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Abstract. The transmission of both optical code division multiple-access (OCDMA) and wavelength division multiplexing (WDM) users on the same band is investigated. Code pulses of spectral amplitude coding (SAC)/optical code division multiple-access (CDMA) are overlaid onto a multichannel WDM system. Notch filters are utilized in order to suppress the WDM interference signals for detection of optical broadband CDMA signals. Modified quadratic congruence (MQC) codes are used as the signature codes for the SAC/OCDMA system. The proposed system is simulated and its performance in terms of both the bit-error rate and Q-factor are determined. In addition, eavesdropper probability of error-free code detection is evaluated. Our results are compared to traditional nonhybrid systems. It is concluded that the proposed hybrid scheme still achieves acceptable performance. In addition, it provides enhanced data confidentiality as compared to the scheme with SAC/OCDMA only. It is also shown that the performance of the proposed system is limited by the interference of the WDM signals. Furthermore, the simulation illustrates the trade-off between the performance and confidentiality for authorized users.
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Subject terms: optical network security; spectral amplitude coding; optical code-division multiple-access; wavelength division multiplexing; modified quadratic congruence.

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1 Introduction

Data confidentiality of optical communication signals is getting more attractive concerning some applications such as military networks and enterprise networks. Optical code division multiple-access (OCDMA) can be overlaid onto existing wavelength division multiplexing (WDM) networks in order to expand the transmission capacity and add some additional functions in the networks such as increasing levels of security. Spectral amplitude coding for the optical code-division multiple-access (SAC/OCDMA) scheme yields a significant reduction in the effects of multiple access interference and, therefore, promises service differentiation in future access networks, where users with various bit rates and quality of service are simultaneously joined.[1] Many codes have been proposed for SAC/OCDMA systems,[2] e.g., Hadamard, balanced incomplete block design, modified frequency hopping, and modified quadratic convergence (MQC). MQC codes[3] are effective codes that can suppress the effects of intensity noise.

Recently, hybrid WDM/OCDMA systems have been proposed for network security and demonstrations of WDM/OCDMA transmission have been performed.[4–7] These studies have focused on hybrid WDM and spectral-phase-encoding/OCDMA networks or hybrid WDM and wavelength-hopping time-spreading/OCDMA networks. Some other studies have concentrated on hybrid WDM and SAC/OCDMA schemes[1,8] without using covertness of signal transmission. In other words, SAC/OCDMA signals have not been overlaid with WDM signals in the same spectral region. Some other researchers[9,10] have proposed techniques using a hybrid SAC/OCDMA-overlay WDM system and frequency hopping techniques have been adopted. However, these previous studies have not evaluated the performance as well as the security of hybrid one-dimensional codes of the SAC/OCDMA-WDM overlay system.

Our previous approach[11] has been simulated for enhancing optical network security based on the hybrid SAC/OCDMA-WDM overlay scheme using MDW code for only three users.

Our aim in this paper is to investigate the feasibility of transmitting both OCDMA and WDM users on the same spectrum band, using MQC code as a signature code. Notch filters have been used for the hybrid system to suppress WDM interference for detection of optical broadband code division multiple-access (CDMA) signals. Both hybrid and nonhybrid systems have been simulated and the performance comparison is presented. Our results indicate that it is possible to transmit both OCDMA and WDM users on the same band, yet achieving an acceptable performance with good data confidentiality.

The rest of the paper is organized as follows. In Sec. 2, we give a brief description of our proposed system, followed by

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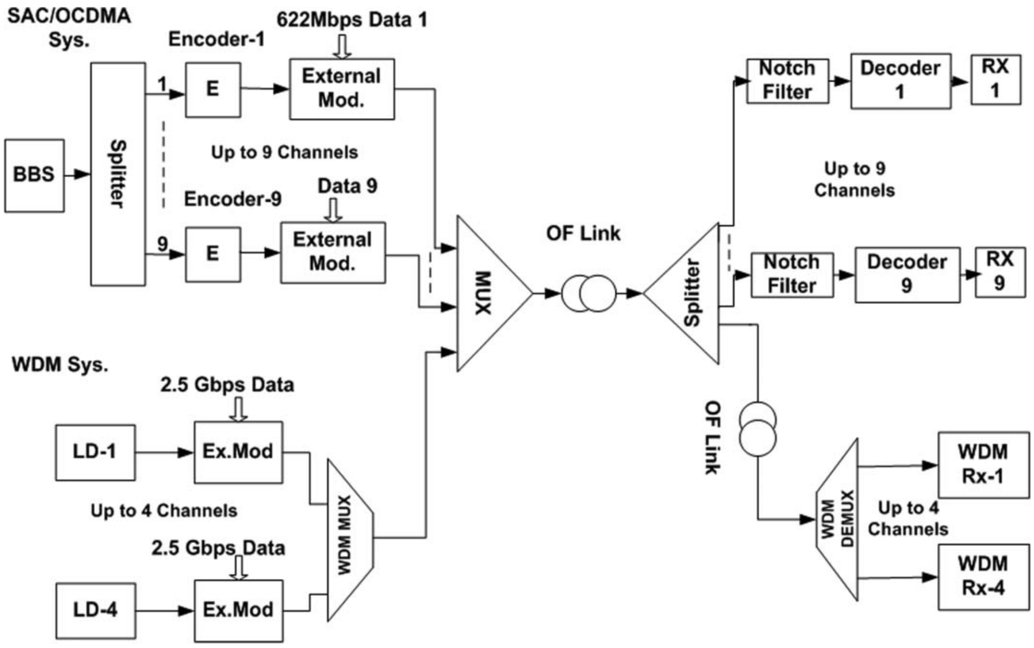


Fig. 1 Block diagram of the hybrid system.

the simulation setup in Sec. 3. Simulation and performance for an eavesdropper's code interceptor is given in Sec. 4. Section 5 is devoted for the results and discussion. Finally, the conclusion of the paper is provided in Sec. 6.

2 System Description

In a hybrid WDM-OCDMA system, the network traffic consists of narrow-band WDM signals overlaid with optical broadband CDMA signals in the same spectral region. The main idea in the proposed system is to enhance the security of SAC/OCDMA by the hybrid scheme. At the receiver side, the main purpose is to eliminate or attenuate the WDM interferences. By using notch filters WDM signals can be properly attenuated. In fact, a notch filter is the simplest technique among other techniques used for optical-carrier suppression.[12,13] As shown in Fig. 1, our SAC/OCDMA system with MQC code consists of a single light-emitting diode source and point-to-point transmission channels modulated at 622 Mbps data rate. The data of each user is encoded by MQC code families $(p^2 + p,\ p + 1,\ 1)$, with $p$as a prime number. The properties of MQC codes are mentioned in Ref. 3, where an MQC code is denoted by $(N,\ w,\ \lambda)$, N is the number of codewords, w is the code weight, and λ is the cross correlation. In this code, the number of users K equals p^2. Table 1 shows the code sequences for parameters $p = 3$ and $N = 12$. The corresponding selected wavelengths are also shown in Table 1. The public WDM system setup consists of cw laser sources for some channels that are modulated at 2.5 Gbps for each user. The two systems are using on-off keying modulation and are combined together over a single fiber link.

Table 1 MQC code sequences with $p = 3$ and $N = 12$ and the corresponding wavelengths.

N	1	2	3	4	5	6	7	8	9	10	11	12
Wavelength (nm)	1549	1549.3	1549.6	1549.9	1550.2	1550.5	1550.8	1551.1	1551.4	1551.7	1552	1552.3
Code sequences	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

Table 2 Typical parameters used for experimental simulation.

Broadband source transmitted power for SAC-OCDMA	16 dBm
Laser source transmitted power for WDM	2 dBm
Data bit rates for SAC/OCDMA and WDM, respectively	622 Mbps and 2.5 Gbps
Bandwidth of encoder/decoder filters	0.3 nm
Bandwidth of notch filter	0.15 nm
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	1×10^{-22} and 1.8×10^{-22} W/Hz
Number of SAC/OCDMA users (K)	9
Number of WDM users (N_w)	4

At the receiver side of the system, the WDM receiver consists of a narrow band-pass filter followed by O/E conversion. The SAC/OCDMA receiver is based on the complementary detection scheme.[3] This well-known balanced receiver should follow a notch filter designed for the hybrid system. Both PIN photodiode or avalanche photodiode (APD) are adopted.

3 Simulation Setup for the Proposed System

The setup of the hybrid scheme, illustrated in Fig. 1, has been simulated using OptiSystem software. The nonhybrid system has also been simulated for comparison with the hybrid system. The MQC code for nine users used in the simulation is (12, 4, 1), while the four WDM channels used are 1551.55, 1550.75, 1549.95, and 1549.15 nm. The system parameters are illustrated in Table 2. The simulation is kept as real as possible by activating all attenuation parameters.

In the hybrid system, the combined signal is transmitted through the optical fiber link and is split into two parts. One for the receivers of SAC/OCDMA signals composed of notch filters, matched decoders, and balance techniques. The other part is for the receivers of the WDM system, composed of narrowband WDM demultiplexer, to attenuate the broadband signal that is coming from SAC/OCDMA source, and standard receiver parts of WDM. For the nonhybrid system, each individual system, under the same previous parameters, was simulated.

4 Simulation and Performance for an Eavesdropper's Code Interceptor

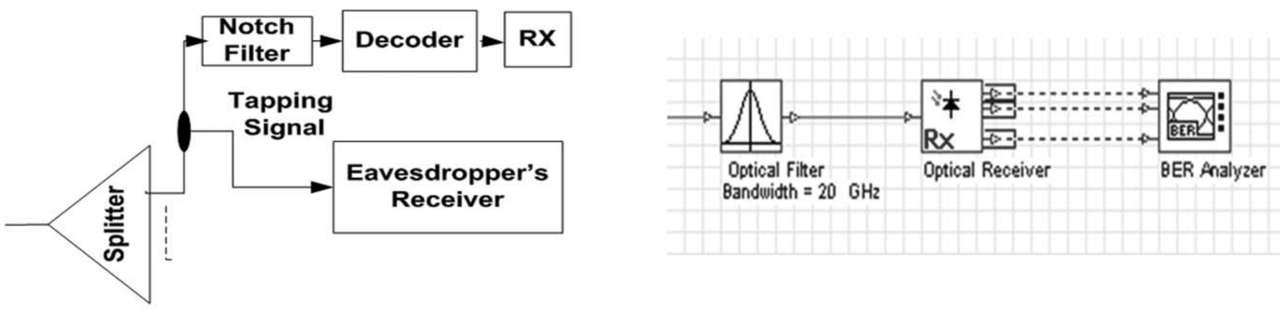
The code information of an optical CDMA network that is known to the smart eavesdropper is the data rates, the type of encoding, and the codes structure, while the employed code for an individual authorized user is not known.[14] An eavesdropper in the network may tap signals from various places within the network. In our simulation, the eavesdropper taps the signals at the receiver side as shown in Fig. 2. Figure 2 also shows the eavesdropper's receiver structure that is based on observing the authorized transmitted signal by scanning all wavelength channels that are used by SAC/OCDMA users for covering the coded signal. However, the eavesdropper does not have the notch filters as the authorized user. Consequently, the combined overlay signal has passed through the receiver of the eavesdropper. It is obvious that the WDM signals cause confusion for potential adversaries due to vague code spectrums.

In order to analyze the performance of the eavesdropper's code interceptor, we utilize the performance in a classical detection theory.[14] The type of data modulation that is used in our system is on-off keying. The eavesdropper can tap an individual user's codeword to detect whether the energy of a single pulse is available or not. This can be done by an optical matched filter. Then, a photodiode is used to detect the output of the matched filter. Idealized transmission components are assumed in this analysis. The calculations are based on the probability of error-free codeword detection for each single spectral pulse. Hence, the overall probability of error-free codeword detection based on SAC/OCDMA for the spectral signal of the system is written as follows:[15]

$$P_{correct} = (1 - P_{miss})^{w}(1 - P_{false})^{(N-w)}, \tag{1}$$

$$P_{false} = \exp\left[-\frac{\gamma}{N_o}\right], \tag{2}$$

where P_{miss} is the probability of missing a transmitted pulse in a given bin and P_{false} is the probability of falsely detecting a pulse in a given bin. In addition, γ is the decision threshold and N_o is the noise power spectral density.



(a) (b)

Fig. 2 (a) Eavesdropper intercepting authorized user's signals and (b) eavesdropper's receiver structure.

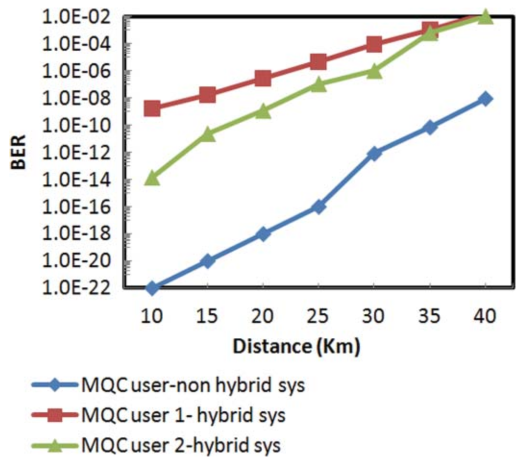


Fig. 3 BER versus distance for MQC users for both hybrid and non-hybrid systems.

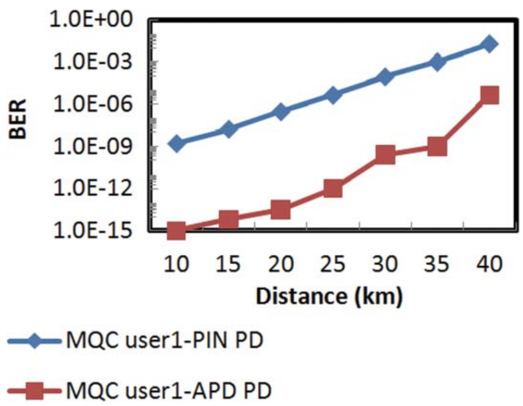


Fig. 4 BER versus distance for an MQC user when adopting PIN or APD photodetectors.

P_{miss} is given by $P_{miss} = 1 - P_{\det.}$, where $P_{\det.}$ is the probability of detection

$$P_{\det.} = Q[\sqrt{2B/N_o}, \sqrt{-2\ln(P_{false})}], \quad (3)$$

where B/N_o is the single pulse signal to noise ratio and Q is the Marcum's function.

Therefore, Eq. (1) can be rewritten as follows:

$$P_{correct} = [Q(\sqrt{2B/N_o}, \sqrt{2\gamma/N_o})]^w \times [1 - \exp(-\gamma/N_o)]^{(N-w)}. \quad (4)$$

5 Results and Discussion

The bit-error rate (BER) performance of the system is evaluated prior to and after hybridization. The BER and the Q-factor performance of eavesdropper detection are also evaluated for each optical wavelength of the MQC code.

Figure 3 shows the BER for users 1 and 2 for both hybrid and nonhybrid schemes with various fiber link distances. Although the BER for the hybrid scheme is worse than that for the nonhybrid scheme (because of the overlapping signals between SAC/OCDMA and WDM), it is still accepted. However, the security of the hybrid scheme is higher than that of the nonhybrid one. This is an expected result, which is illustrated in Table 3 for eavesdropper BER and Q-factor performances. All users of the SAC/OCDMA system have approximately equivalent BERs when the system is nonhybrid, while they have different BERs when the system is hybrid as shown for users 1 and 2 in Fig. 3. This is because some users have more interference by WDM signals than others. To further improve performance we can use an APD. Indeed, this results in a better performance than for normal users who adopt PIN photodetectors because of the gain offered in APDs. Figure 4 shows the BER for the MQC user when switching from PIN photodetector to APD.

Table 3 Simulation scanning results for an eavesdropper.

	Hybrid system			Nonhybrid system		
Wavelength (nm)	BER	Q-factor	B/N_o (dB)	BER	Q-factor	B/N_o (dB)
1549.0	3.73×10^{-2}	1.75	4.86	7.10×10^{-21}	9.3	19.36
1549.3	1	0	0	5.81×10^{-37}	12.5	21.93
1549.6	3.67×10^{-3}	2.68	8.56	6.25×10^{-25}	10.1	20.08
1549.9	3.00×10^{-2}	1.88	5.48	8.40×10^{-31}	11.4	21.13
1550.2	2.52×10^{-2}	1.95	5.8	5.56×10^{-31}	11.4	21.13
1550.5	3.13×10^{-2}	1.84	5.29	1.22×10^{-33}	11.9	21.51
1550.8	4.39×10^{-2}	1.69	4.55	3.92×10^{-28}	10.6	20.5
1551.1	4.40×10^{-4}	3.32	10.42	7.20×10^{-22}	9.4	19.46
1551.4	2.28×10^{-2}	1.97	5.88	4.33×10^{-32}	11.8	21.43
1551.7	2.40×10^{-2}	1.96	5.84	1.75×10^{-29}	10.8	20.66
1552.0	3.35×10^{-6}	4.21	12.48	3.70×10^{-31}	11.5	21.21
1552.3	4.20×10^{-10}	6.37	16.08	7.10×10^{-24}	9.5	19.55

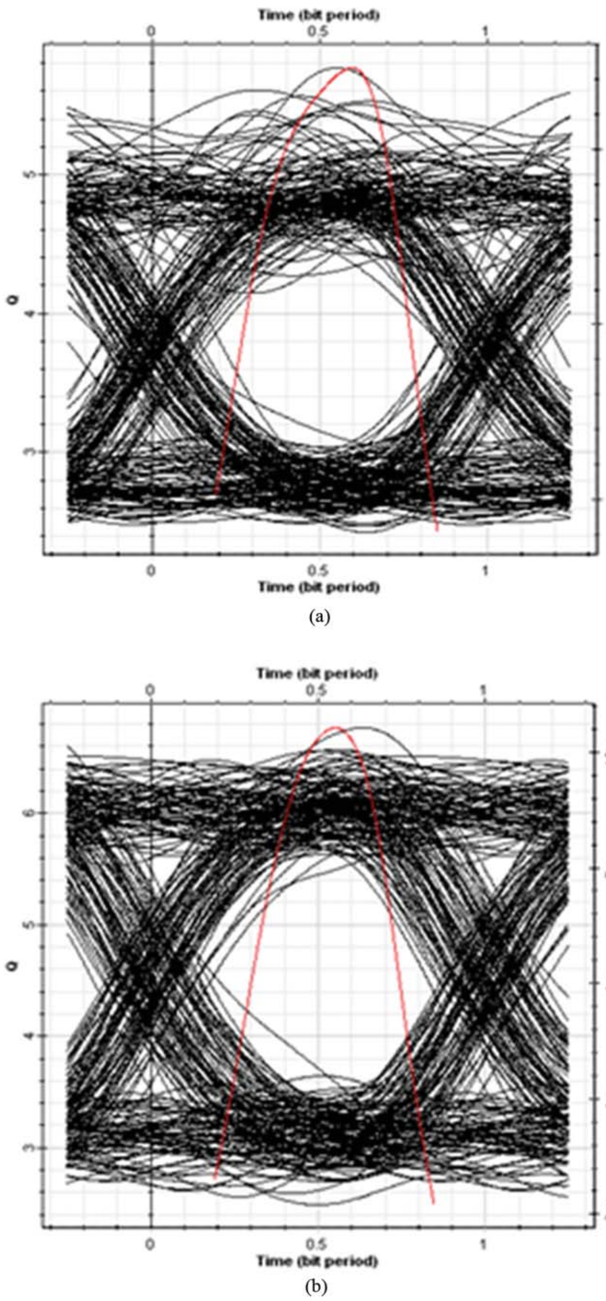


Fig. 5 Eye diagram for a WDM user, (a) hybrid SAC-OCDMA-WDM system with a distance of 70 km and (b) WDM system with a distance of 100 km.

The performance of the WDM system under a hybrid SAC-OCDMA-WDM and lone WDM schemes is shown in Fig. 5 in terms of eye diagrams. These eye diagrams are obtained when a data rate of 2.5 Gbps is transmitted over a 70 km link [Fig. 5(a)] for the WDM system in the hybrid case and a 100 km link [Fig. 5(b)] for WDM system in the lone case. The BER is found to be 3.9×10^{-9} [Fig. 5(a)] and 1.2×10^{-12} [Fig. 5(b)]. It is obvious that the performance for the hybrid system is still acceptable.

Table 3 shows the results of the simulation scanning process for an eavesdropper. The BER and Q-factor for every optical carrier wavelength of the MQC code of SAC/OCDMA are illustrated in Table 3. The single pulse signal-to-noise ratio, B/N_o, values are used in Eq. (4) to evaluate the eavesdropper performance. The Q-factor and BER of the nonhybrid system are more than 9.0 and less than 7.0×10^{-21}, respectively. For the hybrid system, the range of values differs from 0 to 6.37 for Q-factor and 1 to 4.2×10^{-10} for BER. The last two values in the hybrid system are good because the pulses from the two systems do not overlap or the overlapping between them is very small. Figure 6 also shows the comparison of an eavesdropper's SNR per MQC code chip between the hybrid and nonhybrid scheme. The SNR per chip of the eavesdropper decays when the system is hybrid. Some values are better than others due to the location of WDM wavelengths interferes – (1551.55, 1550.75, 1549.95 and 1549.15 nm), however, all values except the SNR per chip 12 have an SNR less than 15 dB. This value is required for raw detector BER of 10.0×10^{-4} as mentioned in Ref. 16. Hence, an eavesdropper would not be able to distinguish between the values of 1 and 0. That is, acquiring knowledge of the entire code of an authorized user would be more difficult by the eavesdropper.

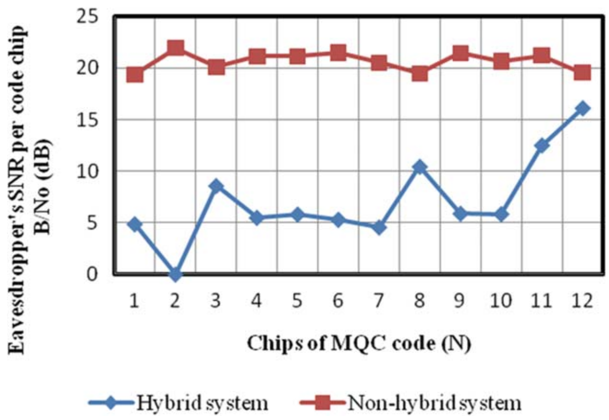


Fig. 6 Eavesdropper's SNR per MQC code chip.

Figure 7 shows the eavesdropper probability of correct detection as a function of signal to noise ratio for a single detected code pulse. It is evaluated based on Eq. (4). Modified quadratic congruence spectral amplitude coding CDMA codes with code length $N = 12$ and code weight $w = 4$ have been employed. The B/N_o values that are in Table 3 have been adopted. The detection threshold is assumed to be an optimum value determined by a search algorithm for an eavesdropper's calculations.[14] In the nonhybrid system, the B/N_o values are more than 16 dB, so that the probability of error-free codeword detection is one, which means that the eavesdropper can easily detect the entire codeword error-free and then try to specify the individual user's code. In comparison with the hybrid system, the range of B/N_o values differs from 0 to 16.08 dBs. Therefore, the probability of error-free codeword detection varies from 0.019 to 1. Consequently, the difficulty and the amount of time for an eavesdropper to intercept and detect the MQC code of hybrid WDM and SAC/OCDMA schemes is much higher.

Figure 8(a) shows the performance BER of eavesdropper for both hybrid and nonhybrid systems, using a receiver that is based on observing the authorized transmitted signal based on the decoder, which is the same as the user's decoder. But the eavesdropper does not have the notch filter as the authorized user has. Therefore, the combined signal has passed

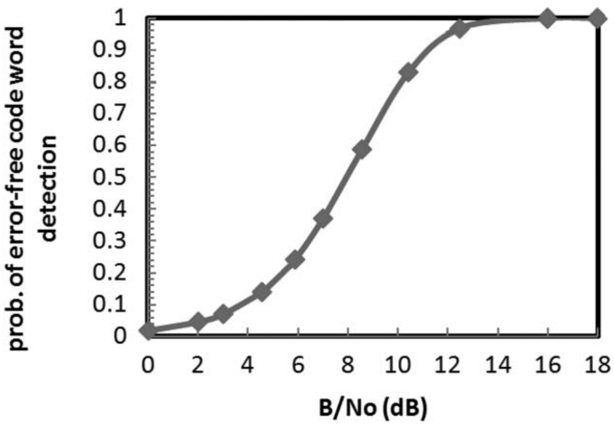


Fig. 7 Eavesdropper's probability of correct detection.

through the receiver of the eavesdropper. Figure 8(b) shows the eye-diagram for the eavesdropper interceptor at a distance of 15 km, which has a bad performance with BER of 1.13 $\times 10^{-3}$. Hence, it is clear that the eavesdropper will never know the authorized user's signal using a SAC/OCDMA-WDM overlay scheme based on these results. In comparison, a network that uses the SAC/OCDMA scheme only will allow the eavesdropper to tap the authorized user's signal with much success.

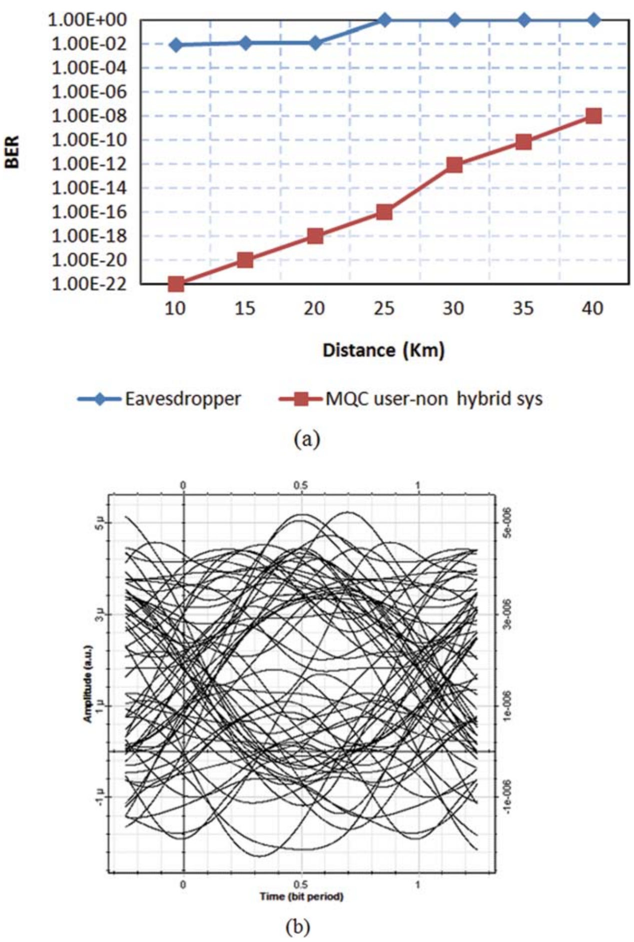


Fig. 8 (a) BER versus distance for eavesdropper for both hybrid and nonhybrid systems and (b) eye diagram for the eavesdropper interceptor at a distance of 15 km.

From the above discussion, we notice that the common side effect of increased security is a performance reduction. Therefore, the system involves a tradeoff between performance and confidentiality for authorized users.

6 Conclusions

In-band transmission of both OCDMA and WDM signals has been investigated. The separation process between different techniques has been presented by utilizing notch filters. In addition, design parameters have been illustrated for simulation of both hybrid and nonhybrid systems. The performance and enhancing security of the hybrid network have also been investigated by measuring the system bit-error-rates and the eavesdropper's probability of correct detection. The results have been compared to the nonhybrid system. APDs have been used instead of PIN photodetectors in order to improve the performance of the MQC users who suffer more from the WDM interferes. Our results indicate that although both OCDMA and WDM users use the same band of transmission, an acceptable performance can still be achieved. In addition, our system provides enhanced data confidentiality as compared to that of the SAC/OCDMA scheme only. Furthermore, continuously changing the transmitted spectrum by changing the spectrum of WDM signals in the hybrid scheme can increase the confidentiality. An enhancement of data networks security can also be increased for this system by using long transmitted code and many channels from WDM transmitters. Finally, the tradeoff between the performance and confidentiality for authorized users has to be considered.

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