectral efficiency and increased transmission overhead. This trade-off becomes particularly problematic for high-capacity satellite optical communication systems.

DFT-spread OFDM (DFT-s-OFDM) provides a suitable framework for exploiting diversity across frequency-domain signal components. However, in conventional DFT-s-OFDM, all subcarriers corresponding to a single

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symbol are transmitted within the same symbol duration and thus experience nearly identical turbulence conditions. Consequently, the signal components of a symbol remain exposed to the same channel realization, limiting the achievable time-diversity gain.

In this paper, we propose subcarrier time-interleaved DFT-s-OFDM, which introduces time diversity by redistributing the subcarriers of each DFT-s-OFDM symbol across multiple temporal positions. Unlike conventional time-diversity techniques, the proposed scheme does not require additional signal repetition or bandwidth expansion. Instead, it rearranges the existing frequency-domain signal components such that different subcarriers experience different turbulence realizations. At the receiver, the temporally dispersed subcarriers are equalized and recombined to reconstruct the original DFT-s-OFDM symbol. The effectiveness of the proposed scheme is investigated through numerical simulations and a 25-Gbps 16-QAM coherent transmission experiment using an emulated turbulence channel. The results demonstrate that subcarrier time-interleaving can provide significant diversity gain and improve the robustness of coherent SOC under strong turbulence while maintaining the spectral efficiency of the original DFT-s-OFDM system.

2. SCHEMATICS

Fig. 1 represents the flow chart of the proposed method. As illustrated in Fig. 1, the proposed subcarrier time-interleaved DFT-s-OFDM system introduces time diversity by temporally dispersing the subcarriers of each DFT-s-OFDM symbol. First, M QAM symbols are generated and transformed into the frequency domain through a DFT. The resulting M subcarriers are then redistributed across N temporal positions according to the proposed subcarrier time-interleaving scheme. After interleaving, the subcarriers are converted into the time domain using an IFFT and transmitted through the FSO channel. By spreading the subcarriers of a single DFT-s-OFDM symbol over multiple time intervals, different subcarriers experience different realizations of the time-varying atmospheric turbulence, thereby providing time diversity without requiring additional signal repetition or bandwidth expansion. At the receiver, the received signals are first subjected to channel estimation and equalization to compensate for the turbulence-induced channel fading. The equalized signals are then processed by the corresponding time-deinterleaving operation to restore the original temporal and subcarrier arrangement. The reconstructed frequency-domain components are subsequently transformed through an FFT and an IDFT to recover the original M QAM symbols. Through this process, the proposed scheme exploits the temporal variation of the turbulence channel while preserving the spectral efficiency of conventional DFT-s-OFDM.

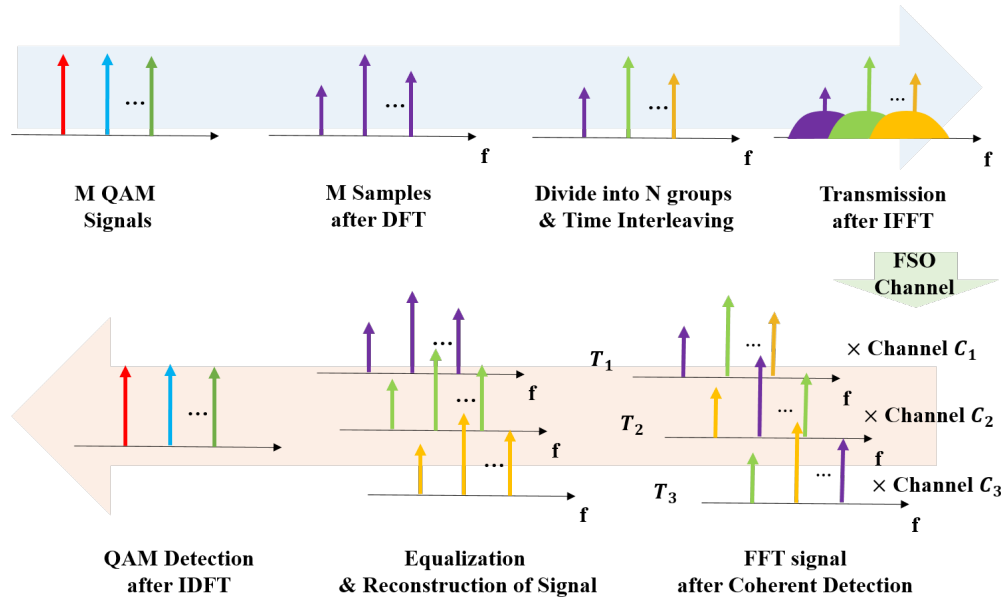


Figure 1. Flow Chart of Proposed Method

After de-interleaving, the signal-to-noise ratio (SNR) of n th symbol could be determined by the following equation:

$$SNR_n = \frac{\sigma_s^2}{\frac{1}{N} \sum_{n=1}^N \frac{\sigma_w^2}{|H_n|^2}} \quad (1)$$

where σ_s^2 indicates the average power of the complex signal received and σ_w^2 indicates the noise power, which is assumed to be AWGN in coherent detection. H_n indicates the channel coefficient. Note that the temporal SNR fluctuates with the term $|1/H_n|^2$. The mean value of the equivalent noise power of n th block is determined as follows:

$$\mathbb{E} \left(\frac{1}{N} \sum_{n=1}^N \frac{\sigma_w^2}{|H_n|^2} \right) = \sigma_w^2 \mathbb{E}(1/|H|^2) \quad (2)$$

whereas the variance in the equivalent noise power of the n th block is determined as follows:

$$VAR \left(\frac{1}{N} \sum_{n=1}^N \frac{\sigma_w^2}{|H_n|^2} \right) = \frac{\sigma_w^4}{N} VAR(1/|H|^2) \quad (3)$$

As N increases, the variance of the equivalent noise power converges to zero. Consequently, for a sufficiently large number of subgroups N , the SNR of the proposed scheme converges as follows:

$$SNR_{LargeN} = \frac{\sigma_s^2}{\sigma_w^2} \frac{1}{\mathbb{E}(1/|H|^2)} \quad (4)$$

Therefore, the proposed scheme can reduce the channel variance as N increases, resulting in a more stable SNR. However, increasing N also introduces a trade-off with the associated latency and computational complexity.

3. NUMERICAL RESULTS

To validate the effectiveness of the proposed scheme, numerical analysis was conducted under various SNR conditions and interleaving depths N . Fig. 2 illustrates the received OFDM constellations obtained with different values of N at different SNR levels. As observed from the figure, the proposed scheme becomes increasingly

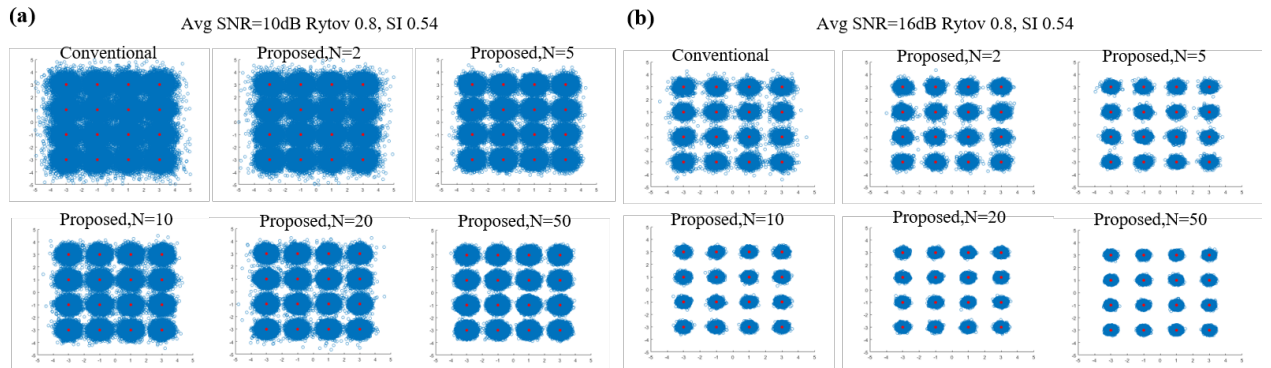


Figure 2. Received OFDM constellations for different N under a Rytov variance of 0.8 ($SI = 0.54$) at average SNRs of (a) 10 and (b) 16 dB

effective as the SNR increases. In addition, a larger interleaving depth N provides a greater performance improvement, demonstrating that the increased temporal separation of the subcarriers can effectively enhance the robustness of the system against turbulence-induced channel fluctuations. As discussed in the previous section, increasing N allows the subcarriers to experience a larger number of statistically independent turbulence realizations, thereby reducing the variance of the effective channel gain. Consequently, the instantaneous SNR exhibits smaller fluctuations around its average value, resulting in more stable signal reception. This effect can be observed in the received constellations, where a larger N leads to a more concentrated distribution of the received symbols, particularly under relatively high-SNR conditions. The larger gain observed at high SNR can be attributed to the effect of instantaneous SNR fluctuations. When the average SNR is sufficiently high, the performance degradation caused by occasional low-SNR channel realizations becomes increasingly significant, even though the average received power remains relatively high. In other words, the system performance is not determined solely by the average SNR but is also strongly affected by fluctuations in the instantaneous SNR. By reducing the variance of the effective channel gain, the proposed time-interleaving scheme mitigates these instantaneous SNR fluctuations and consequently reduces the associated performance penalty. Therefore, the benefit of increasing N becomes more pronounced at higher SNRs, resulting in a larger diversity gain and more stable signal reception.

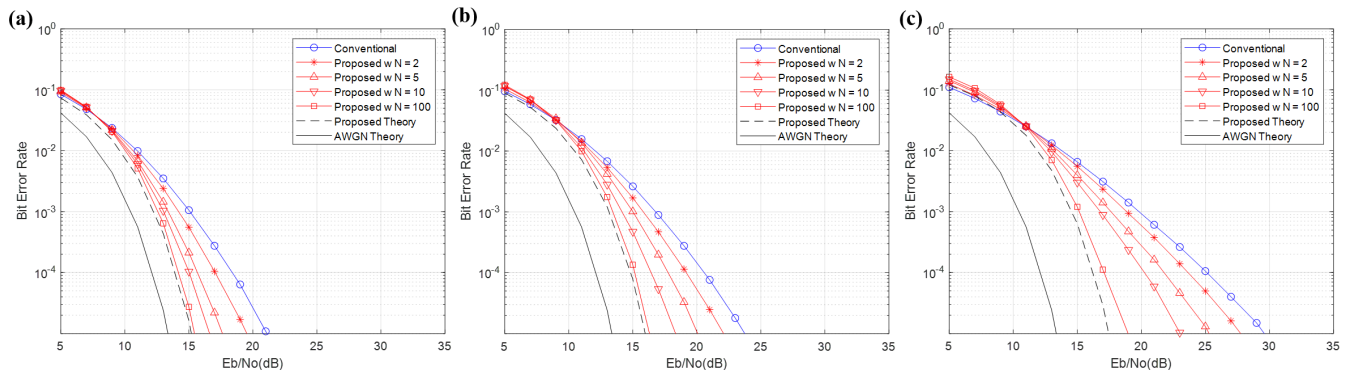


Figure 3. E_b/N_0 vs BER with a modulation order of 16QAM under a Channel with a Rytov Variance of (a) 0.5 (b) 1 (c) 3

Fig. 3 further shows the BER performance of the proposed scheme under different Rytov variances, interleaving depths N , and average SNRs. Consistent with the constellation results, the performance gain of the proposed scheme becomes more pronounced as N and the average SNR increase. In addition, a larger gain is observed under higher Rytov variance, where the turbulence-induced fluctuations of the channel become more severe. Under such conditions, reducing the variance of the effective channel gain through time interleaving provides a greater benefit, resulting in a larger diversity gain. In contrast, at relatively low average SNRs, the proposed scheme can exhibit a performance degradation compared with the conventional scheme. This behavior can be attributed to the average power penalty introduced by the proposed time-interleaving scheme, as described in (2). When the average SNR is low, the benefit obtained from suppressing instantaneous SNR fluctuations is relatively limited, while the reduction in the average received power has a more dominant effect on the BER. As the average SNR increases, however, the impact of instantaneous SNR fluctuations becomes more significant, and the benefit of reducing the channel-gain variance eventually outweighs the average power penalty. Consequently, the proposed scheme provides increasing performance gains at higher average SNRs, with the gain becoming particularly significant under stronger turbulence conditions.

4. EXPERIMENTAL RESULTS

This section presents the results of a proof-of-concept experiment based on a back-to-back coherent detection configuration. The experimental system employed 100 subcarriers with a spacing of 62.5 MHz, resulting in an overall bandwidth of 6.25 GHz. Using 16-QAM modulation, a total data rate of 25 Gbps was achieved. To

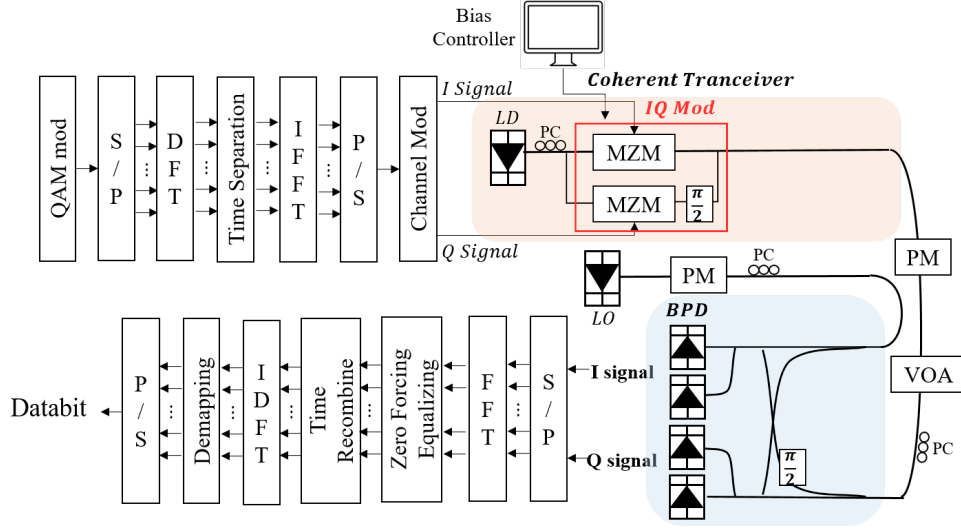


Figure 4. Experimental Schematics

emulate different atmospheric turbulence conditions, randomly generated Gamma-Gamma channel coefficients corresponding to Rytov variances (σ_R^2) of 0.2 and 1.0 were applied to the transmitted symbols. The experimental configuration is illustrated in Fig. 4. Two Thorlabs SFL1550S lasers served as the optical sources, while a Rofea 20G IQ modulator performed optical signal modulation. At the receiver, a Fujitsu FIM24706 coherent receiver was used for optical-to-electrical conversion and signal recovery. The bias voltages V_I , V_Q , and V_π were automatically controlled using a bias controller.

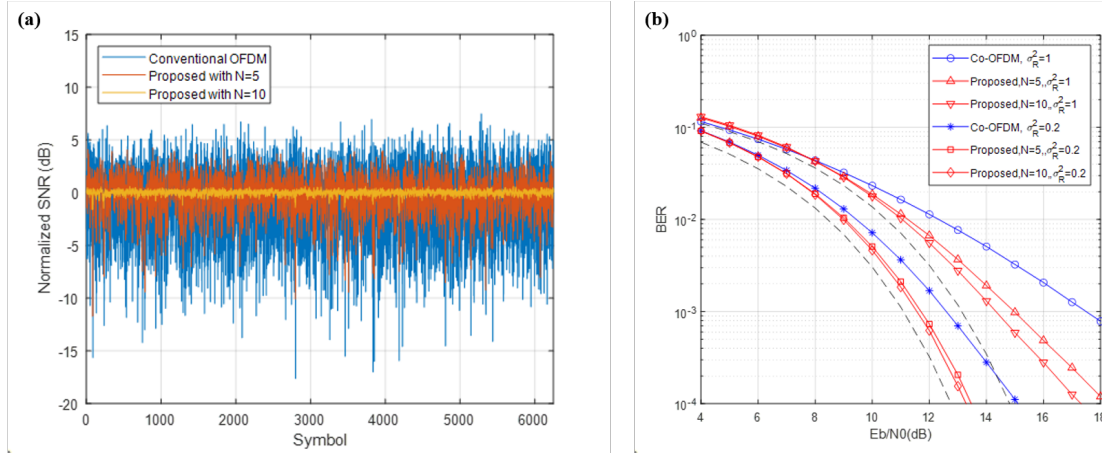


Figure 5. Experimental Results (a) Symbol vs Normalized SNR for the conventional Co-OFDM, and the proposed method with $N = 5, 10$ with the channel of Rytov variance $\sigma_R^2=1$ (b) E_b/N_0 vs BER for the conventional Co-OFDM, and the proposed method with $N = 5, 10$ with the channel of Rytov variance $\sigma_R^2=1$ and 0.2

Fig. 5 presents the experimental results for the proposed scheme, including the normalized instantaneous SNR variations and BER performance under turbulent conditions. Fig. 5(a) illustrates the normalized instantaneous SNR variations over time under a Rytov variance of 1.0, comparing conventional Co-OFDM with the proposed scheme for $N = 5$ and $N = 10$. The SNR was obtained from the EVM measured over 100 subcarriers for each symbol, calculated as the squared reciprocal of the EVM, and normalized by the average SNR of the corresponding sequence. As shown in Fig. 5(a), the instantaneous SNR fluctuations are progressively reduced as N increases, demonstrating the averaging effect of the proposed time-interleaving scheme. Fig. 5(b) presents

the measured BER performance as a function of E_b/N_0 for different turbulence intensities. The blue curves represent conventional Co-OFDM, while the red curves correspond to the proposed scheme with $N = 5$ and $N = 10$, and the dashed black curve indicates the theoretical asymptote approached as N tends to infinity. The experimental results consistently reproduce the trends observed in the numerical analysis, including the SNR gains achieved by increasing N and the dependence of the performance improvement on turbulence intensity and average SNR. In addition, the measurements reveal a slight performance degradation in the low-SNR regime and an increasing deviation from the theoretical asymptote under severe turbulence. The close agreement between the numerical and experimental results confirms the practical effectiveness of the proposed scheme in mitigating turbulence-induced fading and improving the reliability of coherent optical transmission.

5. CONCLUSION

In summary, a subcarrier time-interleaved DFT-s-OFDM scheme was proposed and experimentally demonstrated to mitigate turbulence-induced fading in coherent optical communication systems. By introducing time diversity across subcarriers while preserving spectral efficiency, the proposed scheme reduces instantaneous SNR fluctuations through the redistribution and subsequent recombination of subcarrier components. Its effectiveness was comprehensively evaluated through numerical simulations and a 25-Gbps 16QAM proof-of-concept experiment. The results demonstrate that the proposed scheme achieves substantial SNR improvements over conventional Co-OFDM, with the performance gain becoming more pronounced as the turbulence strength and interleaving depth N increase. The close agreement between the numerical simulations and experimental measurements further confirms the validity and robustness of the proposed approach. Overall, the proposed scheme offers an effective means of improving transmission reliability in turbulent optical channels while maintaining high spectral efficiency, making it a promising approach for next-generation FSO systems, particularly for satellite communication scenarios subject to severe atmospheric turbulence.

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