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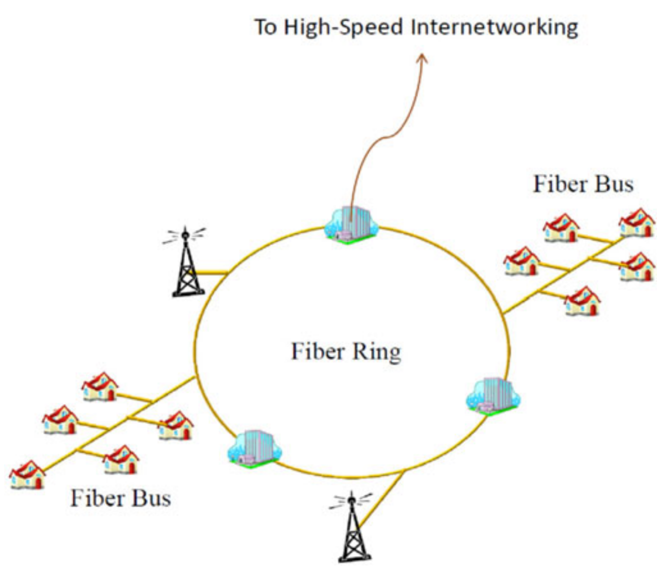

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Throughput Performance Analysis of Asynchronous Optical CDMA Networks With Channel Load Sensing Protocol

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Abstract: In this paper, we propose a channel load sensing protocol (CLSP) to prevent the throughput decrease at heavy traffic conditions in asynchronous optical code-division multiple-access (CDMA) networks. The multiple access-interference (MAI) and beat noise are considered the main deleterious source of the network in addition to thermal, shot, and relative intensity noises. Moreover, we employ optical hard limiters and error correction codes to mitigate the physical channel impairments. However, the packet throughput performance declines severely when the number of active users reaches a certain amount in the network. We employ the proposed CLSP with optimum threshold that successfully mitigates the throughput reduction at heavy load conditions. Numerical results show that the proposed protocol can support a throughput rate above 100 Gb/s, which might be compatible for an eventual standardization for broadband optical access networks.

Index Terms: Optical code-division multiple-access (CDMA), unslotted ALOHA, channel load sensing protocol, carrier-hopping prime code, optical hard-limiter, queuing analysis.

1. Introduction

As different types of broadband services grow rapidly, it has become indispensable to develop high-speed communication systems that supports not only the current traffic demand but the tremendous amount of data traffic that will be generated by emerging multimedia applications as well. For example, ultrahigh definition TV broadcasting via wireless or wired systems will eventually demand more bandwidth capability in the foreseeable future. The passive optical network (PON) is a promising alternative as the broadband platform to fulfill the requirements of these services as well as to accommodate diversified patterns of data traffic.

Several PON schemes have already been proposed and deployed under industrial standards. For instance, the gigabit -capable passive optical network (GPON) was recommended by ITU-T G. 984. In addition, IEEE Ethernet passive optical network (EPON) was devised for local area network or metropolitan area network. Such broadband optical access networks require synchronization among the whole network; of course, more inevitable costs are necessary to deploy network con-

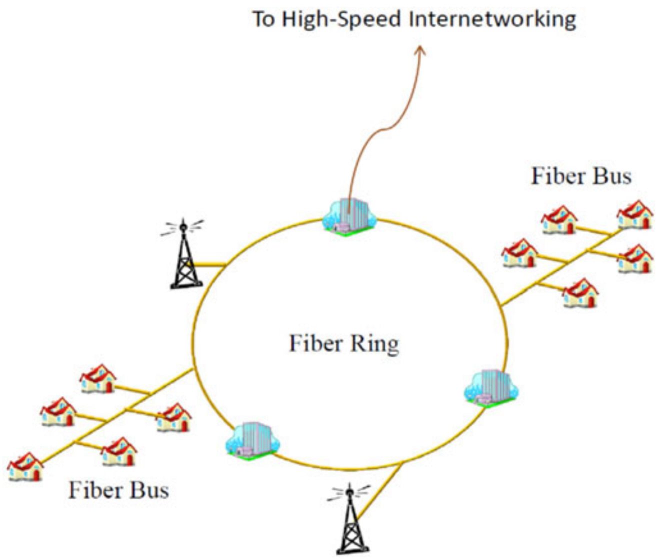

Fig. 1. Hybrid network topology of optical CDMA configuration.

figuration. Alternatively, optical code-division multiple-access (OCDMA) is a prospective approach for broadband optical access networks since it has unique features like, for example, statistical multiplexing, support to random-access protocols, and asynchronous and broadcasting transmission, to name but a few [1]–[6]. Accordingly, each user can transmit data at any time; hence, the synchronization is unnecessary for all the users among the network. Thereupon, off-the-shelf devices might be employed to set up the entire network link. Furthermore, this random access technique can be more flexible to incorporate heterogeneous traffic into the optical network.

Owing to the asynchronous and broadcasting properties, the network topology of optical CDMA may be ring, bus or hybrid [1]–[3]. Fig. 1 illustrates the hybrid network topology of optical CDMA configuration. In such configuration, different types of broadband services can be merged into the optical network simultaneously and asynchronously. For broadband optical access network, it is essential to deploy sufficient capacity for the users to be accommodated in the network. In optical CDMA network, the more active users may yield larger throughput, whereas the MAI will also be enlarged. Once the MAI exceeds to a certain extent, the system performance will turn out to be worse. To mitigate the adverse impact of MAI, we employ optical hard-limiter (OHL) and error correction mechanism in physical layer. In such ways, the optical network can support more active users, and the throughput can be enhanced to a certain degree.

To further enhance the throughput, some literatures discussed the utilization of slotted ALOHA scheme in optical CDMA network [7]–[10]. The slotted ALOHA system divides time into discrete slots, and users must transmit data frame at the beginning of slot. However, in asynchronous optical CDMA system, each user can send the data packet at any time. Especially in local area networks (LANs) or metropolitan area networks (MANs), there is no synchronization mechanism among the network. To address the fully random access traffic, the unsoltted ALOHA is preferable to describe such system [11], [12]. The packet throughput performance of the network can be severely degraded as the number of active users increases. Indeed, the MAI might become the major deleterious source in optical CDMA networks during the condition of heavy traffic loads. To conquer such problem, some prestigious works utilized the concept of sensing the channel condition before sending the information had been addressed [32]–[34]. In [32], Kamath *et al.* proposed interference avoidance scheme with IS/ID (interference sense and interference detection) mechanism to restrict the packet transmission, whereas the effects of beat noise and other noises are still required further investigation. The channel state estimation is the basic requisite to prevent the packet transmission when in heavy load, and several algorithms were proposed [33]. In [34], Khaleghi and Pakravan proposed a very novel media access control (MAC) algorithm with multilevel power transmission to enhance the throughput.

These literatures mentioned above were 1-D optical CDMA system with OOC (optical orthogonal code) as signature sequence. Therefore, the cardinality and flexibility of signature sequence will be greatly reduced. Also, it will limit the throughput and number of active users significantly. In this paper, we propose a channel load sensing protocol (CLSP) to increase the packet throughput of 2-D optical CDMA networks, where the M/M/∞ queuing model is employed. The proposed CLSP not only improves the overall throughput performance of the network, but also supports the maximum achievable level of packet throughput during heavy traffic conditions. The CLSP can support considerably more packet transmissions successfully under an optimum choice of threshold (i.e. maximum number of allowable active users in the network). On the other hand, when the traffic load is above the threshold, the CLSP will reject new packet transmissions. Numerical results show that the proposed protocol can support a throughput rate above 100 Gb/s, which might be eventually compatible for standardization of optical CDMA networks. Through the analytical approach, the proposed work validates the feasibility of optical CDMA as fully asynchronous broadband optical access network.

To simplify the analysis of our proposed work, the same assumptions in [34] are utilized. That is, all nodes in the optical CDMA network can be aware of the exact channel state (i.e. perfect channel estimation). In addition, all nodes observe the same state at the same time on the channel. The rest of this paper is organized as follows. In Section 2, the system architecture is depicted, where the optical hard-limiter, error correction mechanism, and random access scheme with CLSP are introduced. In Section 3, the system performance is analyzed. We demonstrate the numerical results in Section 4. Finally, the concluding remarks are given in Section 5.

2. System Description

In this paper, 2-D time-spreading wavelength-hopping (T/W) optical CDMA system is proposed as the broadband access network. The signature sequence we utilize is carrier-hopping prime code, which is established by algebraic approach [2, pp. 79–87], [3, pp. 150–156]. Besides, it can be represented by a time-wavelength code matrix. In such matrix, the number of columns (i.e., the length of signature sequence) N is equivalent to the cardinality, and the number of rows w (i.e., the available wavelengths) is the code weight. Normally, 2-D codes have superior performance than 1-D codes in addition to better cardinality, flexibility and MAI levels [2], [3], [13], and [14]. Furthermore, the physical implementation of encoder and decoder is also based on the structure of signature sequence [1]–[3]. The carrier-hopping prime code is widely devised in various approaches for such implementation. For example, array waveguide grating (AWG), thin film filter (TTF) and fiber Brag grating (FBG) have been used for prime codes [15]–[17]. Also, the chip rate of encoder and decoder in the advanced optical CDMA system can achieve above hundreds of gigahertz [1], [16], [17].

In Fig. 2, the proposed system architecture is illustrated, where the error correction code and optical hard-limiter are utilized to relieve the channel impairment. The input binary packet data are encoded by the Reed-Solomon encoder. Hereafter, they are spread into signature sequences by the T/W optical CDMA (OCDMA) encoder. The on-off keying (OOK) modulation scheme is utilized in the proposed system. Consequently, only bits 1 are encoded into signature sequences, while bits 0 will not. To lessen the impact of MAI, the optical hard-limiter is placed before the correlator (i.e. decoder) to limit the received optical pulses on a specific level. Henceforth, the correlator will aggregate the optical pulses in the w chip positions of the desired signature sequence (i.e. weight distribution). The correlated optical signal is followed by the photodiode for photodetection, and then it is fed into the Reed-Solomon decoder.

Apart from MAI, beat noise will also bring about severe deterioration in optical CDMA system, and some of the experiments had been verified [18]–[20]. The beat noise originates from the polarization of received optical signals, and the crosstalk ratio (i.e., chip level power ratio in the photodiode of the desired user and the interfering user) will determine the level of beat noise generated [14], [18]. However, the received optical signals from different users have different propagation conditions

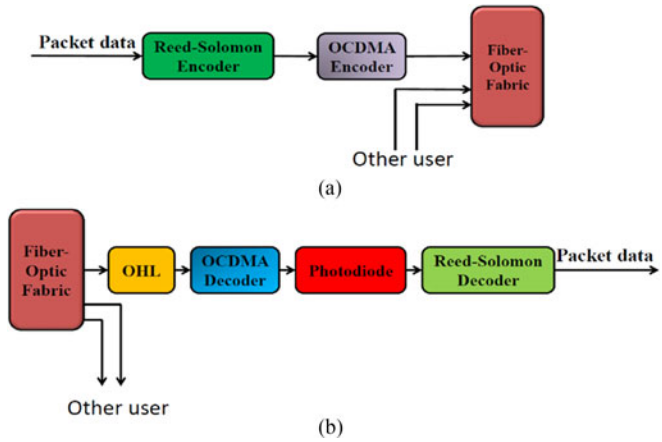

Fig. 2. Proposed T/W optical CDMA system architecture with using optical hard-limiter (OHL) and Reed-Solomon code. (a) Transmitter architecture. (b) Receiver architecture.

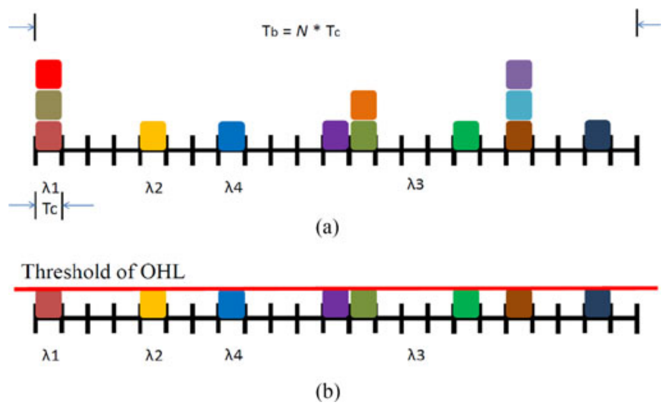

Fig. 3. Carrier-hopping prime code with length $N = 23$, code weight distribution $w(0,4,14,7)$, and the interference pattern vector $\beta(3, 1, 1, 0)$. (a) Received multiple access signal. (b) Clipped optical pulses after optical hard-limiter.

such as optical power, transmission distance, etc. Accordingly, it would be difficult to analyze such effect. To simplify the analysis [13], [14], [31], the worst case for the impact of beat noise is taken into consideration; that is, crosstalk ratio is one and all the received optical signals are assumed to be aligned in polarization. In this way, the beat noise can be completely removed by optical hard-limiter [13], [21], [22], [31]. In this paper, the same approach mentioned above is utilized in our analysis.

Besides, each user (i.e., access node) is deployed on different place among the optical CDMA network. For a specific desired user, the interference may come from nearby or faraway interferers. Therefore, the intensity of interference is different from user to user. In the analysis of optical hard-limiter, our approach is the worst case scenario. That is, all the interfering chips are assumed to be with the same power level and linear superposition over one chip duration. The worst case scenario can simplify the analysis of physical layer in optical CDMA system. Fig. 3 demonstrates such case; also, many literatures are with the same assumption under the employment of optical hard-limiter [13], [21], [22], [31].

To represent the adverse impact of MAI, we designate the interference pattern vector as $\beta = (\beta_1, \beta_2, \beta_3 \ldots . \beta_w)$, which stands for the number of interfering optical pulses over weight distribution. If the optical hard-limiter is applied, it will clip the received optical signals on unit optical pulse level [13], [22]. Consequently, the clipped interference pattern vector can be denoted as $\overline{\beta_j} =$

$(\overline{\beta_{j_1}}, \overline{\beta_{j_2}}, \overline{\beta_{j_3}} \ldots \overline{\beta_{j_w}})$, wherein each element is unity or zero. To analyze the system performance, it is necessary to describe the occurrence probability of the interference pattern vector under specific MAI. Since the carrier-hopping prime code is utilized as signature sequence, the out-of-phase autocorrelation is zero and the cross-correlation is at most one [2], [3]. Based on such properties, if there are j interfering optical pulses hitting on the weight distribution, the interference pattern with corresponding occurrence probability can be given as [13], [31]

$$P(\beta/j) = NDP(\beta) \times MPD(\beta; G_j) \tag{1}$$

where

$$NDP(\beta) = \frac{w!}{\prod_{d=1}^{w} R(\beta_d)!}$$

and

$$MPD(\beta; G_j) = \frac{j!}{w^j \prod_{d=1}^{w} (\beta_d!)}.$$

$R(\beta_{\rm d})$ represents the repetition of element $\beta_{\rm d}$ in pattern β, and G_j stands for the set of basic interference patterns (and all their permutations) from j interferers hitting on the weight distribution.

We demonstrate an example for the use of optical hard-limiter in Fig. 3, where the carrier-hopping prime code with length $N = 23$, code weight distribution $w(0, 4, 14, 7)$, and the interference pattern vector $\beta = (3, 1, 1, 0)$. In the case of $j = 5$ and $w = 4$, all the basic interference patterns of $G_{j=5}$ can be found, respectively, as (5, 0, 0, 0), (4, 1, 0, 0), (3, 2, 0, 0), (3, 1, 1, 0), (2, 2, 1, 0), (2, 1, 1, 1). Hence, the corresponding probabilities of *NDP* for different interference patterns can be evulated as *NDP*(5, 0, 0, 0) = (4!/1!3!), *NDP*(4, 1, 0, 0) = (4!/1!1!2!), *NDP*(3, 2, 0, 0) = (4!/1!1!2!), *NDP*(3, 1, 1, 0) = (4!/1!2!1!), *NDP*(2, 2, 1, 0) = (4!/2!1!1!), *NDP*(2, 1, 1, 1) = (4!/1!3!). In a similar fashion, the corresponding probabilities of *MPD* can be expressed as *MPD*(5, 0, 0, 0) = $(5!/4^5 5!0!0!0!)$, *MPD* (4, 1, 0, 0) = $(5!/4^5 4!1!0!0!)$, *MPD*(3, 2, 0, 0) = $(5!/4^5 3!2!0!0!)$, *MPD*(3, 1, 1, 0) = $(5!/4^5 3!1!1!0!)$, *MPD*(2, 2, 1, 0) = $(5!/4^5 2!2!1!0!)$, *MPD*(2, 1, 1, 1) = $(5!/4^5 2!1!1!1!)$. After optical hard-limiter, all the clipped interference pattern vectors are (1, 0, 0, 0), (1, 1, 0, 0), (1, 1, 0, 0), (1, 1, 1, 0), (1, 1, 1, 0), (1, 1, 1, 1). Therefore, the correlator output $\overline{|\beta_{j=5}|}$ may be 1, 2, 3, or 4.

Aside from optical hard-limiter, the utilization of error correction mechanism in physical layer is also an effective approach to mitigate the channel impairment. In our proposed scheme, since the MAI is greatly reduced by the optical hard-limiter, this will bring about the employment of error correction code more powerful. The Reed-Solomon code is a nonbinary MDS code, which is widely employed in various applications [23], [24]. In this paper, the Reed-Solomon code we utilize is RS(255, 239), which is recommended by ITU-T G. 709 and G. 975 for optical transmission and networking. As the packet length of MAC layer in IEEE 802.3 Ethernet Version 2 must be larger than 1536 bytes [25], we set the packet length as 1673 bytes (i.e., 239 × 7). Therefore, the packet length after RS encoding is 1785 bytes (i.e., 255 × 7). By use of the countermeasures against channel impairment mentioned above, the probability of packet success in the network will be increased significantly.

Since optical CDMA is an asynchronous and broadcasting system, utilizing random access protocol in MAC layer is a preferable way for multiple concurrent packet transmissions. The unsoltted ALOHA is a well-known protocol for random access scheme in the broadcasting channel, where each user can transmit packet at any time [11]. Although CDMA system can support simultaneous users in the network, the large MAI at heavy traffic load will considerably deteriorate the throughput. To prevent this, the CLSP was proposed for CDMA radio/wireless networks and addressed in many articles of the literature, for example, in [26], [27], and [30]. In this paper, we proposed the CLSP to retain the maximum throughput in the optical CDMA networks. Based on the CLSP scheme presented in [26], [27], and [30], Fig. 4 illustrates the flow chart of CLSP, where U is the number of access attempts and the $U_{\rm max}$ is maximum number of access attempts. After an increment of U, if U is less or equal to the $U_{\rm max}$, the user continues to monitor the channel load. On the contrary, the user will discard the packet. Once the monitored channel load is less than a specific threshold

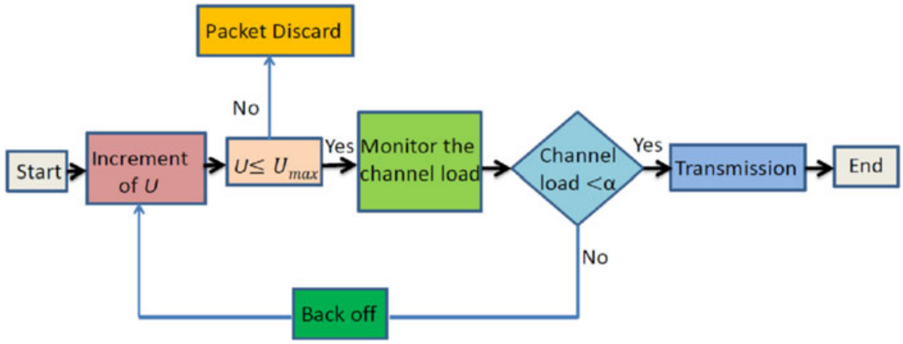

Fig. 4. Flow chart of a user with CLSP scheme.

α, the packet will be transmitted. Otherwise, the packet will be rejected and back off. In such scheme, the number of transmitting packets is perpetually less than or equal to threshold α. The optimum threshold will maintain the maximum throughput in optical CDMA networks that can be found using the queuing analysis results in the next section.

3. System Performance Analysis

As the CDMA system can allow simultaneous transmission and reception of random access packets, the analytical approaches of unsoltted ALOHA with using M/D/∞ queuing model were presented [26], [27]. However, an accurate fashion was developed by M/M/∞ queuing model, which had been proven that it was more precise and compact than that of M/D/∞ queuing model [28], [29]. In this paper, we utilize the M/M/∞ queuing model to analyze the throughput of asynchronous optical CDMA network with CLSP.

It is assumed that there are $(k+1)$ users transmitting packets in the optical network simultaneously and asynchronously. For a specific desired user, the MAI results from other k interferers, which will give rise to j interfering optical pulses hitting on the weight distribution in the desired signature sequence. After optical hard-limiter, the correlator will correlate the clipped optical pulses, and then the correlated optical signal is fed into photodiode for photodetection. Under Gaussian approximation, the mean and variance of the photodetected signal for bit 1 and 0 can be expressed, respectively, as [13], [31]

$$\mu_{j1} = wP_d;\ \ \sigma_{j1}^2 = \sigma_{th}^2 + \sigma_{sh_1}^2 + \sigma_{RIN_1}^2 \tag{2}$$

and

$$\mu_{j0} = \overline{|\beta_j|}P_c;\ \ \sigma_{j0}^2 = \sigma_{th}^2 + \sigma_{sh_0}^2 + \sigma_{RIN_0}^2 \tag{3}$$

where P_d and P_c are the chip level power in the photodiode of the desired user and interferer, respectively, $\overline{|\beta_j|}$ is the correlator output, and w is the code weight. The variances of thermal noise, shot noise, and relative intensity noise (RIN) are given, respectively, as [13], [31]

$$\sigma_{th}^2 = 4K_B T B_e / R_L \tag{4}$$

$$\sigma_{sh_1}^2 = 2q\,(wP_d)\,B_e \tag{5}$$

$$\sigma_{RIN_1}^2 = RIN\,(wP_d)^2 B_e \tag{6}$$

$$\sigma_{sh_0}^2 = 2q\left(\overline{|\beta_j|}P_c\right)B_e \tag{7}$$

$$\sigma_{RIN_0}^2 = RIN\left(\overline{|\beta_j|}P_c\right)^2 B_e \tag{8}$$

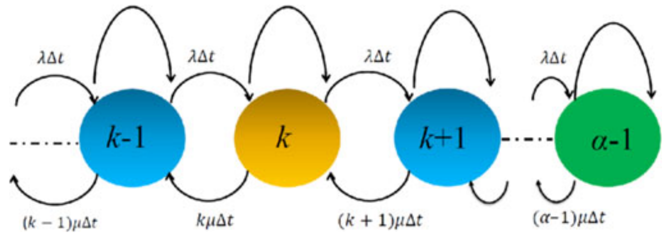

Fig. 5. State transition diagram based on M/M/∞ queuing model with CLSP scheme.

where K_B is the Boltzman's constant, T is the absolute temperature, R_L is the receiver load resistance, B_e is the receiver's electrical bandwidth, and q is the electron charge.

Since the OOK modulation is utilized, only bit 1 is encoded into signature sequence. In addition, the average hit probability from interferer is $h_{av} = w/N$ [13], [14]. If each user transmits data with equal probability, the average bit error rate under k interferers can be represented as [13], [14], [31]

$$P_b(k) = \sum_{i=0}^{k} \binom{k}{i} 2^{-k} \times \sum_{j=1}^{i} \binom{i}{j} (h_{av})^j (1 - h_{av})^{i-j} \times \frac{1}{2} [P(\varepsilon/1) + P(\varepsilon/0)] \tag{9}$$

where

$$P(\varepsilon/1) = Q\left(\frac{wP_d - wP_dD}{\sqrt{\sigma_{th}^2 + \sigma_{sh_1}^2 + \sigma_{RIN_1}^2}}\right),$$

and

$$P(\varepsilon/0) = \sum_{\beta_j \in G_j} NDP(\beta_j) MPD(\beta_j; G_j) \times Q\left(\frac{wP_dD - |\overline{\beta_j}| P_c}{\sqrt{\sigma_{th}^2 + \sigma_{sh_0}^2 + \sigma_{RIN_0}^2}}\right).$$

As the Reed-Solomon code is utilized in the proposed system, the average bit error rate after decoding can be represented as [23], [24]

$$P_{RS}(k) = \frac{1}{n}\left(\frac{2^{m-1}}{2^m - 1}\right) \sum_{i=t+1}^{n} i \binom{n}{i} P_s{}^i (1 - P_s{}^i)^{n-i} \tag{10}$$

where $P_s = 1 - (1 - P_b(k))^m$ is the symbol error rate, m is the number of bits in each symbol (in our case $m = 8$), t is the error correction capability (in our case $t = 8$), and n is the block length.

In optical CDMA system, each user can transmit packet data simultaneously and asynchronously. The unslotted ALOHA (i.e., pure ALOHA) is a preferable manner to describe such random access scheme [11], [12]. Since the optical CDMA network can support random access traffic, the CLSP is a better scheme to maintain the maximum throughput. In the case of heavy load, the serious MAI will greatly deteriorate system performance, and the probability of packet success in MAC layer will be drastically decreased. Thus, the throughput will also be reduced. With using CLSP, the maximum number of allowable active users is limited on the specific threshold, and this can effectively prevent from the serious impact of MAI.

Based on the M/M/∞ queuing model [28], [29], Fig. 5 illustrates the state transition diagram. The threshold α is the maximum number of allowable active users. Without using CLSP, the threshold is infinity. The number of interfering packets k represents the state in the transition diagram. The interference level over one bit interval Δt is assumed to be constant. The packet length T_p consists of L bits (i.e., $T_p = L \times \Delta t$). Each packet has independent identically distributed (iid) exponential service duration, whose arrival and death rate are $\lambda = G/T_p$ and $\mu = 1/T_p$, respectively. The G is offered load.

During one bit interval, the interfering packets may increase, decrease, or remain. Therefore, if there are k interfering packets at the i-th bit in a desired packet, there will be possible k-1, k, or $k+1$ interfering packets at the (i-1)-th bit. This can be referred to Fig. 5. To calculate the probability of packet success, the probability $P_c(k, i)$ is defined as the state transition over a bit duration Δt, which can be calculated recursively as [28]

$$\begin{aligned} P_c(k, i) = {} & P_c(k, i-1) \times (1 - \mu \cdot k \cdot \Delta t - \lambda \Delta t) \times (1 - P_{RS}(k)) \\ & + P_c(k+1, i-1) \times (\mu \cdot (k+1) \cdot \Delta t) \times (1 - P_{RS}(k+1)) \\ & + P_c(k-1, i-1) \times (\lambda \Delta t) \times (1 - P_{RS}(k-1)) \end{aligned} \tag{11}$$

and the initial condition is given as

$$P_c(k, i = 1) = \frac{(\lambda/\mu)^k}{k!} \times \exp(-\lambda/\mu), k = 0, 1, 2, \ldots.$$

Hence, the probability of packet success and throughput can be represented, respectively, as

$$Q_s = \sum_{k=0}^{\infty} P_c(k, L) \times (1 - P_{RS}(k)) \tag{12}$$

$$\Omega = G \times Q_s \times R \tag{13}$$

where R is the code rate of Reed-Solomon code.

Once the CLSP scheme is applied, the packet transmission will be rejected when the channel load is higher than the threshold α. The number of active users is always less than or equal to threshold α. To analyze the throughput with using CLSP scheme, the average offered load based on truncated Poisson distribution is defined as [26], [30]

$$G_{sys} = \frac{\sum_{k=0}^{\alpha} k \times P_c(k, i = 1)}{\sum_{k=0}^{\alpha} P_c(k, i = 1)} = \frac{\sum_{k=0}^{\alpha} k \times \frac{G^k}{k!}}{\sum_{k=0}^{\alpha} \frac{G^k}{k!}}. \tag{14}$$

The average offered load represents the rate of packet transmission. Under the number of interfering packets k less than threshold α, the state transition probability of i-th bit in a packet over one bit duration Δt can be expressed recursively as

$$\begin{aligned} P_{sc}(k \le \alpha - 1, i) = {} & P_{sc}(k, i-1) \times (1 - \mu \cdot k \cdot \Delta t - \lambda \Delta t) \times (1 - P_{RS}(k)) \\ & + P_{sc}(k+1, i-1) \times (\mu \cdot k \cdot \Delta t) \times (1 - P_{RS}(k+1)) \\ & + P_{sc}(k-1, i-1) \times (\lambda \Delta t) \times (1 - P_{RS}(k-1)) \end{aligned} \tag{15}$$

and the initial condition is given as

$$P_{sc}(k \le \alpha - 1, i = 1) = \frac{P_c(k, i = 1)}{\sum_{k=0}^{\alpha-1} P_c(k, i = 1)} = \frac{\frac{G^k}{k!}}{\sum_{k=0}^{\alpha-1} \frac{G^k}{k!}}$$
$$k = 0, 1, 2, \ldots \alpha - 1.$$

Thus, the probability of packet success and throughput can be represented, respectively, as

$$Q_{sc} = \sum_{k=0}^{\alpha-1} P_{sc}(k, L) \times (1 - P_{RS}(k)) \tag{16}$$

$$\Omega_s = G_{sys} \times Q_{sc} \times R. \tag{17}$$

4. Numerical Results and Discussions

In this paper, countermeasures against channel impairment in physical and MAC layer are proposed, which can greatly enhance the probability of packet success. To increase the throughput, it is

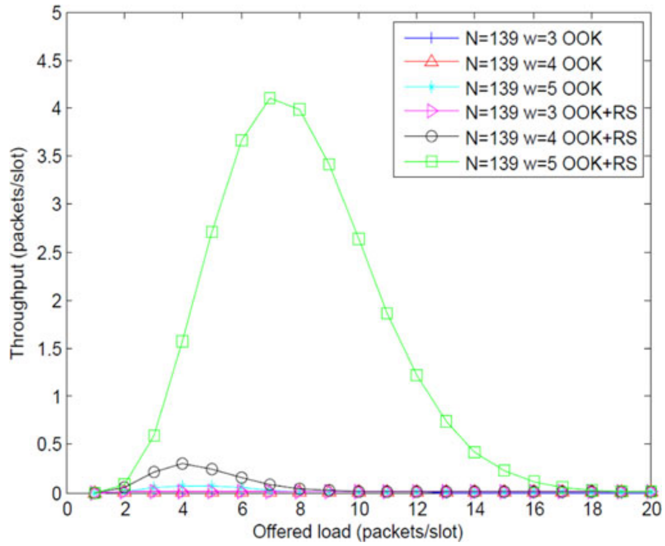

Fig. 6. Throughput versus offered load under OOK and OOK + RS schemes with code length $N = 139$ for code weight $w = 3$, 4, and 5.

expected that more active users can be accommodated in the network. However, once the number of active users is so large, the MAI will considerably make system performance worse. Accordingly, the throughput will be decreased. The CLSP is an effective manner to mitigate such problem as well as to avoid drastic throughput reduction during the conditions of heavy traffic load. In addition, the CLSP can reach a throughput aggregate capacity above 100 Gb/s, which is compatible with the IEEE 802.3 ba recommendation and a prospective scheme for broadband optical access networks. The configuration of optical CDMA network depends on the topographic features. The more flexible infrastructure can make network deployment easily accomplished; therefore the network topology may be ring, bus or hybrid [1]–[3]. The link parameters are given as follows (unless otherwise specified). The data rate for each user is 622.08 Mb/s (i.e., STM-4), $RIN = -150$ dB/Hz, and $P_d = P_c = -44$ dBw. The packet length L is 13 384 bits and 14 280 bits for uncoding and RS coding, respectively. The decision threshold D is 0.5 and 0.9 for OOK and OOK with OHL, respectively [13], [31]. Since the cardinality of carrier-hopping prime code is equal to code length N, the number of users is N when in numerical calculations. Once the CLSP scheme is applied, the number of users is α (i.e. the threshold of CLSP). The traffic pattern is Poisson traffic model.

Figs. 6 and 7 illustrate the throughput performance versus offered load under different schemes (OOK, OOK + RS, OOK + OHL, and proposed (i.e., OOK + OHL + RS)) with code length $N = 139$ for code weight $w = 3$, 4, and 5, respectively. First of all, we can observe that the larger code weight possesses higher autocorrelation peak, which can be more robust against MAI. Hence, the better performance can be obtained. In addition, the optical hard-limiter is an effective countermeasure to relieve the harmful impact of MAI and beat noise, which the channel impairment can be diminished significantly. Once the channel condition is greatly improved, the throughput is highly enhanced. It is expected to obtain higher throughput by increasing the offered load. However, when the offered load is increased to a certain extent, the throughput will be decreased drastically. This is the fact that severe MAI brings about the poor channel condition, which makes the probability of packet success reduced. Therefore, it is necessary to limit the offered load on the specific level to maintain the maximum throughput in the optical network.

In Fig. 8, we illustrate the throughput performance versus offered load under OOK+OHL and proposed scheme with code weight $w = 4$ for code length $N = 107$, 127, and 139, respectively. Since the system employs OOK modulation, each user transmits data bit 1 and may interfere on other active users' sequences. As the average hit probability is $h_{av} = w/N$, increasing the code

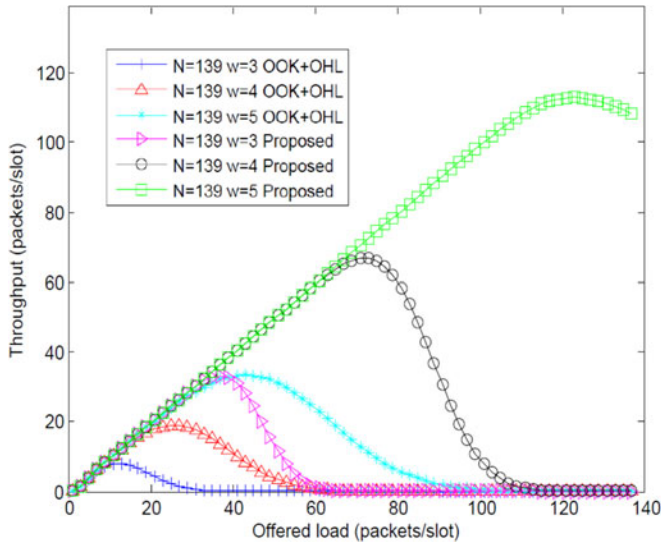

Fig. 7. Throughput versus offered load under OOK + OHL and proposed schemes with code length $N = 139$ for code weight $w = 3$, 4, and 5.

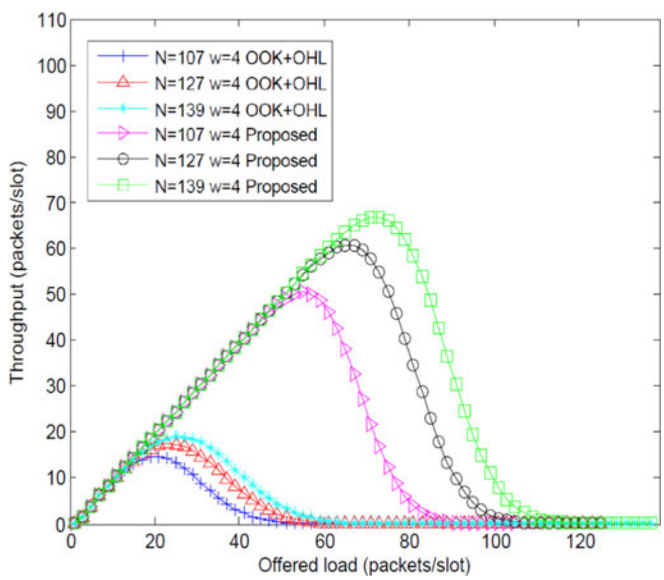

Fig. 8. Throughput versus offered load under OOK + OHL and proposed scheme with code weight $w = 4$ for code length $N = 107$, 127, and 139.

length of signature sequence can further reduce the detrimental effect of MAI. Consequently, the channel condition will be improved and system performance can be enhanced. Under fixed data rate, to increase the code length will also make the chip rate faster; this will lead to more strict requirement in optical spreading and detection [1], [3]. Therefore, it is important to take account of the limitation of chip rate with using appropriate code length.

From Figs. 6 to 8, it is obvious that the throughput will be decreased significantly when in heavy load. In the proposed CLSP scheme, the maximum number of allowable active users is limited on the specific threshold α. In the case of heavy load, the larger threshold α will incur larger amount of MAI that will lead to throughput decreasing. On the other hand, the smaller threshold α suffers

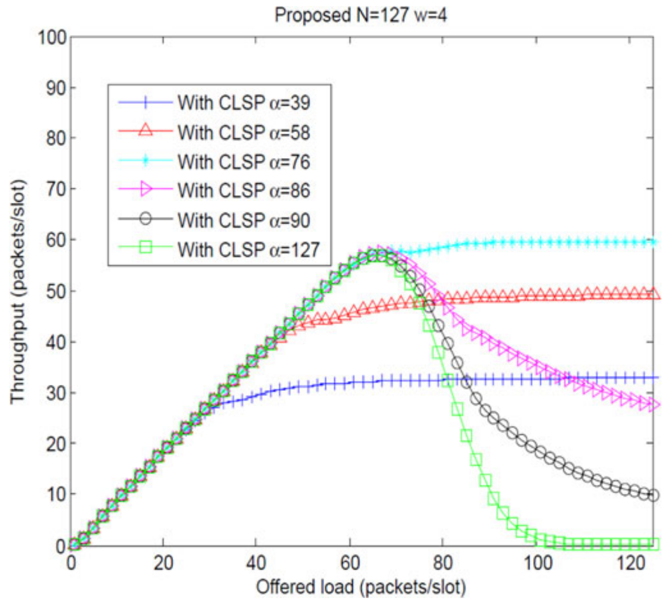

Fig. 9. Proposed scheme with CLSP for code length $N = 127$ and code weight $w = 4$.

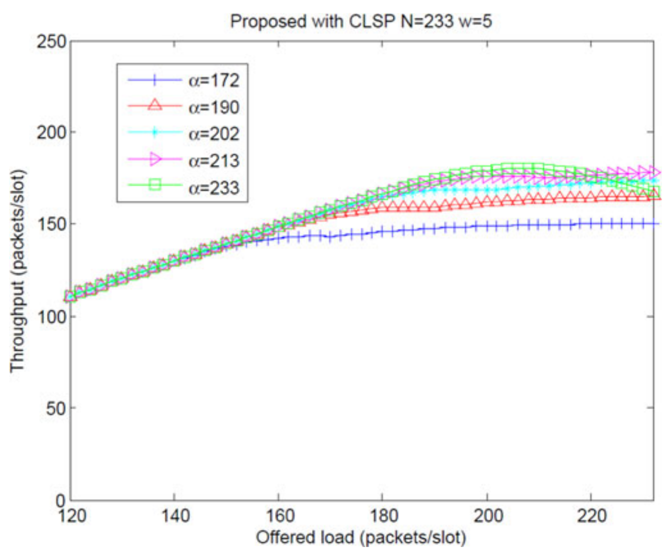

Fig. 10. Proposed scheme with CLSP for code length $N = 233$ and code weight $w = 5$; to reach the expected throughput, the threshold α has to be properly selected.

less impact of MAI, whereas only fewer active users can be accommodated in the network that will constrain the throughput. We set different values of threshold α (from small to high) to calculate their corresponding throughput performances. Step by step, we can find the optimum one. Fig. 9 demonstrates some of our working results, where code length N is 127 and code weight w is 4. When the offered load is small (i.e. less MAI), throughputs are the same for different values of threshold α. While in the case of heavy load, if the value of threshold α is so large, the throughput is similar to that of without using CLSP scheme. Instead, if the value of threshold α is small, only some limited active users can be accommodated in the optical network. Thus, the throughput will be restricted. Therefore, it is necessary to select a proper threshold that can maintain the maximum throughput when in heavy load. In this case, the value of threshold $\alpha = 76$ is an optimum one that can reach the maximum throughput about 60.

With the rapid increase of broadband services, it is indispensable to deploy broadband optical access network as platform to converge the heterogeneous traffic from wireless or wired system. It is expected that the throughput of broadband optical access network is potential to support 100 Gb/s. For example, IEEE 802.3 ba recommends aggregate capacity of 40 or 100 Gb/s EPON in LAN or MAN utilizing wavelength division multiplexed lanes on single mode fiber. Furthermore, it is necessary to allocate the adequate nodes that can accommodate more users in the network. To reach the throughput above 100 Gb/s in the proposed optical CDMA network, Fig. 10 demonstrates our proposed scheme with CLSP for code length $N = 233$ and code weight $w = 5$. Since the data rate for each user is 622.08 Mb/s and RS(255, 239) is utilized, the code rate of RS(255, 239) (i.e., redundant bits) should be taken into consideration. Therefore, the throughput is at least 172 that can reach the aggregate capacity above 100 Gb/s. We can observe that the threshold $\alpha = 202$ can fulfill such requirement. Once the threshold is too large, the throughput will be decreased accordingly. Therefore, to reach the expected throughput the threshold α has to be properly selected.

5. Concluding Remarks

In this paper, we propose CLSP scheme for throughput enhancement of fully random access optical CDMA networks, especially at high traffic load. In such networks, the highly desirable feature of asynchronous transmission can allow each user transmitting data packet at any time. Based on M/M/∞ queuing model, we employ queuing analysis results to evaluate the throughput performance under different CLSP thresholds. Numerical results show that the throughput performance of networks under optimum threshold is substantially better than those under non-optimum thresholds with OHL and FEC. With using the optimum threshold, the maximum throughput can be maintained. Our proposed scheme can reach the throughput above 100 Gb/s, which is a promising platform for broadband optical access networks.

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