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# Performance Evaluation of SAC-OCDMA System in Free Space Optics and Optical Fiber System Based on Different Types of Codes

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**Abstract** In this paper, the Spectral Amplitude Coding-Optical Code Division Multiple Access (SAC-OCDMA) system performance is investigated both in Free Space Optics (FSO) and Optical Fiber Systems (OFS) scenarios focusing on different types of codes. The codes having low cross correlation such as Random Diagonal (RD) and Khazani-Syed (KS), and zero cross correlation such as Zero Cross Correlation (ZCC) and Multi-Diagonal (MD) are used. In the FSO scenario, moderate turbulence and hazy weather conditions are considered. In the OFS scenario, nonlinear effects, attenuation, and dispersion are taken into consideration. Also, the performance of various codes is evaluated under different rain attenuation conditions. The simulation results show that the SAC-OCDMA codes performance is media-dependent. The ZCC codes give better performance than low cross correlation codes in both FSO and OFS scenarios. The MD code gives the best code performance in both scenarios with the ZCC code following. The RD code provides better performance than the KS code in the OFS scenario. However, in the FSO scenario, the KS code performs better than the RD code under the turbulence effect. Furthermore, the MD code performance under different bit rates is investigated to support tri-play services. Its security performance is also investigated.

**Keywords** Low cross correlation (LCC) · Zero cross correlation (ZCC) · Spectral amplitude coding-optical code division multiple access (SAC-OCDMA)

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## 1 Introduction

OCDMA is considered as a promising technique for future photonic networks because it has the characteristics of all-optical processing, asynchronous access, high security, and capacity on demand [1]. Moreover, OCDMA is widely used in OFS and FSO scenarios as a multiplexing technique to support multiple users. As a consequence, many studies have discussed OCDMA in the OFS scenario. These studies agreed that the main issue in OCDMA is the Multiple Access Interference (MAI) and Phase Induced Intensity Noise (PIIN). So, several techniques have been introduced to solve these problems using SAC-OCDMA system, where a unique codeword is allocated to each user to encode the data. These SAC-OCDMA codes either have a zero-cross-correlation property such as MD and ZCC codes, or have a low cross correlation $\lambda_C \leq 1$ such as KS [2], RD [3], Optical Orthogonal Code (OOC) [4], Modified Frequency Hopping (MFH), Hadamard [5, 6], and Modified Quadratic Congruence (MQC) [7] codes. The codes cross correlation has a main effect in reducing MAI and distinguishing codewords of users from each other. In addition, various detection techniques such as complementary [7], AND [8], Modified-AND [9], NAND [10], and XOR [11] subtraction have been used to reduce MAI, but the PIIN effect remains in the system. Unfortunately, these techniques increase the receiver cost and complexity. In the last few years, a direct detection technique has been used to suppress both MAI, and PIIN, and reduce receiver complexity. Reducing MAI and PIIN increases the number of users and provides better system performance [3].

Recently, the FSO scenario captured great attention and found numerous applications in the telecommunications field. This is attributed to its easy setup, immunity to electromagnetic interference, and high security. Some studies discussed OCDMA codes in the FSO scenario, specifically with SAC-OCDMA system. It has a better performance than that of Intensity Modulation (IM), where the transmission distance is improved by 22.7% [12]. It also has an easier implementation than that of the Spectral Phase Coding (SPC). The latter requires knowledge of the phase information and a highly precise phase control. This is a challenge in the fabrication of encoders and decoders such as Super Structured Fiber Bragg Grating (SSFBG) [13, 14]. Optical Orthogonal Code (OOC) achieves a high-speed communication for small scintillation values. However, OOC cannot provide suitable performance under intermediate turbulence [15]. In a comparison between OOC and Complementary Walsh–Hadamard (CWH) code in the FSO scenario using mesh network, CWH performed better than OOC due to its shorter code length and simple design [16]. In addition, the performance of a new form of an m-sequence code has been evaluated under turbulence and noise. The performance has been compared to that of Prime Code (PC) and OOC, where OOC showed the worst performance. Furthermore, the comparison between PC, Quadratic Congruence (QC), and KS codes showed that the code efficiency is media-dependent. This means that if a code family operates well in fiber media, it does not necessarily work well in the FSO scenario. In Ref. [17], it was proved that KS code with code weight 6 provides higher efficiency than QC code with PC code following [17].

In this paper, the FSO theory and attenuations are discussed in Sect. 2. In Sect. 3, a mathematical analysis of OCDMA codes in FSO and OFS scenarios is presented for RD, KS, ZCC, and MD codes. In Sect. 4, different SAC-OCDMA codes are evaluated under the influence of various rain attenuation conditions. In Sect. 5, a comparison is presented between these codes under moderate turbulence and hazy weather in the FSO scenario, and under nonlinear effects, attenuation, and dispersion in the OFS scenario. In Sect. 6, the MD code is evaluated at different QoS values, and its security performance is investigated.

Finally, the concluding remarks are given in Sect. 7. Simulations using Optiwave 13.0 are presented to evaluate the performance of different codes.

## 2 FSO Theory and Attenuation

The FSO scenario can be used in locations where optical fiber cables are difficult to use. It has a lower cost than those of fiber optic cables and radio frequency communications. Moreover, it is unlicensed compared to microwave links. However, the FSO scenario suffers from attenuations due to weather conditions. Some of these attenuations are attributed to the Line-of-Sight (LOS) issue, aerosol scattering effect, and signal fading due to atmospheric turbulence. These effects cause fluctuations in both intensity and phase of the received light signal [15]. The FSO operation depends on LOS, where the transmitter and receiver must see each other. A narrow modulated light beam is sent from a transmission station, propagated through the atmosphere, and then received at a receiving station. Weather conditions limit the FSO scenario performance. Therefore, understanding the optical signal propagation under various climate conditions is critical. Although the clear atmosphere consists of oxygen and nitrogen atoms. The atmosphere can contain large quantities of water vapor and other constituents, which cause scattering and absorption of infrared photons [18, 19]. The attenuation due to scattering and absorption can be described by Beer's law as follows [19].

$$\mathrm{t} = \frac{\mathrm{I}_o}{\mathrm{I}_\mathrm{P}} = \varepsilon^{-\gamma\xi} \tag{1}$$

where $\mathrm{I}_\mathrm{o}$ is the launched intensity, $\mathrm{I}_\mathrm{R}$ is the detected intensity, $x$ is the distance, $\gamma$ is the attenuation coefficient, and $\tau$ is the transmission ratio.

### 2.1 Rain

Rain has an attenuation effect on light signal propagation through the atmosphere. This attenuation effect reduces the propagation distance traveled by the light beam. The rain attenuation effect is less than the fog attenuation effect on the light beam, because the radius of raindrops (200–2000 μm) is larger than the wavelength of the FSO light source [19]. Rain attenuation can be expressed as [20]

$$\alpha_{precipitation} = a\, r^b, \tag{2}$$

where $\alpha_{\mathrm{precipitation}}$ is the rain attenuation in dB/Km, $r$ is the rain rate (mm/hr), $a$ and $b$ are coefficients dependent on frequency and temperature. Various rain conditions, there attenuations, and visibilities are shown in Table 1.

**Table 1** Rain attenuation

| Weather condition | Visibility (km) | Attenuation (dB/km) |
|---|---|---|
| Light fog | 0.5 | 18.3 |
| Very light fog | 1.3 | 6.9 |
| Light mist | 1.9 | 2 |
| Clear air | 3 | 0.6 |

### 2.2 Turbulence

Hot and dry weather also has an attenuation effect on light signal propagation through the air. When the ground warms up in the sun, the air warms up as well. Some air pockets get warmer than others. So, changes occur in the refraction index. As a result, changes occur in the path that the light takes while it propagates. The turbulence intensity is represented by $C_n^2\left[m^{-2/3}\right]$, where the refractive index parameter $C_n^2$ obeys the inequality $10^{-16} \leq C_n^2 \leq 10^{-13}$ [19].

## 3 OCDMA Codes

In OCDMA codes, the cross correlation between two code sequences is expressed as [12]:

$$\lambda_c = \sum_{i=0}^{L} X_i Y_i \tag{3}$$

where $X = (x_1, x_2,\ldots,x_L)$ and $Y = (y_1, y_2,\ldots,y_L)$ are two different code sequences, $L$ is the total code length, and $\lambda c$ is the cross-correlation. Codes having low cross correlation ($\lambda_C \leq 1$ and $\lambda_C = 0$) are used in this study to clarify the effect of cross correlation of codes on SAC-OCDMA system in both FSO and OFS scenarios. The direct detection technique is used for detecting RD, KS, ZCC, and MD codes to eliminate MAI by detecting non-overlapping chips only. As the PIIN is related to the MAI, its effect on system performance is suppressed as well. In addition, both the cost and complexity of the system are reduced.

### 3.1 Mathematical Analysis of SAC-OCDMA System in FSO and OFS Scenarios Using Direct Detection Technique

The performance of the SAC-OCDMA system in the FSO scenario is affected by the climate conditions. The bad climate conditions cause degradation in SNR and increase the Bit Error Rate (BER). The Signal-to-Noise Ratio (SNR) is the average signal power to noise power [21],

$$SNR = \frac{I^2}{\sigma^2} \tag{4}$$

To simplify the analysis, a Gaussian approach is used in the computations. The direct detection technique, shot noise, thermal noise, and rain attenuation are the only considered factors, because the MAI and PIIN are suppressed.

The code properties using the direct detection technique are expressed as [22]

$$\sum_{i=1}^{L} C_N(i) C_K(i) = \begin{cases} W, & \text{for } N = K \\ 0, & \text{Otherwise} \end{cases} \tag{5}$$

where $W$ is the weight of the code. To analyze the system, the following assumptions are used as in [7, 22]:

(a) Each light source is perfectly unpolarized, and the spectrum is flat over the bandwidth $\left[v_o - \frac{\Delta v}{2}, v_o + \frac{\Delta v}{2}\right]$, where $v_o$ is the central optical frequency and $\Delta v$ is the light source bandwidth (Hz).

(b) Each power spectral component has the same spectral width.
(c) Each user has the same power at the receiver.
(d) Each bit stream from every user is synced.

The Power Spectral Density (PSD) of the optical received signal can be written as [7, 22]

$$r(v) = \frac{P_{sr}}{\Delta v}\sum_{K=1}^{K} d_K \sum_{i=1}^{L} C_K(i)\left\{u\left[v - v_o - \frac{\Delta v}{2L}(-L+2i-2)\right] - u\left[v - v_o - \frac{\Delta v}{2L}(-L+2i)\right]\right\} \tag{6}$$

where $P_{sr}$ is the effective power of a broadband source at the receiver, $K$ is the total number of users, $d_K$ is the data bit of the $K$th user which is "1" or "0", and $u(v)$ is the unit step function,

$$u(v)\begin{cases} 1 & v \geq 0 \\ 0 & v < 0 \end{cases} \tag{7}$$

The photocurrent $I$ can be written as [22]

$$I = R\int_0^{\infty} G_d(v)\, dv \tag{8}$$

where $G_d(v)$ is the PSD at the photo-diode

$$I = R\int_0^{\infty} \frac{P_{sr}}{\Delta v}\sum_{K=1}^{K} d_K \sum_{i=1}^{L} C_K(i)C_N(i)u\left[\frac{\Delta v}{L}\right] dv \tag{9}$$

$$I = R\frac{P_{sr}w}{\Delta v} d_L \tag{10}$$

In the FSO Scenario, the noise power can be expressed as [21]

$$\sigma^2 = I_{shot}^2 + I_{thermal}^2 + \alpha_{rain} \tag{11}$$

$$\sigma^2 = 2eBI_{dd} + \frac{4K_B T_n B}{R_L} + \alpha_{rain} \tag{12}$$

$$I_{dd} = R\int_0^{\infty} \frac{P_{sr}}{\Delta v}\sum_{K=1}^{K} d_K \sum_{i=1}^{L} C_K(i)C_N(i)u\left[\frac{\Delta v}{L}\right] dv \tag{13}$$

As in [23], when the users are transmitting bit "1", we have $\sum_{i=1}^{K} d_K \approx 1$,

$$\sigma^2 = 2eBR\frac{P_{sr}w}{L} + \frac{4K_B T_n B}{R_L} + \alpha_{Rain} \tag{14}$$

When all users are sending bit "1", and the probability of sending bit '1' at any time for every user is 50%, the SNR becomes

$$SNR = \frac{I^2}{\sigma^2} = \frac{\left(\frac{RP_{sr}w}{L}\right)^2}{eBR\frac{P_{sr}w}{L} + \frac{4K_BT_nB}{R_L} + \alpha_{Rain}} \quad (15)$$

In the OFS scenario, the impacts of shot noise and thermal noise only are considered [23]

$$\sigma^2 = 2eBR\frac{P_{sr}w}{L} + \frac{4K_BT_nB}{R_L} \quad (16)$$

$$SNR = \frac{I^2}{\sigma^2} = \frac{\left(\frac{RP_{sr}w}{L}\right)^2}{eBR\frac{P_{sr}w}{L} + \frac{4K_BT_nB}{R_L}} \quad (17)$$

Using Gaussian approximation, the BER is expressed as [7]

$$BER = 0.5\, erfc\left(\sqrt{SNR/8}\right) \quad (18)$$

where *erfc* is the complementary error function, $K_B$ is Boltzmann's constant, and $R$ is the responsivity of the photodiode given by $R = \eta e/hf_c$.

## 3.2 Low Cross Correlation Codes

### 3.2.1 RD Code

The RD code consists of a (0,1) sequence of code length $L$, code weight $W$, cross correlation $\lambda_C$, divided into two groups; data segment and code segment. The code has zero cross correlation in the data segment and variable $\lambda_C$ in the code segment [3]

$$L = K + 2W - 3 \quad (19)$$

For $W = 4,\ K = 3,$ and $L = 8$, the code is $\begin{bmatrix} 0 & 0 & 1 & 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix}$

### 3.2.2 KS Code

The KS code depends on the arrangement of two sub-codes, $A = ([1\ 1\ 0])$ and $B = ([0\ 1\ 1])$ by determining the position of each of the sub-codes for each user so that the cross correlation between any two code sequences $\lambda_C \leq 1$ [2]

$$K = (W/2 + 1) \quad (20)$$

$$L = 3\sum_{i=1}^{W/2} i \quad (21)$$

For $W = 4,\ K = 3,\ L = 9$, the code is $\begin{bmatrix} 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 \end{bmatrix}$

## 3.3 Zero Cross Correlation Codes

### *3.3.1 ZCC Code*

The ZCC code is one of the SAC-OCDMA codes. It has several advantages including the simple construction using transformation method, and the possibility of choosing any natural number for the code weight. Also, it has zero cross correlation, a property which improves the OCDMA system performance by suppressing MAI. It also eliminates PIIN leading to a better BER performance [22]

$$K = W + 1 \tag{22}$$

$$L = W(W + 1) \tag{23}$$

For $K = 4$, $W = 3$, and $L = 12$, the code is $\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$

### *3.3.2 MD Code*

The MD code has a simple construction based on identity matrix, flexibility in choosing the code weight and number of users, and zero cross correlation property [24]

$$L = K \times W \tag{24}$$

For $K = 4$, $W = 3$, and $L = 12$, the code is $\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$

## 3.4 System Description

Figures 1 and 2 show the FSO system for both RD and KS codes. The data is optically modulated at the transmitter into a code sequence with an optical external modulator. Then, the modulated code sequences are combined together and are transmitted through the FSO scenario. The whole code spectra must be transmitted to maintain the addressing signature. At the receiver side, different modulated code sequences are separated. The decoder depends on direct detection, where only clean chips are filtered as the information is assumed to be recoverable from non-overlapping chips, and overlapping chips are discarded to remove interference. The signals are detected with a PN photo-detector. Finally, the incoming signals are filtered using a Low-Pass Filter (LPF) to recover the original signal [3]. Figure 3 shows the system for ZCC and MD codes. The system is the same, but all chips will be detected as there are no overlapping chips.

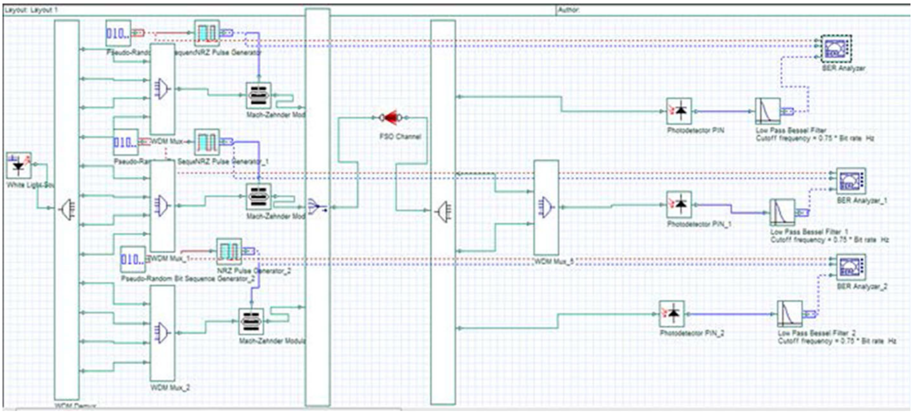


**Fig. 1** FSO system for RD code

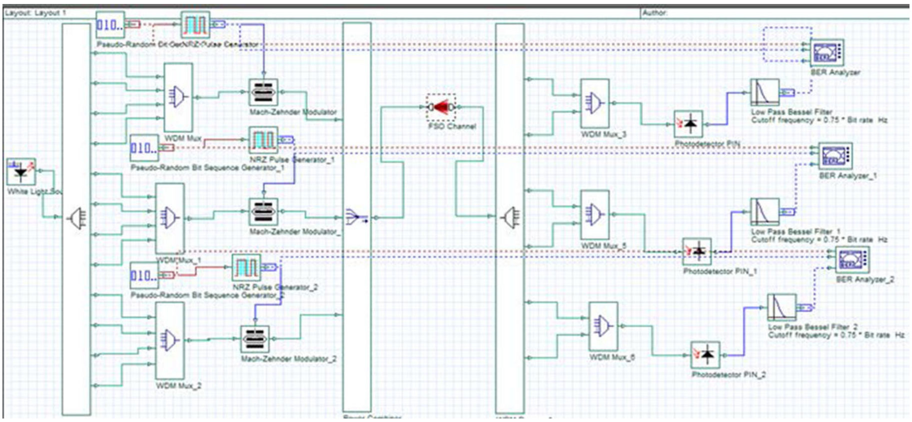


**Fig. 2** FSO system for KS code

## 4 Rain Attenuation Effect on RD, KS, ZCC and MD Codes

Figures 4 and 5 show a comparison between the performance of RD, KS, ZCC, and MD codes under different rain attenuation conditions (clear, light mist, very light fog, and light fog). The simulation is carried out using Optiwave.13 for 3 users with code weight 4 using the parameters listed in Table 2. The noise generated at the receivers is set to be random and totally uncorrelated. Figure 4 shows the BER versus distance. It can be easily seen that as the distance increases, the BER increases under all rain conditions for the four codes as the quality of signal becomes worse with distance. It also indicates that the ZCC codes (MD and ZCC) give better performance than low cross correlation codes (KS and RD) under different rain attenuation conditions because all the chips of zero cross correlation codes are detected at the receiver side, as there is no overlapping between code sequences. The larger the number of detected chips, the larger the received power will be. In contrast, not all the chips of low cross correlation codes are detected; only the non-overlapping chips.

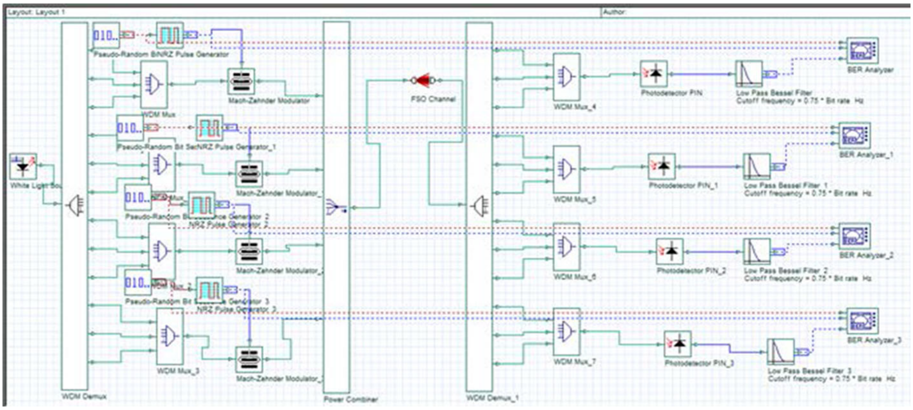


**Fig. 3** FSO system for ZCC and MD codes

Figure 4a, b indicate that the RD code provides better performance than the KS code under clear air and light mist rain conditions. This is attributed to the zero cross correlation property of the RD code in the data segment part, which reduces the MAI effect. Moreover, the attenuation values of 0.6 and 2 dB/km for clear air and light mist rain conditions are small and do not have great effect on the system performance. Figure 4c, d show that the RD code gives better performance than the KS code for small distances. However, when the distance increases, the KS code begins to outperform the RD code. This is attributed to the large weather attenuation of 6.9 dB/Km for very light fog and 18.3 dB/Km for light fog. This attenuation has a dominant effect on the performance. For the KS code, the receiver receives more chips than those of the RD code, as it has less overlapping chips as shown in Fig. 1. The power received has a dominant effect on the system performance at large distances.

Figure 5 illustrates the effect of variations in light beam divergence on BER at 300 m. Divergence is considered as an advantage in FSO transmission. The narrower the laser beam, the better the signal quality and the higher the system security. Therefore, as the beam divergence increases, the BER increases under all rain conditions. Figure 5a, b show the same results obtained for Fig. 4a, b as the RD code provides better performance than the KS code. Figure 5c, d reveal that under high attenuation of 6.9 and 18.3 dB/Km and large divergence, the KS code performance is better than that of the RD code. The reason is that more chips are detected at the receiver in the case of KS code.

## 5 Comparision Between the Performances of SAC-OCDMA in FSO and OFS Scenarios

A comparison between the performances of the SAC-OCDMA in FSO and OFS scenarios is presented focusing on different types of codes. The numerical values for the system parameters used in this section are listed in Table 2. In the FSO scenario, moderate turbulence and hazy weather conditions are considered. In the OFS scenario, the nonlinear effects, attenuation, group velocity dispersion, and third-order dispersion are taken into consideration to simulate the real environment.

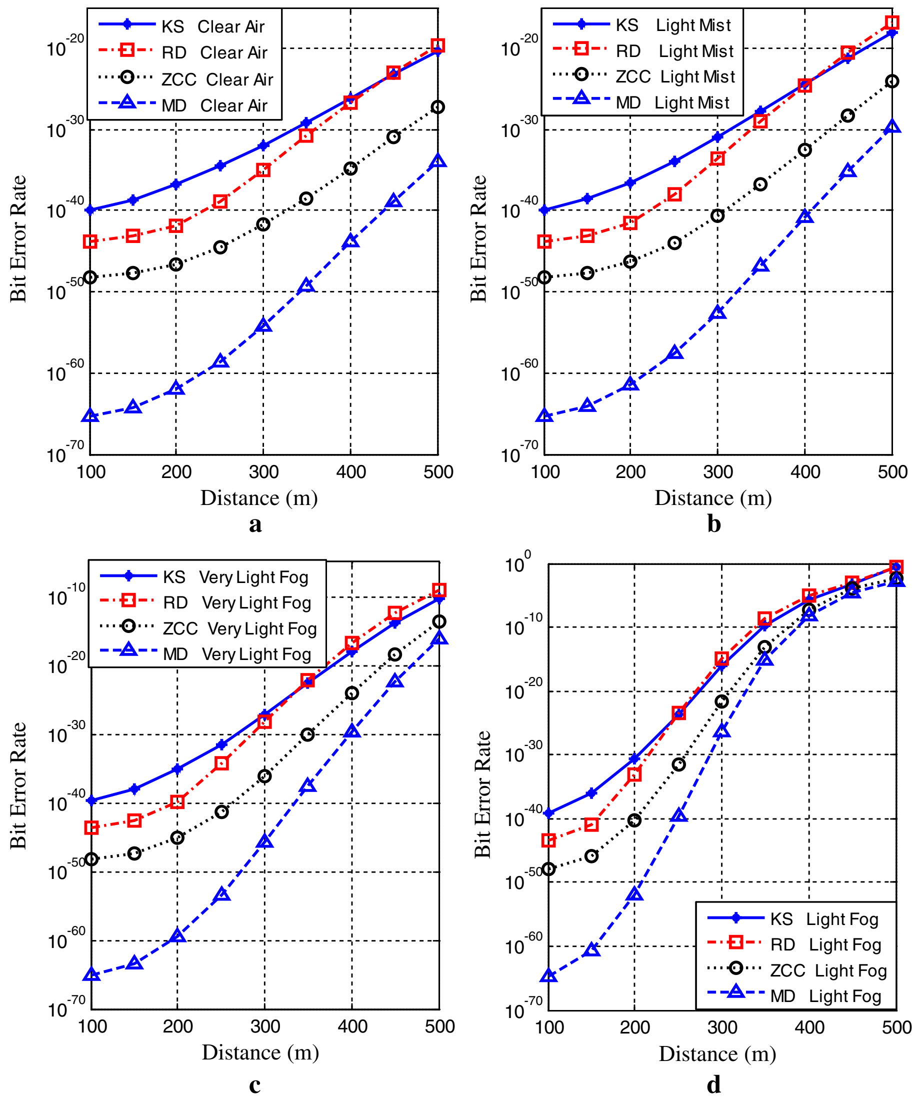


**Fig. 4** BER versus distance. **a** Clear air. **b** Light mist. **c** Very light fog. **d** Light fog

Figures 6 and 7 indicate that the performance of codes having zero cross correlation (MD and ZCC) is better compared to those of the codes having low cross correlation (RD and KS). The reason is that there is no overlapping between code sequences in ZCC codes. Therefore, more chips are detected at the receiver side, which increases the received power. Although both the ZCC and MD codes have zero cross correlation, the same code length, and the same code weight, the MD code provides better performance than that of the ZCC code as the MD code construction depends on the unity matrix.

As shown in Fig. 6 for distances larger than 200 m, the performance of the KS code is better than that of the RD code. This is attributed to the fact that with the KS code, a larger number chips is detected at the receiver than that achieved with the RD code as it has less

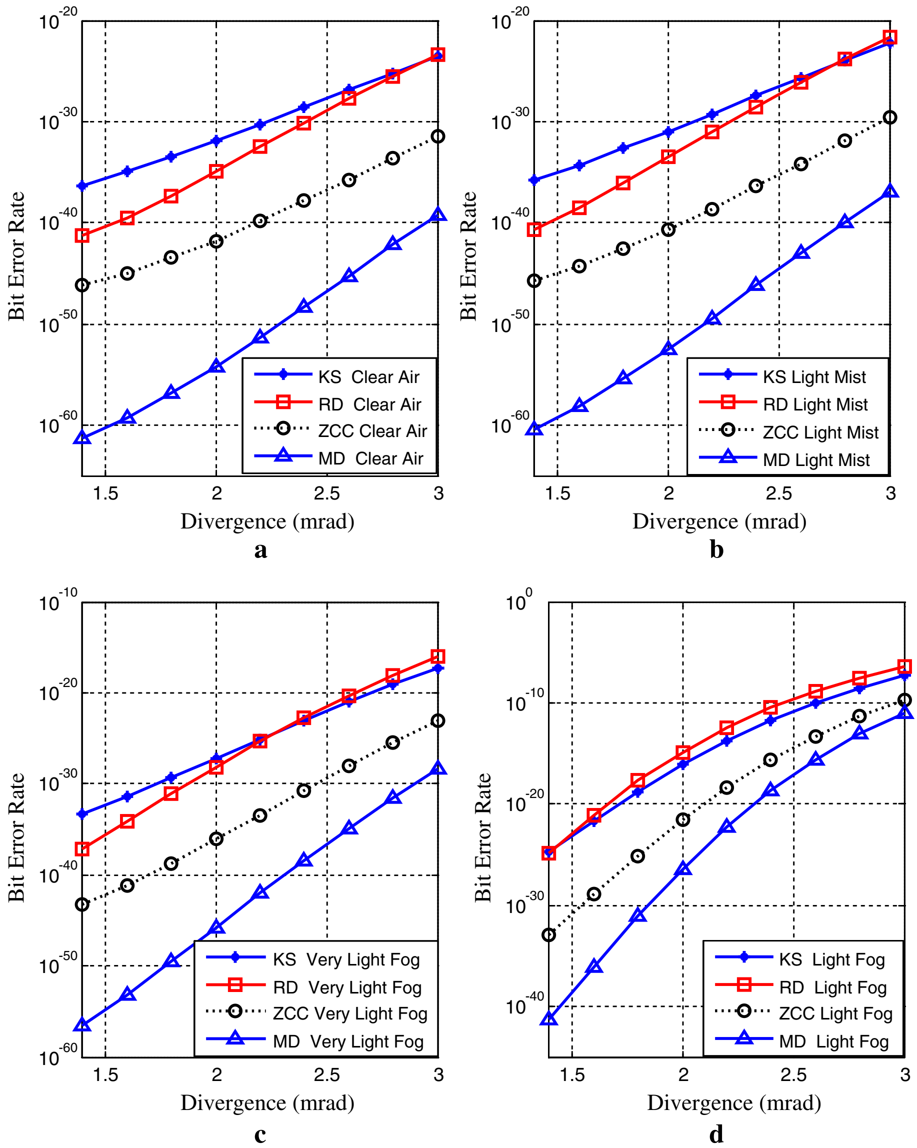


**Fig. 5** BER versus divergence. **a** Clear air. **b** Light mist. **c** Very light fog. **d** Light fog

overlapping chips. Moreover the RD code has susceptibility to turbulence effect. Also, the power received has a dominant effect on the performance at large distances. On the other hand, the RD code provides better performance than that of the KS code for distances from 100 to 200 m. This is attributed to the zero cross correlation property of the RD code in the data segment part, which reduces the MAI effect. In addition, for small distances, the power does not have a dominant effect on the code performance. It is clear also that the KS code with the same code weight but with doubled number of users leads to an increase in the BER due to interference from other users.

**Table 2** FSO simulation parameters

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Chip spectral width | 0.8 nm | Thermal noise coefficient | $1.8 \times 10^{-23}$ w/Hz |
| Data rate | 622 Mbps | Low-pass filter bandwidth | 0.75 GHz |
| Distance (FSO) | 100–500 m | Wavelength | 1550 nm |
| Transmitter aperture diameter | 10 cm | Hazy weather attenuation | 3 dB/Km |
| receiver aperture diameter | 32 cm | Moderate turbulence $C_n^2$ | $8 \times 10^{-14}$ $m^{-2/3}$ |
| Beam divergence | 2 mrad | Dispersion | 18 ps/nm/km |
| Dark current | 5 nA | Attenuation | 0.25 dB/km |

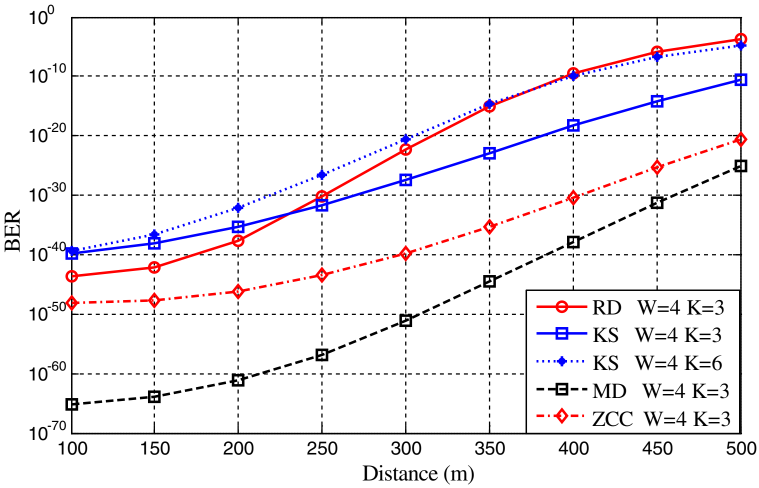


**Fig. 6** BER versus distance for KS, RD, ZCC and MD codes under moderate turbulence and hazy weather

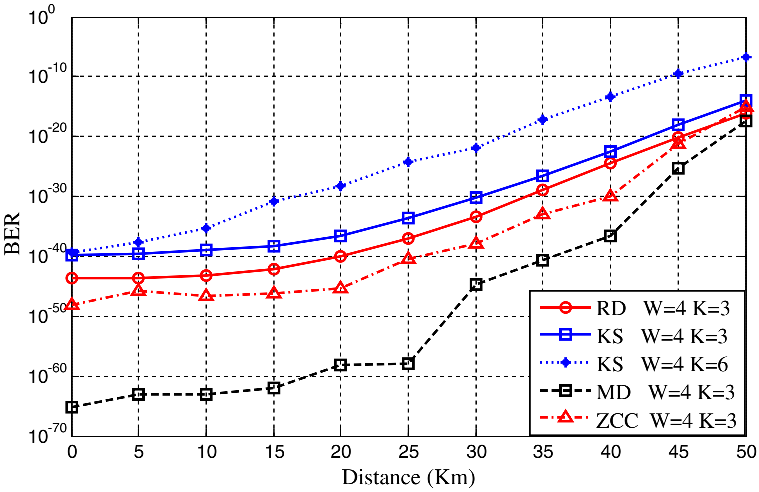


**Fig. 7** BER versus distance for KS, RD, ZCC and MD codes in OFS scenario

Figure 7 reveals that the RD code has better performance than that of the KS code in the OFS although the receiver detects more chips for the KS code than those detected with the RD code. This is attributed to the fact that KS code has a large vulnerability to dispersion and attenuation in optical fiber cables. Therefore, it is clear that the performance of codes is media-dependent. The FSO limits the SAC-OCDMA system performance by the attenuation effect due to weather conditions such as rain and turbulence. The OFS also limits the SAC-OCDMA system performance by dispersion, attenuation and nonlinear effects in optical fiber cables.

Figure 8 shows the eye diagrams for RD, KS, ZCC, and MD codes in the FSO scenario under hazy sky and moderate turbulence at 350 m, where the BER = $2.6 \times 10^{-15}$, $3.8 \times 10^{-23}$, $4.6 \times 10^{-36}$, and $8.5 \times 10^{-45}$, respectively. Figure 9 shows the eye diagrams for RD, KS, ZCC, and MD codes in the OFS scenario at 40 km, where the BER = $9.18 \times 10^{-25}$, $8.35 \times 10^{-23}$, $3.42 \times 10^{-30}$, and $8.86 \times 10^{-37}$, respectively. Both figures clearly reveal that the zero cross correlation codes provide better performance and have a larger eye opening than those of low cross correlation codes. Moreover, the KS code

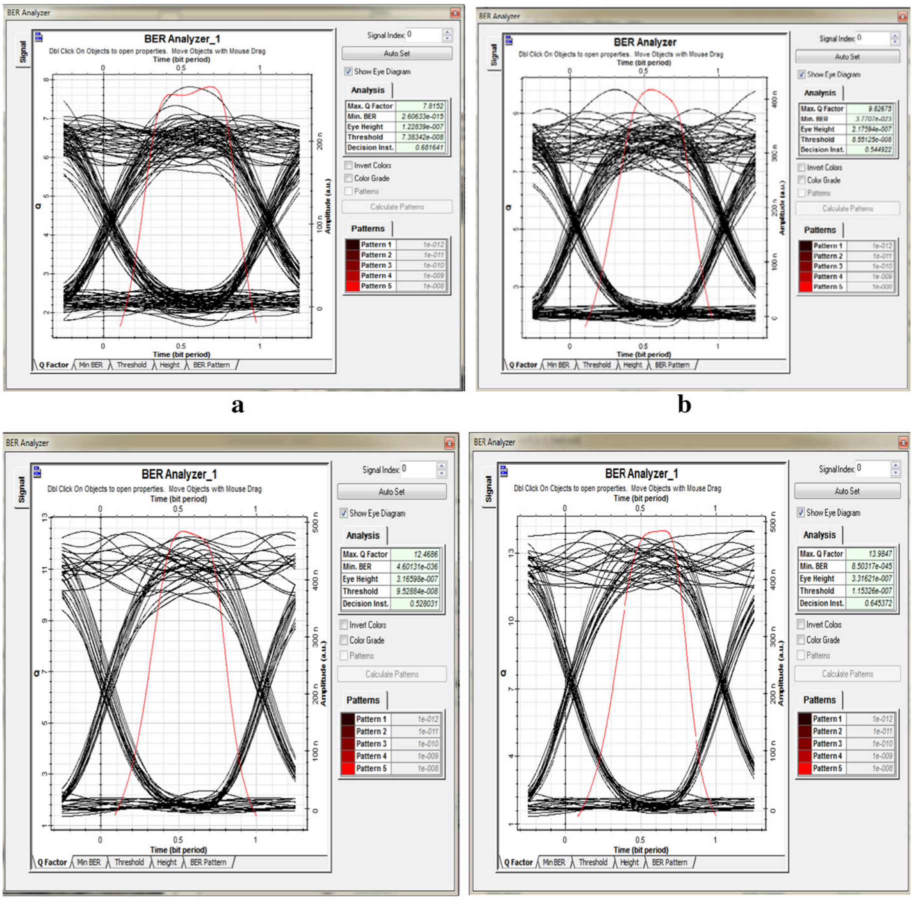


**Fig. 8** Eye diagram for RD, KS, ZCC and MD codes in the FSO senario. **a** RD code. **b** KS code. **c** ZCC code. **d** MD code

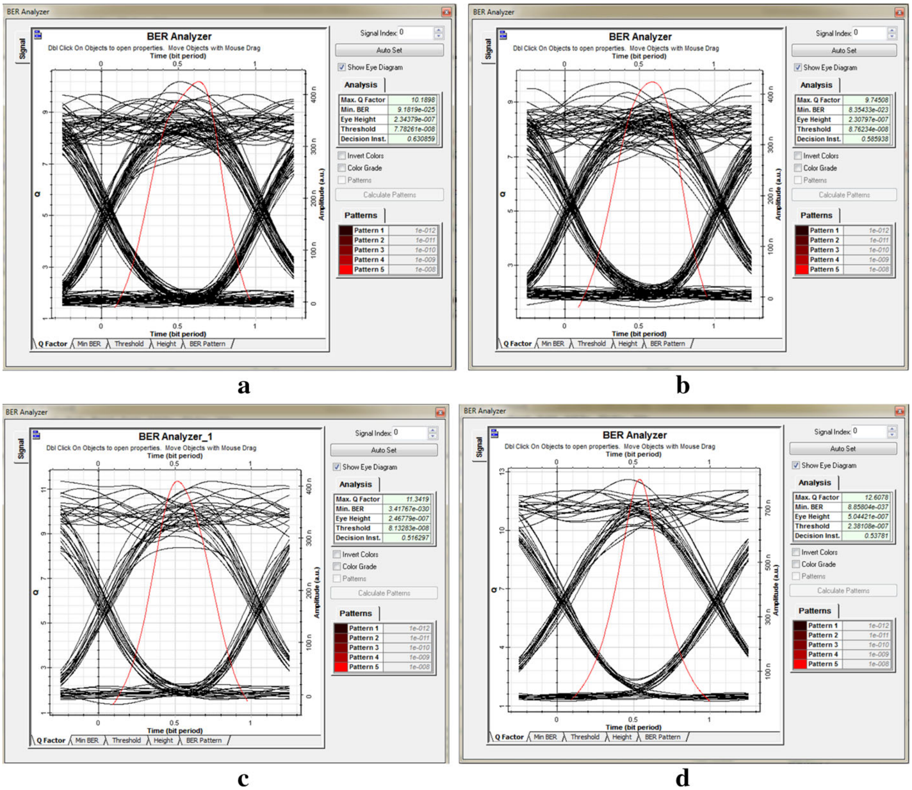


**Fig. 9** Eye diagram for RD, KS, ZCC, and MD codes in OFS scenario. a RD code. b KS code. c ZCC code. d MD code

**Table 3** Codes comparison

| Code | Code weight | BER |
|---|---|---|
| PC | w = 5 | $10^{-3}$ |
| QC | W = 5 | $10^{-9}$ |
| KS | w = 4 | $10^{-10}$ |
| RD | w = 4 | $10^{-6}$ |
| ZCC | w = 4 | $10^{-12}$ |
| MD | W = 4 | $10^{-18}$ |

has a better performance than that of the RD code in the FSO scenario under turbulence conditions. In contrast, the RD code has a better performance than that of the KS code in the OFS scenario. Table 3 shows a comparison between codes in the FSO scenario at 400 m and bit rate of 2.5 Gbps under hazy weather conditions (attenuation = 3 dB/km) and moderate turbulence $C_n^2 = 8\times10^{-14}$ m$^{-2/3}$. This table shows that the cross correlation codes (MD and ZCC) provide better performance than those of low cross correlation codes.

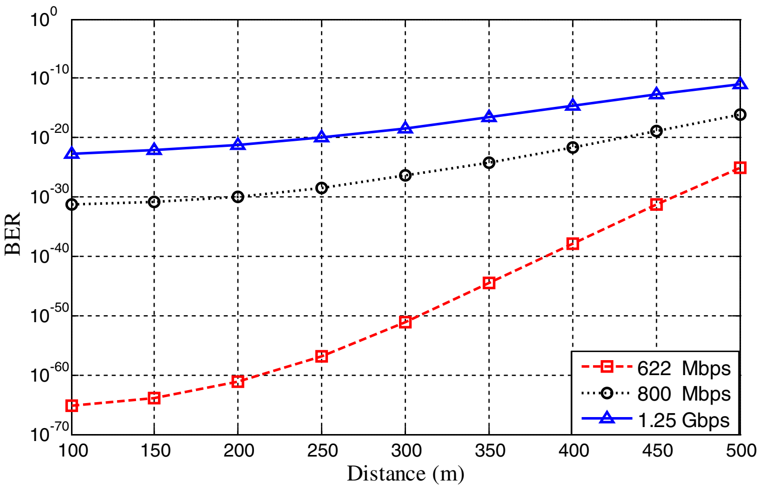


**Fig. 10** BER versus distance at different bit rates for MD code in the FSO scenario

## 6 Performance of MD Code at Different QoS and Security Levels

Figure 10 shows the MD code performance in the FSO scenario at different bit rates to support different Quailty-of-Service (QoS) values of multimedia (audio, video, and data). One of the OCDMA advantages is the high security, but there is a trade-off between security and OCDMA code performance. The degree of security depends on the code dimensions. The relationship between the SNR of the user per data bit and the eavesdropper SNR is given as [25],

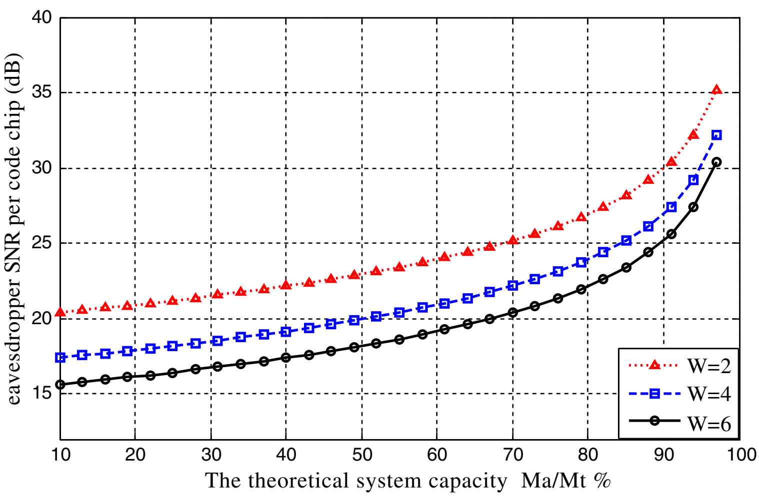


**Fig. 11** Eavesdropper's SNR per code chip versus theoretical system capacity at different code weights for the MD code

**Table 4** System parameters for the security scenario

| Parameter | Symbol | Value |
|---|---|---|
| User SNR to achieve the required BER | $E_u/N_{0u}$ | 22 dB |
| Number of tabs in the broadcast star coupler | $n_u$ | 100 |
| Efficiency of eavesdropper's fiber tap | $e_t$ | 0.01 |
| Authorized user receiver's multichip energy combining efficiency | $e_u$ | 0.8 |
| Ratio of receiver noise density to the authorized user's receiver noise density of the eavesdroppers | $\alpha_{ed}$ | 1 |
| Eavesdropper effective SNR per code chip | $E_{ed}/N_{0ed}$ | – |
| System parameters of design | $\sigma_d$ | – |
| Actual number of simultaneous users | $M_A$ | – |
| Maximum number of simultaneous users at a particular maximum BER | $M_T$ | – |

$$\frac{E_{ed}}{N_{0ed}} = \sigma\left(\frac{1}{W}\right)\left(\frac{1}{1-\frac{M_A}{M_T}}\right)\left(\frac{E_u}{N_{0u}}\right)_{spec} \tag{25}$$

$$\sigma_d = \left(\frac{e_t\, n_u}{\alpha_{ed}\, e_u}\right) \tag{26}$$

Figure 11 shows the SNR of eavesdropper per code chip at different theoretical system capacities for code weights 2, 4, and 6. When the eavesdropper SNR is equal to 22 dB and sufficient power is transmitted, the system capacity will be 30, 65, and 77%, respectively. The eavesdropper is assumed to use a receiver that is equal in sensitivity to the authorized user's receiver. The system parameters for the security scenario are given in Table 4.

## 7 Conclusions

The utilization of the SAC-OCDMA system in both OFS and FSO scenarios has several advantages such as increasing the number of users, enhancing security, and allowing flexibility in allocating channels. This paper discussed the performance of the SAC-OCDMA system in both FSO and OFS scenarios focusing on different types of codes. It also clarified the effect of cross correlation value and rain attenuation on the system performance. In addition, the security performance and QoS for the MD code have been discussed. Simulation results have shown that the performance of the SAC-OCDMA codes is media-dependent. The codes having zero cross correlation outperform the codes having low cross correlation. The MD code provides the best performance with the ZCC code following in both FSO and OFS scenarios. However, the RD code provides better performance than that of the KS code in the OFS scenario, while the KS code offers better performance than that of the RD code in the FSO scenario under turbulence effect. In the future, important efforts and attention should be allocated for generating codes having zero cross correlation, large cardinality, and practical code lengths.

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