Multirate and Multi-Quality-of-Service Passive Optical Network Based on Hybrid WDM/OCDM System

Hamzeh Beyranvand and Jawad A. Salehi, Sharif University of Technology

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ABSTRACT

In this article we present a new scheme to support multirate and multi-quality-of-service transmission in passive optical networks based on a hybrid wavelength-division multiplexing/optical code-division multiplexing scheme. The idea is to use multilength variable-weight optical orthogonal codes as signature sequences of a hybrid WDM/OCDM system. To provide the requested classes of service, the code weight and code length of MLVW-OOCs are designed based on the characteristics of the requested classes of service. In order to mitigate multiple access interference, we propose to utilize a multilevel signaling technique and interference remover structure based on advanced optical logic gate elements. We show that utilizing such a technique improves the QoS of the proposed scheme.

INTRODUCTION

The increasing growth of Internet Protocol (IP) and the popularity of the web are resulting in altering the traffic pattern in data networks such that voice- and text-oriented traffic have changed to data- and image-based traffic. Furthermore, the emergence of IP based multimedia applications such as VoIP, IPTV, video conferencing, and so on, diversifies data traffic having different data rate and quality of service (QoS) requirements. Therefore, designing a high-capacity network to handle diverse and bulky data traffic is an essential challenge toward next-generation data networks.

Optical networks exploiting tremendous fiber optic bandwidth is a promising solution to transmit bulky data traffic. Various techniques have been proposed to utilize fiber optic capacity in the access and backbone of the network. Fiber to the home (FTTH) is an interesting solution proposed to exploit fiber optic capacity in access networks. The passive optical network (PON) is a promising scheme to implement FTTH cost effectively [1].

Currently time-division multiplexing (TDM)-PON has been implemented. Ethernet PON (EPON) based on IEEE 802.3ha, asynchronous transfer mode (ATM) PON (APON) based on ITU-T G.983.1, and Gigabit PON (GPON) based on ITU-T G.984 are typical examples of the implemented TDM-PON [1]. However, due to the uplink time-sharing, TDM-PON systems are limited in supporting bursty traffic and providing multirate transmission.

Wavelength-division multiplexing (WDM)-PON is another technique introduced to resolve TDM-PON's shortcomings. Furthermore, maturing key optical technologies and the emergence of advanced optical devices are reducing the cost of WDM-PON deployment. Therefore, it is expected that WDM-PON schemes will be standardized and widely implemented. However, in WDM-PON the number of available wavelengths is not adequate to support users of access networks. Moreover, assigning an individual wavelength to a user decreases bandwidth efficiency and increases the coarseness of data granularity.

Optical code-division multiplexing (OCDM) as a viable multiplexing technique is receiving much attention as a promising access technique to share common resource among asynchronous users without any central controller [2]. The OCDM technique is becoming an attractive candidate in the next-generation optical network and has been considered to be used in a PON. This is mainly due to the attractive properties of OCDM such as flexible and asynchronous bandwidth sharing, statistical multiplexing, provisioning differentiated QoS at the physical layer, and the capability to secure data transmission using a pseudo random signature. Hybrid OCMD/WDM-PON is another interesting scheme proposed to resolve WDM-PON and utilize OCDM capabilities in future PONs [3].

In this article we introduce a novel hybrid OCDM/WDM PON scheme to support multirate and multi-QoS transmission in PON. The idea is based on utilizing multilength variable-weight optical orthogonal codes (MLVW-OOCs) as the signature sequence of the OCDM scheme. The length and weight of OOCs are designed based on the characteristics of the supported classes of service. Furthermore, in order to improve the throughput of the presented scheme, we propose to employ a multilevel signaling technique and an interference remover structure based on advanced optical logic gates [4, 5].

The rest of the article is organized as follows. In the next section we review conventional TDM-PON, WDM-PON, and WDM/OCDM-PON. Our proposed multirate multi-QoS WDM/OCDM-PON is then presented. We introduce multilevel signaling and the interference remover via optical logic gates. The article is concluded in the final section.

Passive Optical Network

As mentioned above, the ultimate solution to handle increasing data traffic at the access network is FTTH. Basically, three architectures may be used to implement FTTH as shown in Fig. 1

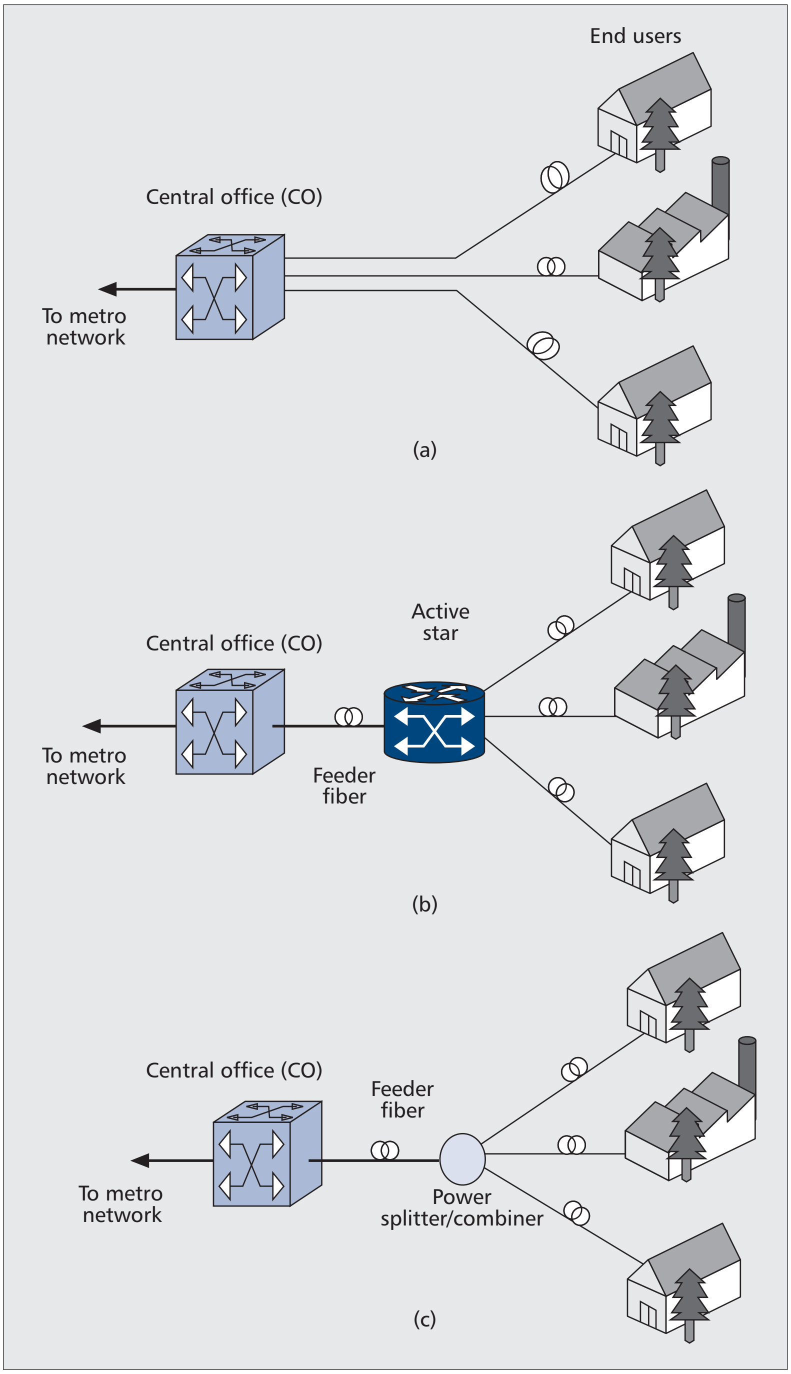

Figure 1. *Different architectures for FTTH: a) point-to-point; b) active star; c) passive star.*

[1]. The possible architectures are *point-to-point*, *active star*, and *passive star*. In the point-to-point architecture an individual fiber runs between the central office (CO) and each end user. Although point-to-point architecture provides the ultimate capacity and can support possible future high-data-rate applications, it needs many fibers, which increases the installation cost. Furthermore, for each fiber (home) we need a terminal at the CO, which complicates the CO architecture and raises scaling and powering issues. On the other hand, in the active star architecture a single fiber runs between the CO and an active node closed to end users. End users are connected to the active star by individual branching fibers. In the active star architecture only a single fiber is needed as a feeder, with a number of short branching fibers to connect end users and the active star, so installation cost is reduced. However, due to the presence of the active star, the powering issue remains. In the passive star architecture the active node of the active star architecture is replaced by a passive node. The passive node acts as a power splitter and power combiner to split the received signal from the feeder fiber among the branching fibers and aggregate branching fibers signals into the feeder fiber, respectively. In such an architecture, in addition to the cost reduction due to using feeder fiber, the passive power splitter/combiner resolves the power issue. Therefore, the passive star architecture as a cost-effective solution has received much attention and is becoming a popular architecture to implement FTTH. It is interesting to note that the passive star architecture is referred to as a passive optical network (PON).

Based on the multiplexing method used to share the common resource of the feeder fiber among end users, we have three scenarios: TDM-PON, WDM-PON, and OCDM-PON. These scenarios are compared in Fig. 2. As shown in the figure, in the TDM-PON scenario bandwidth of the feeder fiber is slotted in the time domain, and each user (optical network unit, ONU) is assigned a dedicate time slot. On the other hand, in the WDM-PON scenario, bandwidth of feeder fiber is divided into multiple bands, and each user is assigned a dedicated wavelength. As shown in Fig. 2, in the OCDM-PON scenario bandwidth of feeder fiber is divided among end users in code space. In this scenario each user is assigned a specific code considered as the user address and employed to transmit bitstreams. In an OCDM system employing on-off keying modulation, to send bit "1," users transmit the signals encoded by the assigned codeword; and to send bit "0," they transmit no signal. At the receiver front-end, by using the corresponding decoder the bitstream can be extracted.

In comparison to TDM-PON, WDM-PON provides more bandwidth and can support future large amoaunts of data traffic. However, the number of available wavelengths is not adequate, and data granularity of the access network is coarse. On the other hand, OCDM-PON provides flexible bandwidth, and users can transmit asynchronously. In OCDM-PON the QoS of the users is limited by multiple access interference (MAI), which is a function of the number of transmitting users [2]. In order to guarantee the desired QoS, the number of transmitting users needs to be restricted. So in OCDM-PON the number of supported end users is limited by the number of available codewords and MAI.

Hybrid WDM/OCDM-PON is an ultimate solution to resolve scarceness of the number of available channels and codes, and the coarseness of the data granularity [6]. To resolve the MAI limit of the OCDM system, we propose to use a recently introduced multilevel signaling technique based on advanced optical logic gates [4, 5].

MULTIRATE AND MULTI-QOS HYBRID WDM/OCDM PON

In hybrid WDM/OCDM-PON, OCDM is used in each WDM channel to share the available bandwidth among end users. In Fig. 3a the bandwidth classification of the hybrid WDM/OCDM-PON is presented. As shown in the figure, in each wavelength N_c channels are available where N_c is the number of available codewords.

Generally, OCDM, based on coding principles, is divided into two types, coherent and incoherent. In a coherent OCDM scheme, the phase of an optical signal is encoded by bipolar codes such as m-sequence, Gold code, or Hadamard. On the other hand, in an incoherent OCDM scheme the intensity of an optical signal is encoded by unipolar codes such as OOC or prime code. In this article we employ an incoherent OCDM scheme based on OOCs.

An OOC is a family of (0, 1) sequences with good auto- and cross-correlation properties [2]. In the literature an OOC is characterized by (L, w, λ) where L is the code length, w is the code weight that determines the total number of ones in each codeword, and λ is the maximum value of shifted auto-correlation and cross-correlation. The number of available OOCs (N_c) is limited by the well-known *Johnson bound* as follows [2]:

$$N_c \le \frac{(L-1)(L-2)\ldots(L-\lambda)}{w(w-1)(w-2)\ldots(w-\lambda)}. \quad (1)$$

Equation 1 indicates that the number of available OOCs, N_c, is a function of code parameters (L, w, λ). As an example, for $L = 101$, $w = 5$, and $\lambda = 1$ we have $N_c \le 5$ while for $\lambda = 2$ we have $N_c \le 165$. Thus, increasing the maximum correlation increases N_c at the expense of interference excess and performance degradation.

It is worth noting that the QoS in such an OCDM system depends on the number of interfering users (NI) and the code parameters (L, w, λ). The code weight has a direct effect on QoS. By increasing the code weight, QoS of transmitting users is improved, while according to the *Johnson bound*, N_c is reduced. On the other hand, code length has a reverse relation with transmission rate and a direct relation with the number of available codewords. So for a specific bandwidth, N_c of high data rate is less than N_c of low data rate.

In conventional OOCs all codes have the same parameters, so all users have the same

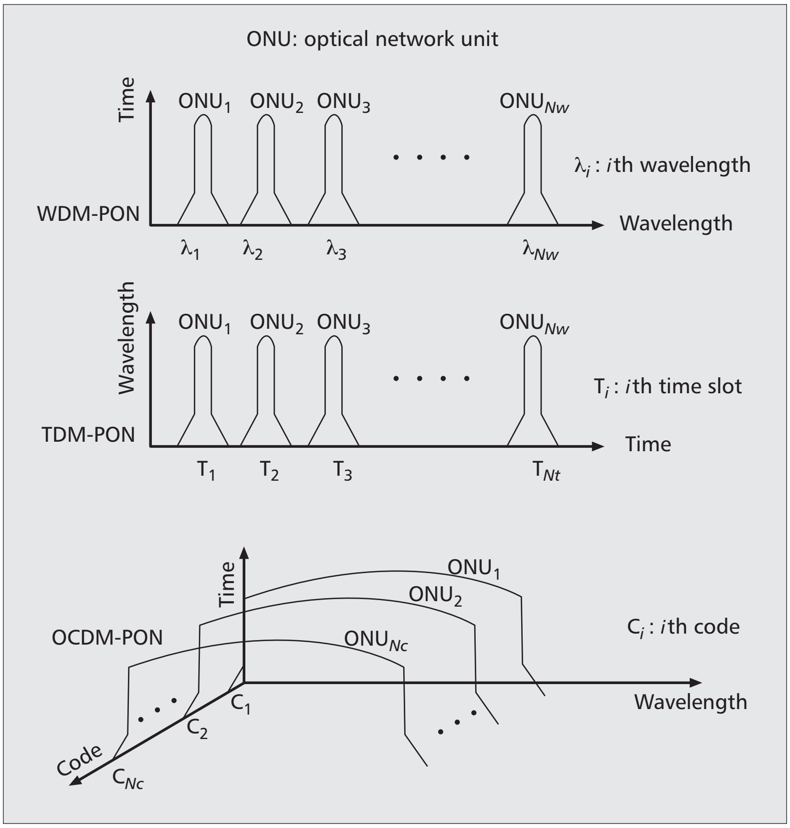

Figure 2. *Bandwidth classification in different PON schemes.*

transmission rate and QoS. Multilength OOCs (ML-OOCs) have been designed to support multirate transmission. In ML-OOCs codewords are divided into multiple classes. Although all codewords have the same weight, each class has a specific code length. So using ML-OOCs, we can support multirate transmission. In order to support multi-QoS transmission, variable-weight OOCs (VW-OOCs) are designed. In VW-OOCs all codewords have the same code length and codewords are divided into multiple classes having specific code weight. So using VW-OOCs, we can support multi-QoS transmission in access network.

In order to jointly support multirate and multi-QoS transmission, MLVW-OOCs have been designed. In MLVW-OOCs codewords are divided into multiple classes, and codewords of each class have a specific code length and code weight. So utilizing MLVW-OOCs, we can jointly support multirate and multi-QoS transmission. In OCDM based on MLVW-OOCs, high-weight codewords are assigned to high QoS users and short-length codewords are assigned to high-rate users. In Fig. 4 different OOC families are compared.

Generally, MLVW-OOCs are characterized by ($L = \{L_1, L_2, \ldots, L_Q\}$, $w = \{w_1, w_2, \ldots, w_Q\}$, $N_c = \{N_{c_1}, N_{c_2}, \ldots, N_{c_Q}\}$, Q, Γ), where L_i, w_i, and N_{c_i} denote the code length, code weight, and number of available codes in class i, respectively. In addition, Q denotes the number of specified classes in the network, and Γ indicates the cross correlation matrix, which is defined as $\Gamma = \{I_{(n,m)}$, for $n,m = 1, 2, \ldots, Q\}$. $I_{(n,m)}$ denote the maximum correlation between class n and

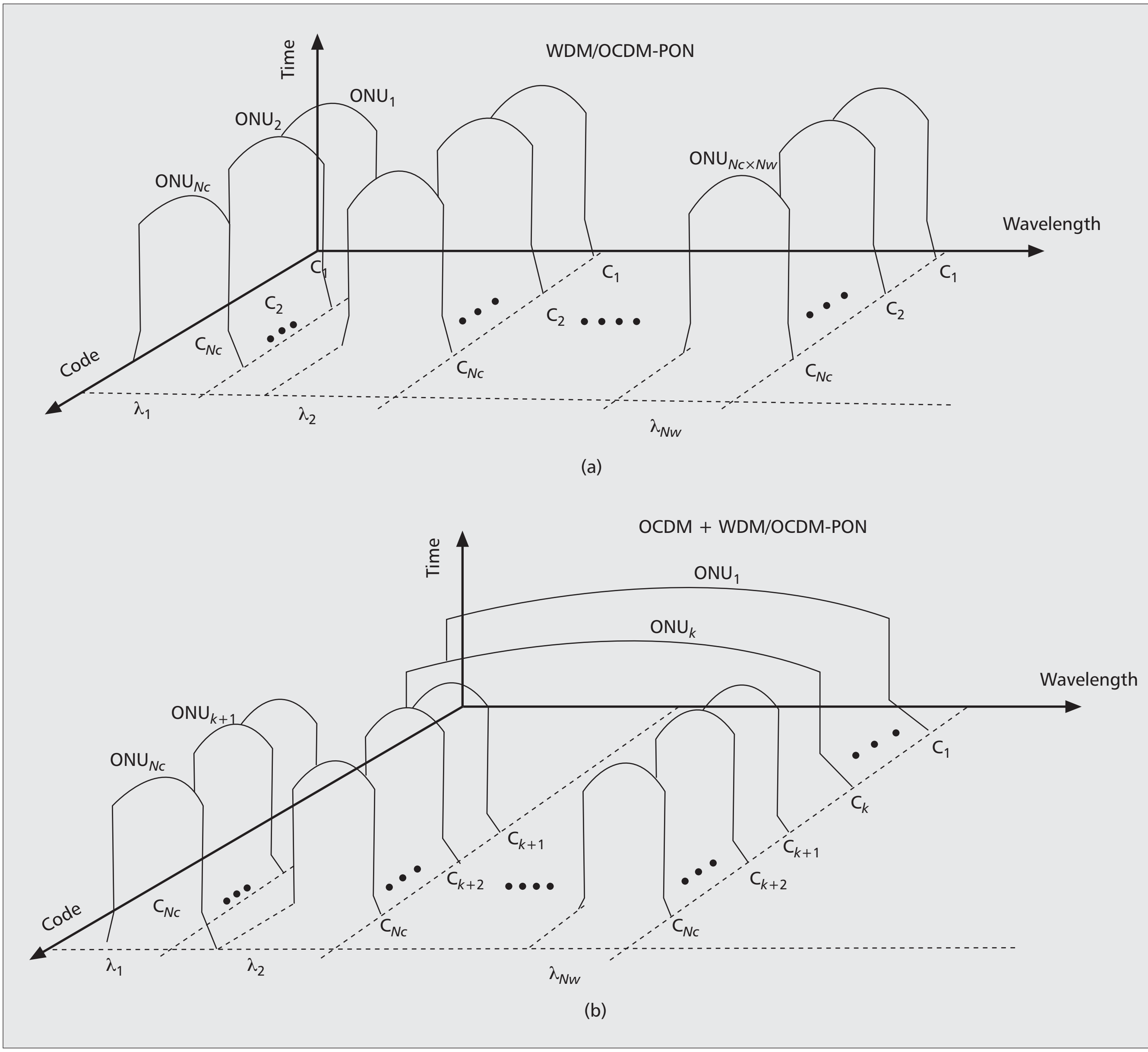

Figure 3. *a) Bandwidth classification in WDM/OCM-PON, b) bandwidth classification in OCDM+WDM/OCDM-PON.*

class m codewords. If $n = m$, $I_{(n,m)}$ is referred to as *intra-cross-correlation*, which indicates the maximum cross-correlation between the same class codewords; if $n \neq m$, $I_{(n,m)}$ is referred to as *inter-cross-correlation*, which shows the maximum cross-correlation between two codes from different classes.

It is worthy to note that in the proposed multi-rate hybrid WDM/OCDM-PON the maximum transmission rate is limited by the shortest code length. Furthermore, the maximum transmission rate in hybrid WDM/OCDM-PON is less than that of OCDM-PON. In order to support ultra high rate services we propose to design a PON scheme utilizing both OCDM and hybrid WDM/OCDM scenario. In this scheme, a number of codewords are used to encode optical signal along all wavelength, same as OCDM PON. The remained codewords are used in the wavelength windows, the same as in WDM/OCDM-PON. The bandwidth sharing in this scheme is shown in Fig. 3b. As it can be seen in the figure, codes C_1 up to C_k are used in OCDM scenario to support ultra high rate service and codes C_{k+1} up to C_{N_c} are used in the hybrid WDM/OCDM scenario to support high-, medium-, and low-rate services. We refer to this scheme as OCDM+WDM/OCDM-PON scenario.

MAI Mitigation Using a Multilevel Signaling Technique

Multiple access interference is the dominant factor degrading QoS of an OCDM system. In [4], multilevel signaling technique has been introduced to mitigate MAI. In conventional incoherent one-level OCDM system, all users transmit at the same power level. In such a system, tapped delay lines (TDLs) and an AND logic gate (ALG) structure are used as encoder and decoder, respectively.

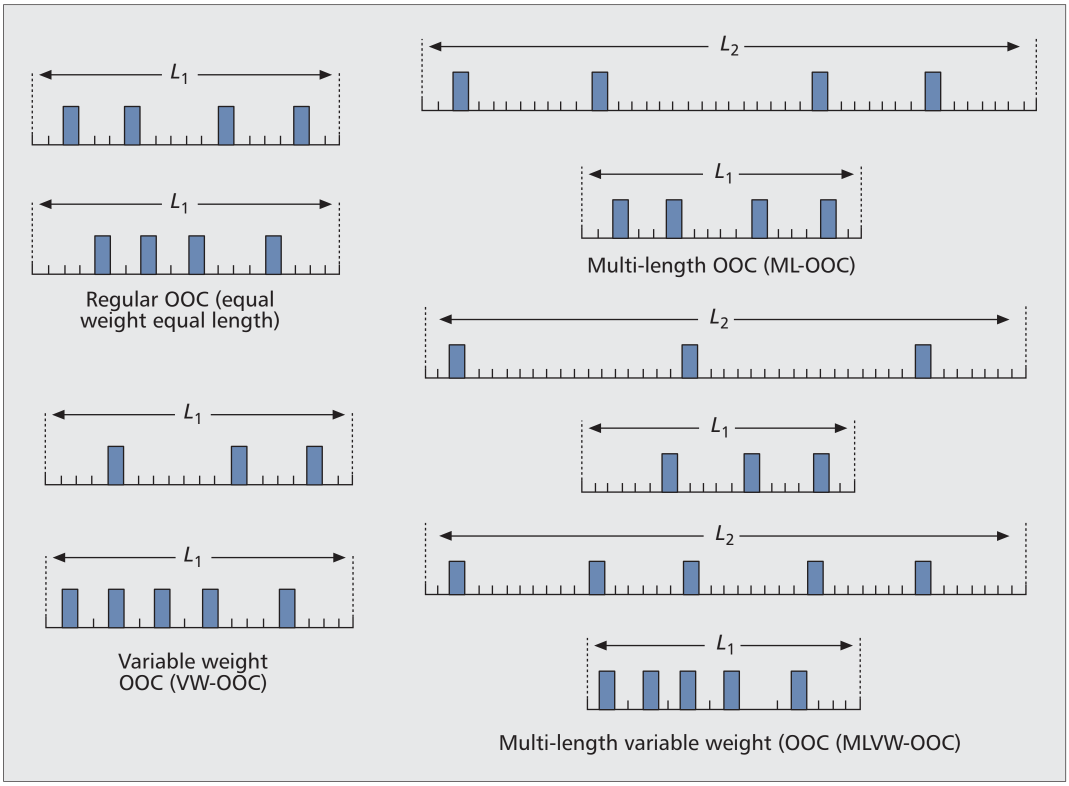

Figure 4. *Different OOCs families.*

In a multilevel signaling technique, users are categorized into multiple groups and users of each group transmit at a specific power level. In such a system a multi-stage interference remover based on optical logic gates is an essential element to mitigate interference of users transmitting at other power levels.

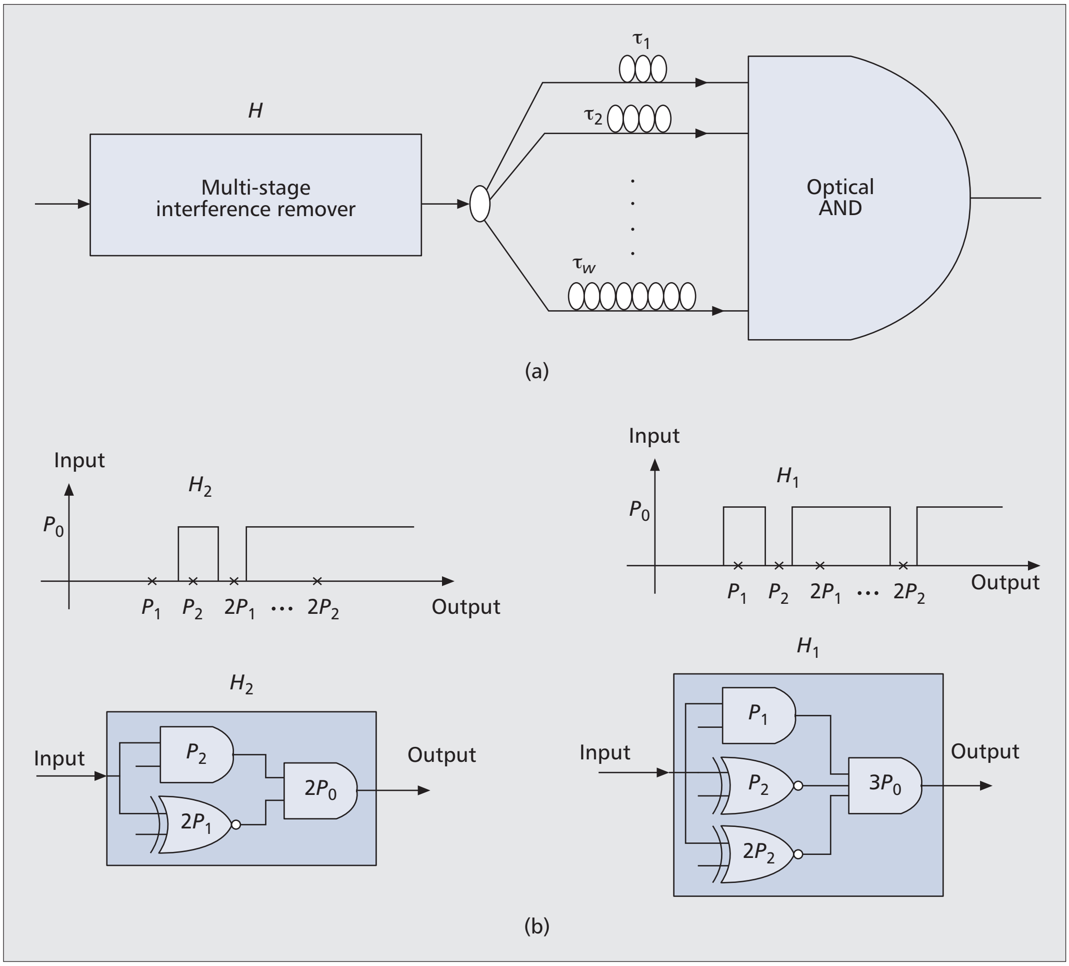

Figure 5. *a) Multi-stage receiver structure, b) interference remover structure.*

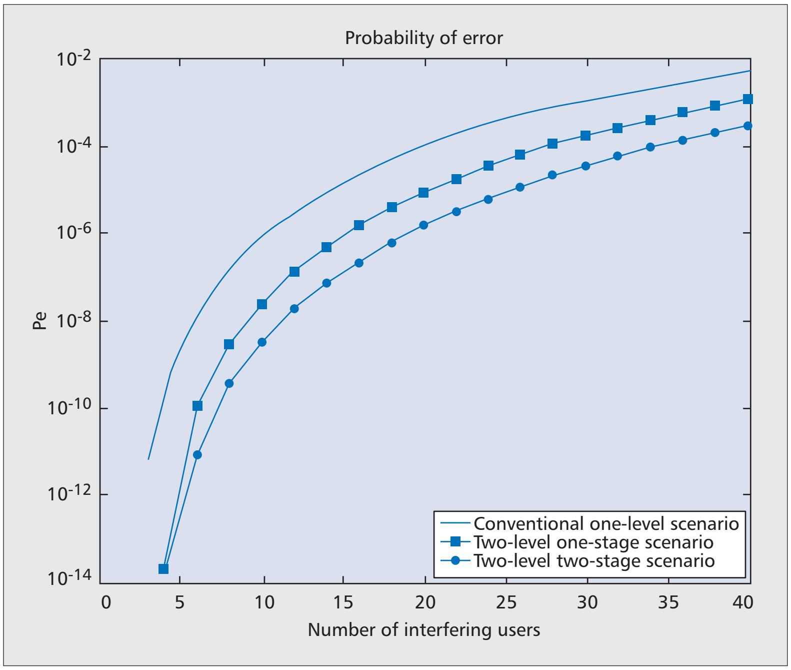

Figure 6. *Probability of error of one-level and two-level OCDM systems.*

In a multilevel signaling technique, users are categorized into multiple groups, and users of each group transmit at a specific power level. In such a system a multistage interference remover based on optical logic gates is an essential element to mitigate interference of users transmitting at other power levels. The structure of a typical receiver based on multi-stage interference remover is shown in Fig. 5a. The structure of interference remover relates to the number of power levels and the depth, i.e., the number of stages, of interference removing. In Fig. 5b the structure of two-stage interference remover in a two-level system is shown [4]. In the two-level system users are divided into two groups, group 1 and group 2. The users of group 1 and group 2 transmit at power levels P_1 and P_2, respectively (assume $P_2 > P_1$). In the figure, H_1 and H_2 are the interference remover of group 1 and group 2 users, respectively. From Fig. 5b we can observe that H_1 removes interferences at power levels P_2 and $2P_2$ and H_2 removes interferences at power levels P_1 and $2P_1$. So, in such a two-stage two-level system for group 1 users pulses at power level P_1 and $3P_2$ have the same effect. On the other hand, for group 2 users pulses at power level P_2 and $3P_1$ have the same effect. As a matter of fact, in multilevel signaling technique by transmitting at different power levels and utilizing multi-stage structure, pulses at the other power levels can be distinguished and removed.

Obviously increasing the number of power level results to the performance improvement due to the increase of the interference mitigation capability of a multistage structure. In Fig. 6 the probability of error of two-class OCDM system using MLVW-OOC characterized by (L = {400, 400}, w = {8, 12}, N_c = {12, 12}, Q = 2) is shown. As it can be observed in the figure, using multilevel signaling technique the probability of error is decreased. Furthermore, the increase of the number of stages of interference remover results to the performance improvement.

Conclusion

In this article we have presented a new scheme to support multirate multi-QoS transmission in optical passive networks. Utilizing MLVW-OOC in hybrid WDM/OCDM-PON we can provide the requested classes of services. The code weight and the code length of MLVW-OOC are designed based on the characteristics of the requested classes of services. Furthermore, to support ultra high rate service, we have proposed to use a combination of OCDM and WDM/OCDM scheme in PON, OCDM+WDM/OCDM-PON.

In order to mitigate MAI and to increase network throughput sufficiently, we have utilized a multilevel signaling technique and interference remover based on advanced optical logic gates elements. In such a technique interference remover, mitigate inference based on the power level on the input signals. We have showed that using this multilevel signaling technique, the QoS of the system is improved.

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Biographies

HAMZEH BEYRANVAND (beyranvand@ee.sharif.edu) received a B.S. degree (with honors, first rank) in electrical engineering from Shahed University, Tehran, Iran, in 2006 and an M.S. degree from Sharif University of Technology (SUT), Tehran, Iran, in 2008. He is currently working toward a Ph.D. degree in the Department of Electrical Engineering at SUT. Since summer 2007, he has been working as a member of the Optical Networks Research Laboratory (ONRL), SUT.

JAWAD A. SALEHI [M'84, SM'07, F'10] (jasalehi@sharif.edu) received a B.S. degree from the University of California, Irvine, in 1979, and M.S. and Ph.D. degrees from the University of Southern California (USC), Los Angeles, in 1980 and 1984, respectively, all in electrical engineering. From 1984 to 1993 he was a member of technical staff of the Applied Research Area, Bell Communications Research (Bellcore), Morristown, New Jersey. He is currently a full professor at the ONRL, Department of Electrical Engineering, SUT.