# Performance and Confidentiality Comparison of Different Hybrid SAC/OCDMA-WDM Overlay Schemes

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**Abstract**— Code pulses of a spectral amplitude coding/optical code division multiple-access (SAC/OCDMA) system are overlaid onto a multichannel wavelength division multiplexing (WDM) system. Modified quadratic congruence (MQC) codes are developed as the signature codes for the SAC/OCDMA system. The developed code is to avoid the overlapping between signals of both systems with no use of notch filters. In addition, performance and confidentiality results of this scheme are compared to our previous hybrid SAC/OCDMA-WDM overlay scheme which utilizes normal MQC codes with notch filters. The system performance and data confidentiality are evaluated in terms of bit-error rate (BER) and eye diagrams. The eavesdropper's interceptor that is based on a simple energy detector can scan all corresponding SAC/OCDMA wavelengths to detect an entire coded signal of an authorized user. Our results indicate that the performance and confidentiality have inverse relationship between the two hybrid systems. For a first hybrid scheme that does not adopt notch filters, the BER performance, when a data rate is 622 Mbps, for OCDMA users is about $10^{-15}$ at 4 dB of an optical attenuator, and BER for eavesdropper detection values vary from $10^{-6}$ to $10^{-15}$ due to different overlapping effects between WDM interferes and OCDMA pulses. On the second hand for a hybrid scheme that contains notch filters, the BER performance for OCDMA users is about $10^{-12}$ at 4 dB of an optical attenuator, and for eavesdropper detection values are mostly about $10^{-2}$. However, it is concluded that an eavesdropper faces immunity from SAC/OCDMA system in both cases because WDM channels act as a partial masking over encoded signals in a hybrid scheme. Furthermore, the tradeoff between the performance and confidentiality for authorized SAC/OCDMA users is considered.

## 1. INTRODUCTION

The main Optical CDMA and WDM systems have been of widespread implementation for local and metro access network. This is because OCDMA systems provide users both simultaneous and asynchronous access to networks with high security [1, 2], and WDM systems provide a relatively high transmission capacity [13]. In addition, OCDMA can be overlaid onto existing WDM networks in order to enhance the network security [3, 4]. It has been shown that modified quadratic congruence (MQC) code is an effective code for spectral amplitude coding/optical CDMA (SAC/OCDMA) [5]. This code can reduce the effects of both phase induced intensity noise (PIIN) and multiple access interference (MAI).

Recently, each WDM channel can employ the same set of SAC/OCDMA systems [6, 7]. In [8, 9], a hybrid WDM-OCDMA scheme has been demonstrated using spectrally phase-encoded OCDMA channels. In [10–12], we have also demonstrated in-band transmission of both SAC/OCDMA and WDM signals using MQC codes.

In this paper, we develop a new MQC code for simultaneous transmission of several OCDMA channels and WDM channels on the same spectral band without spectrum overlapping. In addition, we apply the eavesdropper's technique, used in [10], for comparison of performance and confidentiality between this scheme and our previous scheme [10, 11] in terms of both bit-error rate (BER) performance and eye diagrams.

The remainder of this paper is organized as follows. In Section 2, the development of our new MQC code is presented for the proposed system. Different hybrid schemes designs and simulations are demonstrated in Section 3. Section 4 is devoted for our results and discussions. Finally the conclusion of the paper is provided in Section 5.

## 2. NEW MQC CODE DEVELOPMENT

A new MQC code for simultaneous transmission of both SAC-OCDMA and WDM channels without spectrum overlapping is to be developed. The MQC code that is mentioned in [5] has code families

Table 1: MQC binary sequences, S with $p = 3$ and $N = 12$; and the corresponding wavelengths.

| **N** | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ | $C_{11}$ | $C_{12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Wavelength** (nm) | 1549 | 1549.2 | 1549.4 | 1549.6 | 1549.8 | 1550 | 1550.2 | 1550.4 | 1550.6 | 1550.8 | 1551 | 1551.2 |
| **Code sequences of S matrix** | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 |
| | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 |
| | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |

$(N, w, \lambda) = (p^2 + p, p + 1, 1)$, with $p$ a prime number. Here, $N = p^2+p$ is the code length, $w = p+1$ is the code weight, and $\lambda = 1$ is the cross-correlation. This code allows $K = p^2$ simultaneous users. Table 1 shows some binary code sequences, S, for parameters $p = 3$ and $N = 12$; and the corresponding wavelengths.

A new binary MQC sequences, Q, is generated based on the old binary MQC sequences, S, by using a shifting technique. This technique can be done by a multiplication of S and an $A_x$ matrix, as defined below. A basic matrix $A_1$ is given by a $3 \times 4$ matrix:

$$A_1 = \begin{bmatrix} 1000 \\ 0100 \\ 0010 \end{bmatrix}_{3\times 4} \tag{1}$$

The matrix $A_x$ is defined as

$$A_x = \begin{bmatrix} A_1 & 0 & \dots & \dots & 0 \\ 0 & A_1 & 0 & \dots & 0 \\ 0 & 0 & \ddots & \dots & \dots \\ \vdots & \vdots & \dots & \ddots & \dots \\ 0 & 0 & \dots & 0 & A_1 \end{bmatrix}_{N\times(N+x)} \tag{2}$$

where $x = \frac{N-(N \bmod 3)}{3}$ represents the number of $A_1$ matrices in $A_x$ and the zeros in $A_x$ are of dimension $3\times4$. If S matrix has size $K\times N$, then the size of $A_x$ is $N\times M$ where $M = N+\frac{N-(N \bmod 3)}{3}$. The result is a new binary code sequences, Q, with a size of $K \times M$. We notice that the number of columns of Q increases by one for each old three columns with consideration of integer number. In our proposed system, we assume that the bandwidth of a WDM channel, $B_w$ equals that of a chip of MQC code of SAC/OCDMA, $B_c$. That is, $B_w = B_c = 0.2$ nm. The WDM channels are allocated at every 100 GHz (or equivalently 0.8 nm in wavelength). Therefore, for each 3 elements of MQC chip, there is 1 channel of WDM system. This method can also be applied on any code of SAC/OCDMA. In this paper, we present as an example; MQC code sequences with $p = 5$ and $K = 25$, so the size of S is $25 \times 30$. Hence, the size of $A_x$ $30 \times 40$ and the size of $Q = S \times A_x$ is $25 \times 40$. This leads to having 10 locations for WDM channels as shown in Table 2. This technique is important to avoid the direct spectrum overlapping between the signals from both subsystems, which improves the performance compared to that of our previous systems [10, 11].

## 3. DIFFERENT HYBRID SCHEMES DESIGN AND SIMULATION

In a hybrid scheme as shown in Fig. 1, broadband OCDMA signals and narrow band WDM signals are combined together in one system. We have two techniques to reduce the overlapping between these signals. The first technique that mentioned in [10, 11] utilizes notch filters at the receiver side. The second one that was introduced in the above section does not need notch filters. The two

Table 2: MQC binary sequences with shifting process, Q with $p = 3$, $x = 4$ and $M = 16$.

| **N** | $C_1$ | $C_2$ | $C_3$ | $W_1$ | $C_4$ | $C_5$ | $C_6$ | $W_2$ | - - - | $C_{28}$ | $C_{29}$ | $C_{30}$ | $W_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **λ (nm)** | 1546.0 | 1546.2 | 1546.4 | 1546.6 | 1546.8 | 1547.0 | 1547.2 | 1547.4 | - - - | 1553.2 | 1553.4 | 1553.6 | 1553.8 |
| **Code sequences of Q matrix** | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - - - | 1 | 0 | 0 | 0 |
| | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | - - - | 0 | 1 | 0 | 0 |
| | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | - - - | 1 | 0 | 0 | 0 |
| | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | - - - | 1 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | - - - | 0 | 1 | 0 | 0 |
| | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | - - - | 0 | 0 | 0 | 0 |

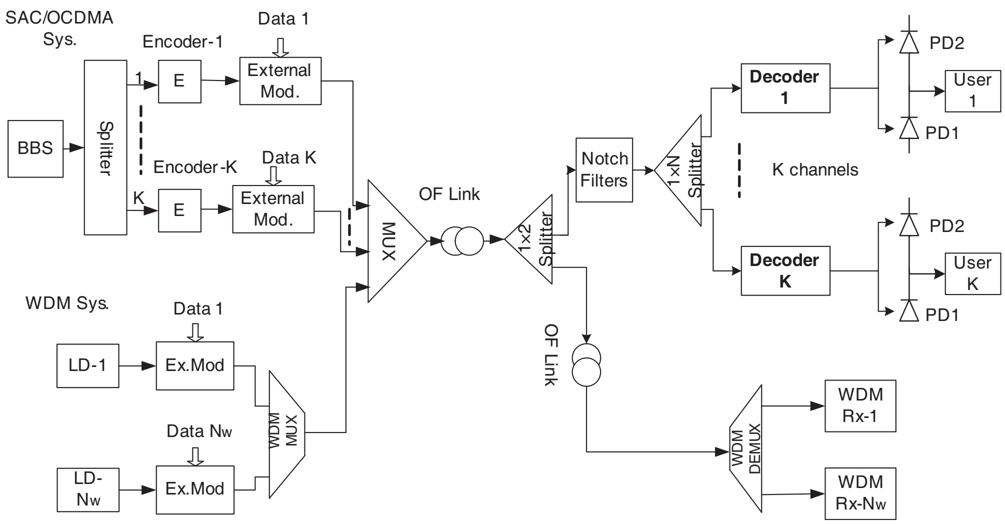



Figure 1: A hybrid system block-diagram.

Table 3: Typical parameters used for simulation.

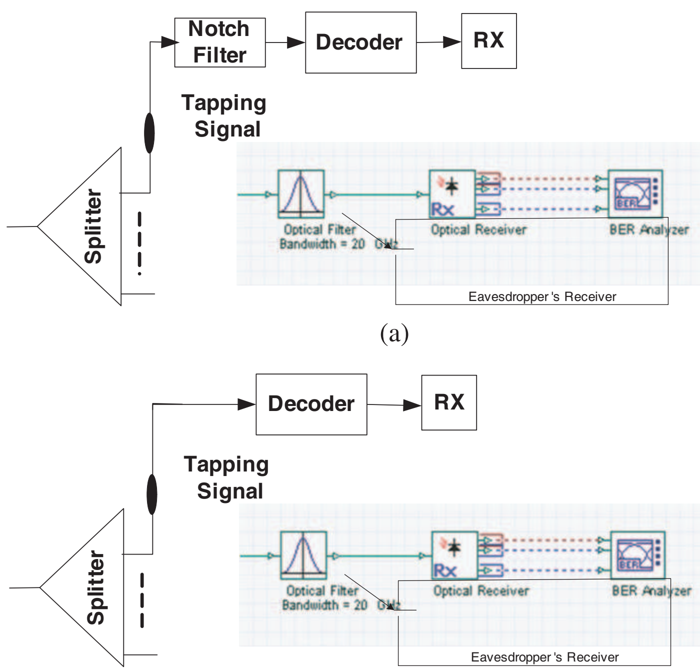
| | |
|---|---|
| Broadband source transmitted power for SAC/OCDMA | 16 dBm |
| Laser source transmitted power for WDM | 1 dBm |
| Data bit rates for SAC/OCDMA and WDM, respectively | 622 Mbps and 2.5 Gbps |
| Bandwidth of encoder/decoder filters | 25 GHz |
| Fiber link attenuation | 0.2 dB/km |
| Fiber dispersion | 17 ps/nm-km |
| Dispersion slope | 0.075 ps/$\sqrt{}$km |
| External modulator extinction | 30 dB |
| Dark current | 5 nA |
| Thermal noise coefficient of the photodetector for SAC/OCDMA and WDM, respectively | $1 \times 10^{-22}$ W/Hz and $1.8 \times 10^{-22}$ W/Hz |
| Number of SAC/OCDMA users | 25 |
| Number of WDM users | 8 |

different schemes have been simulated for performance comparison. The MQC code for 25 users used in the simulation is ($N$, 6, 1), while used WDM channels are eight with 100 GHz frequency spacing. The typical system parameters, considered for the simulation, are illustrated in Table 3.

For data confidentiality comparison, an eavesdropper's code interceptor that is based on scanning all corresponding wavelengths used by SAC/OCDMA users is used in the simulation. This technique of an eavesdropper basically depends on a classical detection theory [14]. The eavesdropper can tap a codeword of the OCDMA system to detect whether the energy of a single pulse is available or not. An optical matched filter and a photodiode can perform this detection. After some calculations by a smart eavesdropper, the data for an authorized user will be read. The receiver structure of an eavesdropper is shown in Fig. 2. However, due to WDM signals that perform a partial masking over OCDMA pulses, the eavesdropper faces challenges to distinguish between the 0's and 1's pulses of a SAC/OCDMA code, and hence, he or she will take more time to detect the entire code and to read the authorized data.

## 4. RESULTS AND DISCUSSION

The bit-error rate (BER) performances for both hybrid systems are evaluated and plotted in Figs. 3 and 4. Fig. 3 shows the BER for an OCDMA user with various optical attenuator values for both hybrid schemes. The BER for the hybrid scheme that without notch. This is expected because the effect of overlapping is more in the former case. For example, at 4 dB of an optical attenuator, the BER performance for OCDMA users are about $10^{-12}$ and $10^{-15}$ for the first and second schemes,




(a)

(b)

Figure 2: Eavesdropper's technique at: (a) an OCDMA receiver has notch filters; (b) an OCDMA receiver has no notch filters.

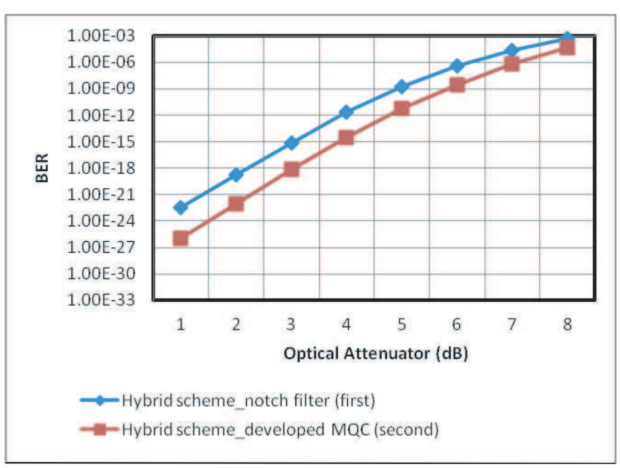



Figure 3: BER versus optical attenuator values for OCDMA user for both hybrid schemes.

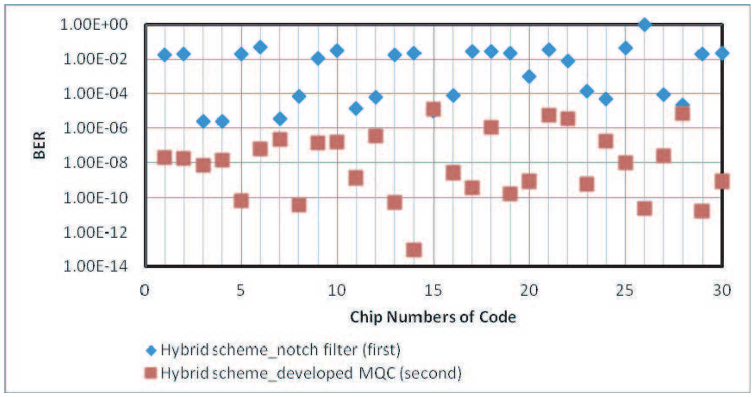
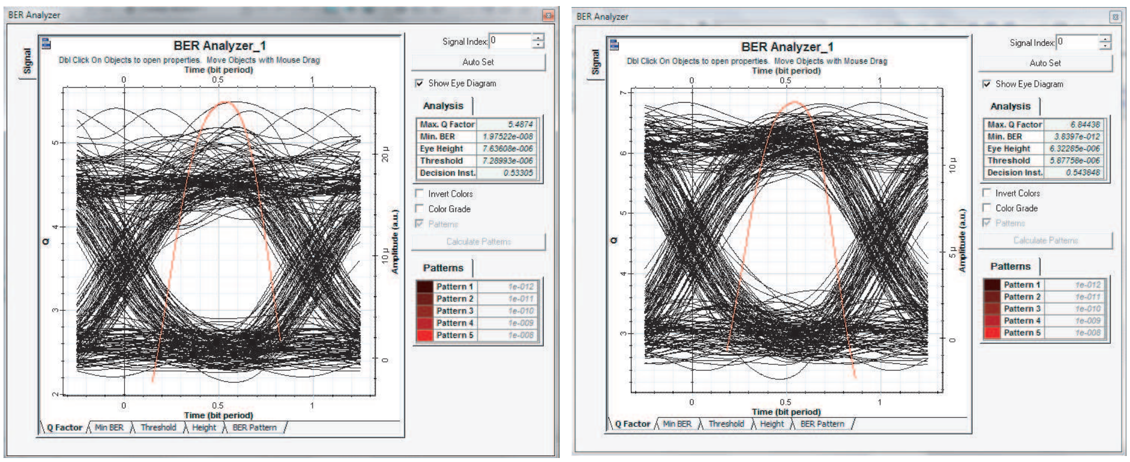



Figure 4: BER versus chip numbers of MQC codes for eavesdropper's interceptor for both hybrid schemes.




(a) (b)

Figure 5: Eye diagrams for a WDM user at 4 dB optical attenuator: (a) Hybrid scheme_notch filter (first); (b) Hybrid scheme_developed MQC (second).

respectively. Fig. 4 also shows the BER but for an eavesdropper's interceptor for both hybrid schemes with versus chip numbers of MQC codes. At the first scheme, the BER for eavesdropper detection values are mostly about $10^{-2}$, while at the second scheme the BER values vary from $10^{-6}$ to $10^{-15}$ due to different overlapping effects between WDM interferes and OCDMA pulses. These results indicate that the data confidentiality for the first hybrid scheme is better than that for the second one. Hence, the performance and confidentiality have inverse relationship between the two hybrid systems.

The eye diagrams for evaluating the performance of WDM systems under both hybrid schemes are shown in Fig. 5. These diagrams are obtained at 12 dB optical attenuator and 2.5 Gbps data rates. The BER is found to be $1.9 \times 10^{-8}$ for first scheme setup as in Fig. 3(a) and $3.8 \times 10^{-12}$ for second scheme setup as in Fig. 3(b). It is obvious that the performance relationship of WDM systems under the two schemes is as mentioned above for OCDMA system.

## 5. CONCLUSIONS

The separation process between WDM and SAC/OCDMA systems has been presented by developing a new MQC code. In addition, BER performance and confidentiality results of this scheme have been compared to hybrid SAC/OCDMA-WDM overlay scheme which utilizes normal MQC codes with notch filters. Our results indicate that the performance and confidentiality have inverse relationship between the two hybrid schemes. It is also concluded that an eavesdropper faces immunity from SAC/OCDMA system in both cases because WDM channels act as a partial masking over encoded signals in a hybrid scheme. Furthermore, the tradeoff between the performance and confidentiality for authorized SAC/OCDMA users is considered.

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