

## Performance of Optical OFDM Systems in Atmospheric Turbulence Channel

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### ABSTRACT

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Mitigation of atmospheric turbulence effects on the bit-error rate performance for both asymmetrically clipped optical orthogonal frequency-division multiplexing (ACO-OFDM) and modified ACO-OFDM is studied using a single-input multiple-output configuration.

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## 1. Introduction

Free Space optics (FSO) is one of leading optical communication technology. To date, research in free-space optical (FSO) communications has been extensive due to the potential to provide very high data rates in the order of gigabits per second [1]. One of the most damaging impairments on FSO performance is atmospheric turbulence induced irradiance fluctuations, referred to as scintillation [1]. Scintillation takes place as a result of heating of the earth's surface, which results in the rise of thermal air masses. These masses are then combined forming regions with different densities and sizes, which cause differences in the refractive indices that vary with time; these regions cause fluctuations in the irradiance of the received laser beam. A multiple-input multiple-output (MIMO) approach has been investigated as a solution, and in a dispersive channel, inter-symbol interference (ISI) is highly detrimental [1]. The use of OFDM in conjunction with MIMO has been suggested to overcome both the ISI and the induced fading caused by atmospheric turbulence. MIMO-OFDM is used currently in the 4G wireless communication systems [2]. It is proven that deploying diversity at the receiver is more efficient than its use at the transmitter [1].

In this paper, we investigate the BER performance of both ACO-OFDM [3] and MACO-OFDM [4], [5] in a turbulent channel with the aid of a SIMO configuration. The rest of the paper is organized

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as follows. In Sec. 2, scintillation statistics and the system model are defined. In Sec. 3, the results of the estimation of BER performance for both systems is presented. It also gives a detailed discussion for MACO-OFDM capacity in different atmospheric turbulent channels: weak, moderate and strong turbulence. Finally, concluding remarks are given in Sec. 4.

## 2. Scintillation Statistics and System Model

A SIMO OFDM system with  $N$  photo-detectors at the receiver side is considered. Each receiver collects a portion of transmitted optical power and by the use of the maximal ratio combining (MRC) diversity technique, fading induced errors can be mitigated [1]. Several distributions have been proposed to describe the irradiance fluctuation depending on the strength of the atmospheric turbulence; log-normal, K-distribution, and gamma-gamma are the most commonly used models [1]. The Gamma-gamma distribution has recently been demonstrated to model atmospheric turbulence from the weak to strong regimes [1]; throughout the paper, the gamma-gamma channel model is adopted, the probability density function of which is the product of two independent gamma random variables [6]

$$f(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{(\alpha\beta)I}) \quad (1)$$

where  $I$  is the signal intensity  $\Gamma(\cdot)$  is the gamma function,  $K_{\alpha-\beta}$  is the modified Bessel function of the second kind of order  $\alpha-\beta$ , and  $\alpha$  and  $\beta$  are the effective positive parameters of the large- and small-scale eddies that characterize the irradiance fluctuation pdf [1]

$$\alpha = \left( \exp \left[ \frac{0.49\sigma_l^2}{(1 + 1.11\sigma_l^{12/5})^{7/6}} \right] - 1 \right)^{-1}$$

$$\beta = \left( \exp \left[ \frac{0.51\sigma_l^2}{(1 + 0.69\sigma_l^{12/5})^{5/6}} \right] - 1 \right)^{-1} \quad (2)$$

where  $\sigma_l$  is the Rytov variance for plane wave which is defined as [6]

$$\sigma_l^2 = 1.23C_n^2 k^{7/6} L^{11/6} \quad (3)$$

where  $C_n^2$  is the refractive-index structure parameter,  $k = 2\pi/\lambda$  is the wave number, and  $L$  is the link length. The strength of atmospheric turbulence is represented by a factor known as scintillation index  $SI$ , which depends on the Rytov variance [6]

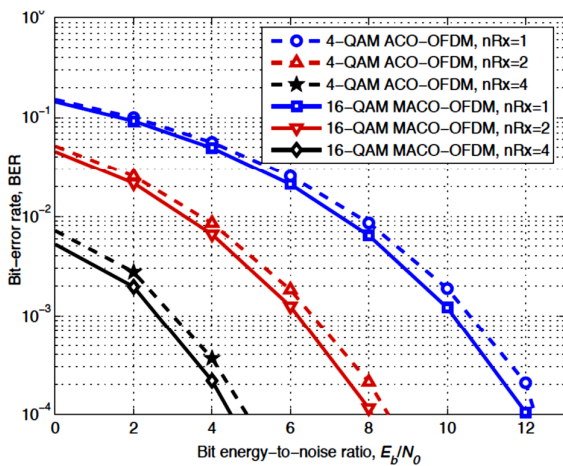
$$SI = \alpha^{-1} + \beta^{-1} + (\alpha\beta)^{-1} \quad (4)$$

## 3. Results and Discussion

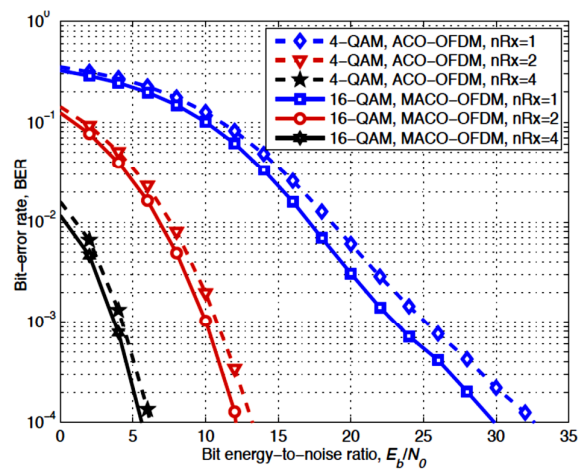
Monte Carlo simulations are carried out to study the bit error rate (BER) performance of both ACO-OFDM and Modified ACO-OFDM system using MRC diversity technique at the receiver for  $N \in$

{1, 2, 4} at different atmospheric conditions. As the SI value increases the turbulence strength increases and so does the induced irradiance fluctuations. As ACO-OFDM offers double the spectral efficiency of MACO-OFDM and in order to have a fair comparison between their performances, the data rates of both systems are fixed i.e. 4-QAM ACO-OFDM is compared to 16-QAM MACO-OFDM. Figure 1 shows a comparison for the case of weak turbulence (SI = 0.11). As expected, the performances of both systems improve as the number of receiving photodetectors (nRx) increases. Specifically at a BER of  $10^{-4}$ , the performance of MACO-OFDM is better than that of ACO-OFDM by nearly 0.5 dB for N = 1, 2, and 4, respectively.

Figure 2 shows the BERs when increasing the SI to 0.7 representative of moderate turbulence. The performances of both systems degrade, however the MACO-OFDM still outperforms ACO-OFDM. The improvement of MACO-OFDM over ACO-OFDM (at a BER of  $10^{-4}$ ) is about 2.6 dB, 1 dB and 0.5 dB for N = 1, N = 2, and 4, respectively.

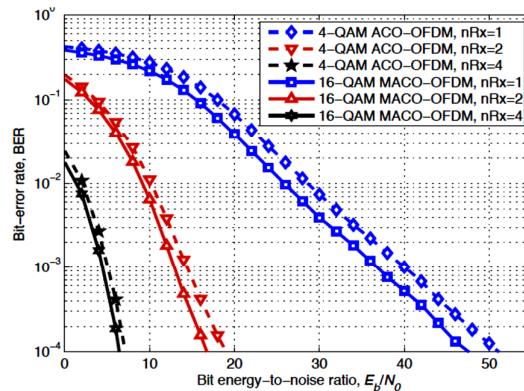


**Fig. 1.** BERs of both ACO-OFDM and MACO-OFDM versus the bit energy-to-noise ratio at SI = 0.11,  $\alpha = 18.2530$  and  $\beta = 16.5793$



**Fig. 2.** BERs of both ACO-OFDM and MACO-OFDM versus the bit energy-to-noise ratio at SI = 0.7,  $\alpha = 4.3939$  and  $\beta = 2.5636$

Finally, for the case of strong turbulence (SI = 0.98) similar conclusions can be obtained as shown in Fig. 3. However, the difference in the performance improvement increases. Specifically, the improvement in performance becomes 4 dB, 2.2 dB and 0.5 at N = 1, N = 2 and 4, respectively.



**Fig. 3.** BERs of both ACO-OFDM and MACO-OFDM versus the bit energy-to-noise ratio at SI = 0.98,  $\alpha = 3.9929$  and  $\beta = 1.7018$

### 3.1 MACO-OFDM capacity

The capacity of the system can be readily estimated by applying Shannon capacity formulation [7]. As there are  $2N$  samples instead of  $N$  as is the case for ACO-OFDM, the effective bandwidth of the channel for MACO-OFDM is halved such that

$$C_{ModACO-OFDM} = \frac{1}{2} \times \left( \frac{1}{4} \log_2 \left( 1 + \frac{S}{N} \right) \right) \quad (5)$$

where  $S$  is the signal and  $N$  is the noise power respectively. The estimated capacity of both MACO-OFDM and ACO-OFDM is displayed in Fig. 4. As expected, the capacity of ACO-OFDM is higher than that of MACO-OFDM. The capacity for a  $SNR > 20\text{dB}$  is high as the distribution of the signal plus noise is nearly equal to the distribution of the signal only; however at relatively low SNRs, the effect of noise on the distribution becomes more significant. As is evident in Fig. 4, at low SNR the capacities of both techniques are similar but as the SNR increases, the capacity of ACO-OFDM becomes significantly higher.

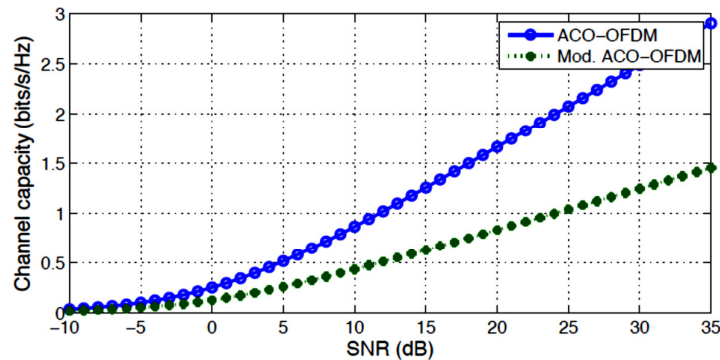


Fig. 4. Channel capacities for an optical channel with mean optical power constraint for ACO-OFDM and MACO-OFDM

### 3.2 SIMO MACO-OFDM capacity in atmospheric turbulent channel

The Gamma-Gamma distribution is used to model atmospheric turbulence as it represents all regimes from weak to strong turbulence accurately. Furthermore, as the performance of OFDM degrades in the presence of turbulence, SIMO is used to combat fading and increase the capacity of the system. Higher bandwidths, data rates and hence capacities are achieved through the use of multiple photodetectors at the receiver.

The channel capacity for MIMO OFDM is given by [7–10]

$$C = E \left[ \frac{1}{N} \sum_{n=1}^N \log_2 \left( I_m + \frac{\rho}{M_t} \tilde{H}_n \tilde{H}_n^H \right) \right] \quad (6)$$

where  $N$  is the number of OFDM subcarriers,  $\rho$  is the average SNR,  $M_t$  is the number of transmitting sources,  $m$  is the  $\min(n_{Rx}, M_t)$ ,  $n_{Rx}$  is the number of receiving apertures,  $\tilde{H}$  is the gamma-gamma channel coefficient matrix at subcarrier  $n$ , and  $H$  denotes the Hermitian

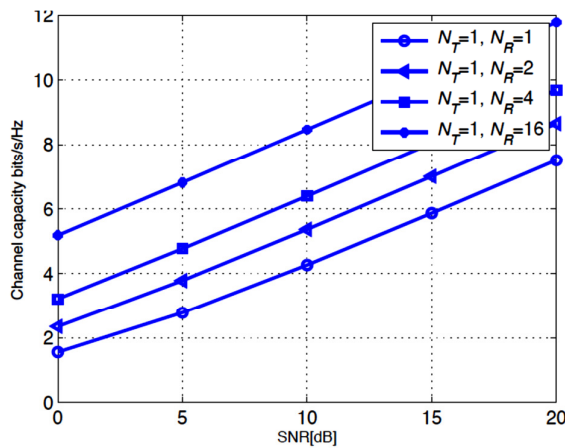
transpose. In case of SIMO,  $M_t = 1$  and, therefore the channel capacity takes the form [9, 11–14]

$$C = E \left[ \frac{1}{N} \sum_{n=1}^N \log_2 \left( 1 + \rho \|\tilde{H}_n\|^2 \right) \right] \quad (7)$$

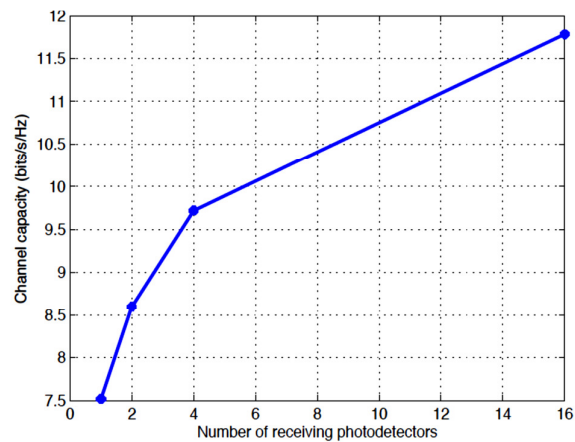
The channel capacity is estimated through a MATLAB based simulation for SIMO MACO-OFDM assuming a gamma-gamma channel.

### 3.3 SIMO MACO-OFDM capacity in weak atmospheric turbulence

Channel capacity has been evaluated in weak turbulence at  $SI = 0.11$  as shown in Fig. 5. An increase of 2 bits/s/Hz in the capacity in all orders results as the SNR increases by 5 dB. As expected as the number of receiving photodetectors increases, the capacity increases as depicted from Fig. 6.



**Fig. 5.** Channel capacities for an optical channel with mean optical power constraint for MACO-OFDM in weak atmospheric turbulence



**Fig. 6.** Channel capacities vs the number of receiving photodetectors

Table 1 summarizes system capacity at a SNR = 20 dB as a function of the number of receivers; the capacity increases from 7.5 bits/s/Hz, 8.6 bits/s/Hz, 9.7 bits/s/Hz to 11.8 bits/s/Hz for SISO: (1×1, 1×2, 1×4 and 1×16, respectively).

**Table 1**

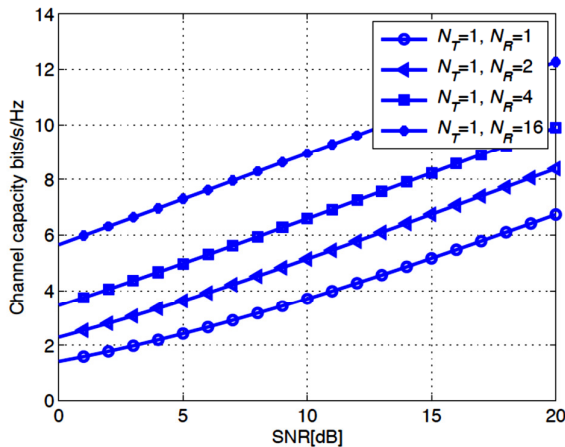
Comparison for SIMO MACO-OFDM capacity at SNR=20 dB by increasing receiving photodetector numbers in case of weak atmospheric turbulence

nRx	Channel capacity
1	7.5164
2	8.6007
4	9.7178
16	11.7842

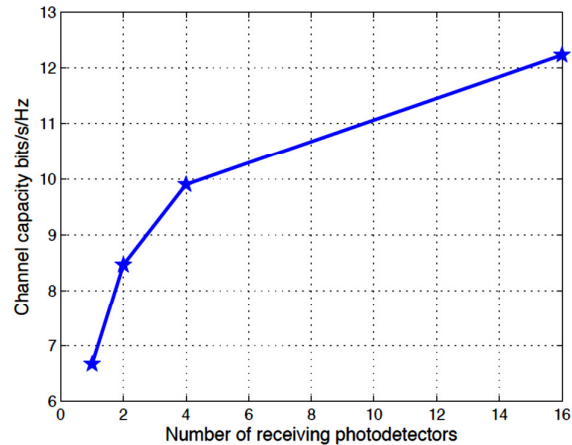
### 3.4 SIMO MACO-OFDM capacity in moderate atmospheric turbulence

Similarly, channel capacity is also evaluated for SIMO MACO-OFDM in moderate atmospheric turbulence, at  $SI = 0.7$ , as shown in Fig. 7. As expected, the channel capacity increases as the number of receiving photodetectors increases.

At a  $SNR = 20$  dB, channel capacity is estimated at a range of orders:  $1 \times 1$ ,  $1 \times 2$ ,  $1 \times 4$ , and  $1 \times 16$  and depicted in Fig. 8. The capacity improves as the diversity order increases.



**Fig. 7.** Channel capacities for an optical channel with mean optical power constraint for MACO-OFDM in moderate atmospheric turbulence



**Fig. 8.** Channel capacities vs the number of receiving photodetectors in moderate atmospheric turbulence

Table 2 presents system capacity at a  $SNR = 20$  dB as a function of the number of receivers; the capacity increases from 6.7 bits/s/Hz, 8.4 bits/s/Hz, 9.9 bits/s/Hz to 12 bits/s/Hz for SISO:  $1 \times 2$ ,  $1 \times 4$ , and  $1 \times 16$ , respectively.

**Table 2**

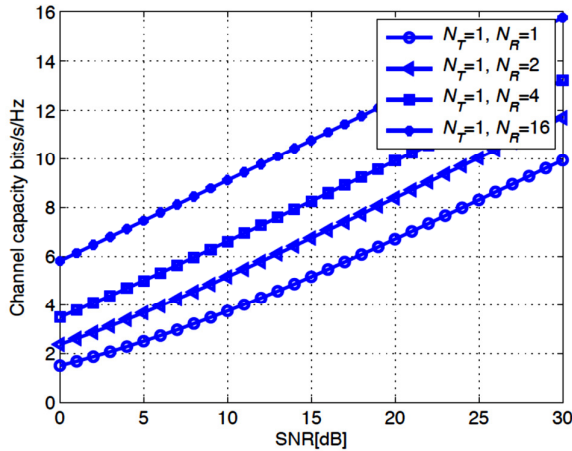
Comparison for SIMO MACO-OFDM capacity at  $SNR = 20$  dB by increasing receiving photodetector numbers in case of moderate atmospheric turbulence

nRx	Channel capacity
1	6.6216
2	8.4912
4	9.8701
16	12.2589

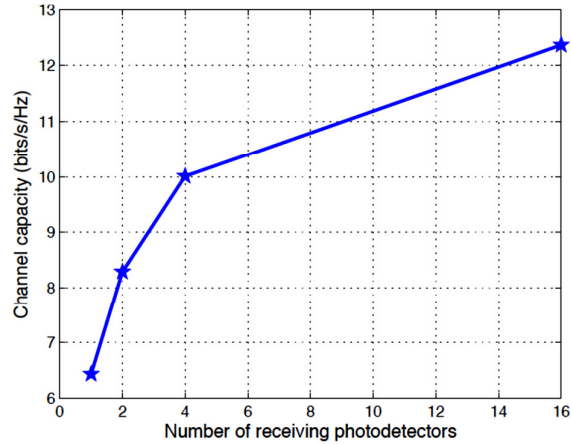
### 3.5 SIMO MACO-OFDM capacity in strong atmospheric turbulence

Finally, channel capacity is estimated for SIMO MACO-OFDM in strong atmospheric turbulence, at  $SI = 0.98$  as shown in Fig. 9. Channel capacity increases as the number of receiving photodetectors increase; an increase of 2 bits/s/Hz in the capacity for all orders results from an increase in the SNR of 2 dB. Also noticeable is that the channel capacity performance is nearly similar to that for moderate atmospheric turbulence as the difference in the  $SI$  value is not significant. Figure 10 shows the relationship between channel capacity and the number of receiving

photodetectors; the capacity improves as the diversity order increases. Table 3 presents system capacity at a SNR = 20 dB as a function of the number of receivers; the capacity increases from 6.4 bits/s/Hz, 8.3 bits/s/Hz, 10.0 bits/s/Hz to 12 bits/s/Hz for SISO: 1×2, 1×4, and 1×16, respectively. The relationship between channel capacity and the number of receiving photodetectors is direct proportional.



**Fig. 9.** Channel capacities for an optical channel with mean optical power constraint for MACO-OFDM in strong atmospheric turbulence



**Fig. 10.** Channel capacities vs the number of receiving photodetectors in strong atmospheric turbulence

Table 3 presents system capacity at a SNR = 20 dB as a function of the number of receivers; in case of strong turbulence.

**Table 3**

Comparison for SIMO MACO-OFDM capacity at SNR=20 dB by increasing receiving photodetector numbers in case of strong atmospheric turbulence

nRx	Channel capacity
1	6.4008
2	8.3023
4	9.8625
16	12.3929

#### 4. Conclusion

The BER performance of the MACO-OFDM system, adopting SIMO diversity technique and MRC at the receiver, has been investigated in turbulent channels. Results have been compared to that of traditional ACO-OFDM system. It has been shown that MACO-OFDM outperforms ACO-OFDM in most turbulent regimes. The capacity of MACO-OFDM is presented in case of turbulent channel.

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