Performance comparison between S-ALOHA and R^3T protocols for multirate OFFH-CDMA systems in optical packet networks

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We discuss two newly proposed multiple-access control (MAC) protocols for multirate optical code-division multiple access (OCDMA) networks. The first protocol is slotted ALOHA/optical fast-frequency-hopping code-division multiple access (S-ALOHA/OFFH-CDMA), and the second is round-robin receiver–transmitter/optical fast-frequency-hopping code-division multiple access (R^3/OFFH-CDMA). Our main subject is to exploit the potential of the optical fast-frequency-hopping CDMA using a fiber Bragg grating when jointly used with two different MAC protocols in a link layer as an effective way of integrating multirate traffic. The system throughput and the average packet delay are compared for both systems. It is shown that S-ALOHA is better than R^3T when the user's activity and the offered load are high, whereas R^3T is better for smaller values. Both protocols can be competitive in terms of the system throughput, with the advantage going to the R^3T protocol at a moderate offered load. However, the R^3T protocol suffers a higher delay mainly because of the presence of additional modes. Finally, the overlapped OCDMA system always outperforms the variable processing gain (VPG) OCDMA system regardless of the protocol used. © 2006 Optical Society of America

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1. Introduction

Asynchronous optical code-division multiple access (OCDMA) has received more interest recently [1–3] due to its excess bandwidth, which offers to serve the ever-increasing network dimensions, especially in the presence of diverse multimedia traffic in today's communication systems. This, in turn, requires a more complex control mechanism to handle the flow of information in such a network [4]. In fact, when the number of transmitting terminals exceeds the link capacity, part of the data will be lost on its way to the destination and part will be received incorrectly. One way to resolve these contentions is to impose certain rules on the transmission and the reception of information packets in the vulnerable period, and this is usually performed at the link layer of the optical network [4–6]. We refer to such control mechanisms as multiple-access control (MAC) protocols.

Two MAC protocols, namely, slotted ALOHA (S-ALOHA) [4,5,7] and round-robin receiver–transmitter (R^3T) [8], have recently been proposed and analyzed for OCDMA systems in optical packet networks. Our objective is to compare the performance of two multirate optical fast-frequency-hopping code-division multiple-access (OFFH-CDMA) systems controlled at the link layer by the proposed protocols. These two mul-

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tirate systems are the variable processing gain (VPG) OCDMA [9] and the overlapped OCDMA [10] systems.

This paper is organized as follows. Section 2 introduces the system model for both protocols. The packet correct probability is derived in Section 3. Section 4 presents the performance evaluation of the two protocols in terms of the throughput and the average packet delay. Numerical results are covered in Section 5. Finally, concluding remarks end the paper in Section 6.

2. System Model

Consider the OFFH-CDMA communication network proposed in Refs. [9] and [10], where K users are exploiting this network in a star topology. This system makes use of fiber Bragg gratings (FBGs) that passively and temporally slice the incoming pulse to perform the encoding and decoding operations for each terminal user. The round-trip time between two consecutive gratings determines the chip duration T_c and the number of gratings G, with the chip duration determining the nominal bit duration $T_n = GT_c$. Consequently, the nominal transmission rate is defined as $R_n = 1/T_n$. Based on this, each user is assigned a unique code by means of the frequency-shifted version (FSV) proposed in Ref. [9]. We assume in this architecture that each user is equipped with a fixed transmitter and a tunable receiver (FTTR).

In a slotted optical packet network, the time is virtually partitioned into equal intervals, called slots, so that each user initiates his transmission at the beginning of the time slot during which up to K users can transmit up to K packets. We assume that the slot duration equals the length of the packet, i.e., $T_p = LGT_c$, where L designates the number of bits per packet.

2.A. S-ALOHA/OFFH-CDMA

The S-ALOHA/OFFH-CDMA had been analyzed in detail in Ref. [7]. Initially, the system is empty and users generate ξ_o new packets with probability P_o. Transmitted over the optical channel, some packets will be received correctly with a probability P_c and some will be received in error due to collision and multiple-access-interference (MAI) as illustrated in Fig. 1. The terminal whose packets are incorrectly received is backlogged, and it retransmits the packets after a random delay with a probability P_r. Each backlogged terminal utilizes an electronic buffer to store the blocked packets, and it cannot generate new packets until all the backlogged packets are correctly retransmitted. When a backlogged packet is retransmitted, it leaves out the electronic buffer to be optically modulated and transmitted over the optical channel. At the next time slot, the arrivals are composed of ξ_o new packets and ξ_r retransmitted packets. In general, the composite arrivals are modeled as a Markov chain of three states representing three modes: origination mode (O), transmission mode (T), and backlogged mode (B). Each user can be in one of the three modes at a time as described in Fig. 2.

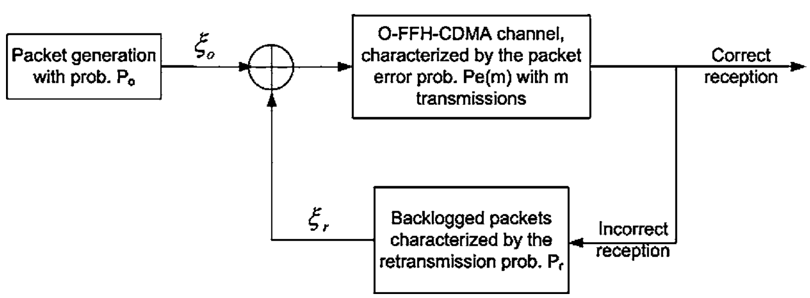

Fig. 1. Optical S-ALOHA/OFFH-CDMA system model.

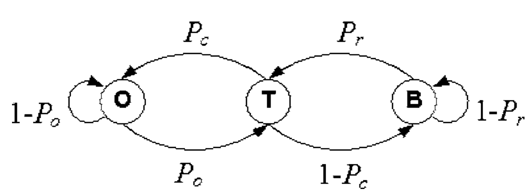

Fig. 2. Traffic model.

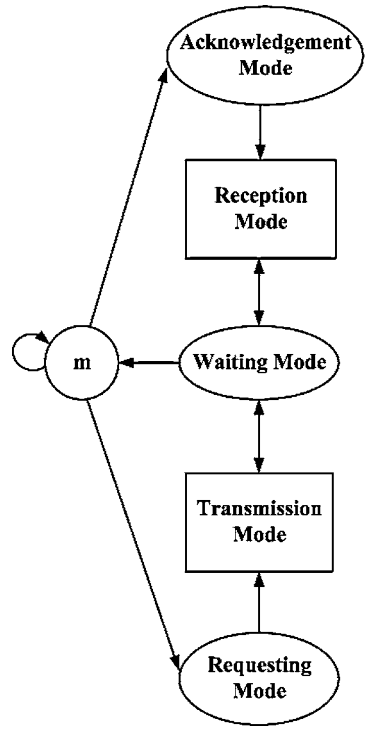

Fig. 3. Block diagram of the R^3T protocol.

2.B. R^3T/OFFH-CDMA

Besides the S-ALOHA protocol, we attempt to control the packet flow of users using the R^3T protocol [8]. We assume that a packet corresponds to one bit and L bits form a message so that the message length is equal to the packet length in S-ALOHA. Each user transmits his message with a probability A, called the user's activity. This message is stored in a single electronic buffer, freed once the message is sent correctly. Any message that arrives concurrently at a nonempty buffer will be discarded. The terminal behavior is described by the block diagram shown in Fig. 3. The user wishing to transmit his packets sends a request to the destination station at first, and therefore he is in the requesting mode. The receiver of the destination station scans across all codes in a round-robin fashion, switches to the desired code signature at the next time slot, and sends acknowledgements to the transmitting station to proceed on its transmission. At this time, the receiving station enters the reception mode.

Before the time-out duration τ_o expires, if the transmitting station receives the acknowledgement, it enters the transmission mode and transmits the first t packets following the go-back-n protocol [8], where $n=t$ is the two-way propagation time in slots between the transmitting and receiving stations. It can be $t \leqslant L$ or $t \geqslant L$. It then enters the waiting mode, waiting for acknowledgements. If there are no acknowledgements after the time-out duration, the station retransmits its last t packets in a round-robin fashion as well. Once the message is received correctly and the station has nothing to transmit, it returns to its initial state m.

At the reception side, once a packet is received correctly, an acknowledgement is being sent. Otherwise, the receiving station sends an ask-for-retransmission to the transmitting station and enters the waiting mode. If there is a message arrival and there is no request, then the receiving station asks the transmitting one for a connection request. If the latter does not respond, the receiving station returns to its initial state m.

3. Packet Correct Probability

In this paper we consider that all users employ an ON–OFF keying (OOK) modulation scheme to transmit their data. In addition, the bit error rate (BER) is obtained from simulation using the extended hyperbolic congruential codes (EHC) [11], and it is given by P_b.

3.A. VPG OFFH-CDMA

Assume a fixed packet time duration of $T_p=LT_n=LGT_c$, where L is the nominal packet length. In the VPG OFFH-CDMA system, the variable transmission rate is accomplished by varying the processing gain G_V in such a way that increasing the transmission rate by a factor of $\alpha \geqslant 1$ allows the reduction of the spreading factor by the same amount $G_V=G/\alpha$ [7]. The bit rate in this case is given by

$$R_s = \alpha R_n \text{ (bits/s)} . \tag{1}$$

In a packet network, $X_b^{(V)}=\lfloor \alpha L \rfloor$ bits are allocated in a time slot instead of L, as shown in Fig. 4, where $\lfloor x \rfloor$ is the highest integer less than x. Then, the new transmission rate becomes

$$R_s = \frac{X_b^{(V)}}{L} R_n \text{ (bits/s)} . \tag{2}$$

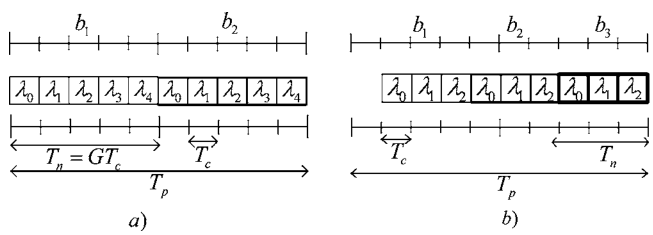

Fig. 4. Optical VPG-OFFH-CDMA packet model of a single user in a given packet time slot: (a) $G_V=5$, (b) .$G_V=3$.

In Fig. 4(a), we present a case study in which $G_V=5$ and $L=2$, which means that the nominal rate is two bits per packet. On the other hand, in Fig. 4(b), we have decreased the processing gain (PG) to $G_V=3$ (which means $\alpha=5/3$) to increase the transmission rate to three bits per packet. In this figure λ_i denotes the transmitted wavelength at the ith chip position.

Because the interference is counted at every bit position i, $P_b(i)$ may differ at each bit position. However, in a VPG system $P_b(i)$ is the same for all i. Therefore, the packet correct probability can be written as

$$P_c(K) = [1 - P_b(i)]^{X_b^{(V)}} . \tag{3}$$

3.B. Overlapped OFFH-CDMA

In Ref. [10], we showed that, due to the linearity of the encoder–decoder set and when the data rate increases beyond R_n, multibits will be coded and transmitted. This process is revealed in Fig. 5. At the receiver end, the decoder observes practically multiple codes, which are delayed according to the transmission rate of the source.

Accordingly, in the overlapped OFFH-CDMA, to increase the number of bits per packet of fixed length L, we increase the source transmission rate above the nominal rate without decreasing the PG as in the previous system. When a terminal transmits at a rate of $R_s > R_n$, it introduces a bit overlap coefficient ε_s, which represents the number of overlapping chips between two consecutive bits [7]. Accordingly the new bit rate is related to R_n by the following equation:

$$R_s = \frac{G}{G - \varepsilon_s} R_n . \tag{4}$$

Let ε_s be the overlapping coefficient and $X_b^{(O)}$ be the total number of overlapped bits in a packet time slot. For an overlapped packet to be complete for transmission, the following inequality must be satisfied:

$$\varepsilon_s + \underbrace{(G - \varepsilon_s) + \ldots + (G - \varepsilon_s)}_{X_b^{(O)} \, times} \leq LG \tag{5}$$

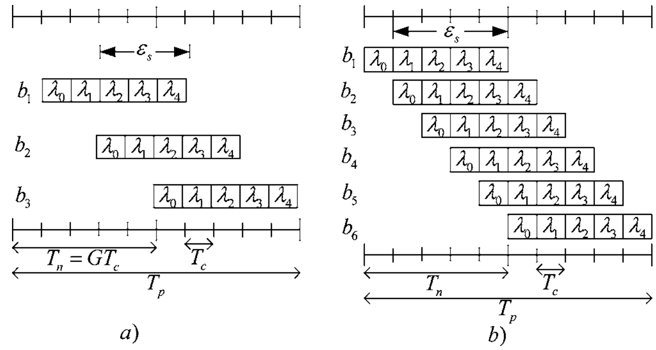

Fig. 5. Optical overlapped OFFH-CDMA packet model of a single user in a given time slot: (a) $\varepsilon_s=3$, (b) $\varepsilon_s=4$.

$$X_b^{(O)} \leqslant \frac{LG-\varepsilon_s}{G-\varepsilon_s} . \tag{6}$$

Thus,

$$X_b^{(O)} = \left\lfloor \frac{LG-\varepsilon_s}{G-\varepsilon_s} \right\rfloor . \tag{7}$$

Consequently, the rate in a packet network will be

$$R_s = \frac{X_b^{(O)}}{L} R_n \text{ (bits/s)} . \tag{8}$$

Figure 5 illustrates an example of the overlapping process in a packet time slot. In this example, the packet length is $L=2$, and the PG is $G=5$. If the transmission rate is the nominal rate, the packet format is as shown in Fig. 4(a), which means $\varepsilon_s=0$ and the transmission rate is two bits per packet. When the overlapped coefficient is increased to $\varepsilon_s=3$, as shown in Fig. 5(a), the transmission rate is increased to three bits per packet. On the other hand, Fig. 5(b) shows the case where $\varepsilon_s=4$. Accordingly, the transmission rate is six bits per packet.

The relationship between the reduction factor α of the time-slotted/VPG-FFH-CDMA system and the overlapping coefficient ε_s of the time-slotted/O-FFH-CDMA system can be easily obtained by equating Eqs. (2) and (8) to obtain

$$\alpha = \frac{G - \dfrac{\varepsilon_s}{L}}{G-\varepsilon_s} . \tag{9}$$

Since $P_b(i)$ differs at every bit position, the packet correct probability is given by

$$P_c(K) = \prod_{i=0}^{X_b^{(O)}-1} [1 - P_b(i)] . \tag{10}$$

4. Performance Evaluation

4.A. S-ALOHA/OFFH-CDMA

OCDMA throughput as obtained in Ref. [1] is the average number of successfully received S packets given that M packets are transmitted and K users are available in the system, and it is expressed by

$$\beta(K) = E\{S\} = E\{E\{S|M\}\} = E\left[\sum_{s=0}^{K} s \binom{M}{s} P_c^s (1-P_c)^{M-s} \right] . \tag{11}$$

The average offered traffic is composed of newly generated successfully transmitted packets and successfully retransmitted packets, and it is computed as

$$R = (K - \bar{n}) P_o + \bar{n} P_r . \tag{12}$$

The average packet delay is defined by Little's theorem as the average number of backlogged users over the system throughput as

$$D = \bar{n}/\beta. \tag{13}$$

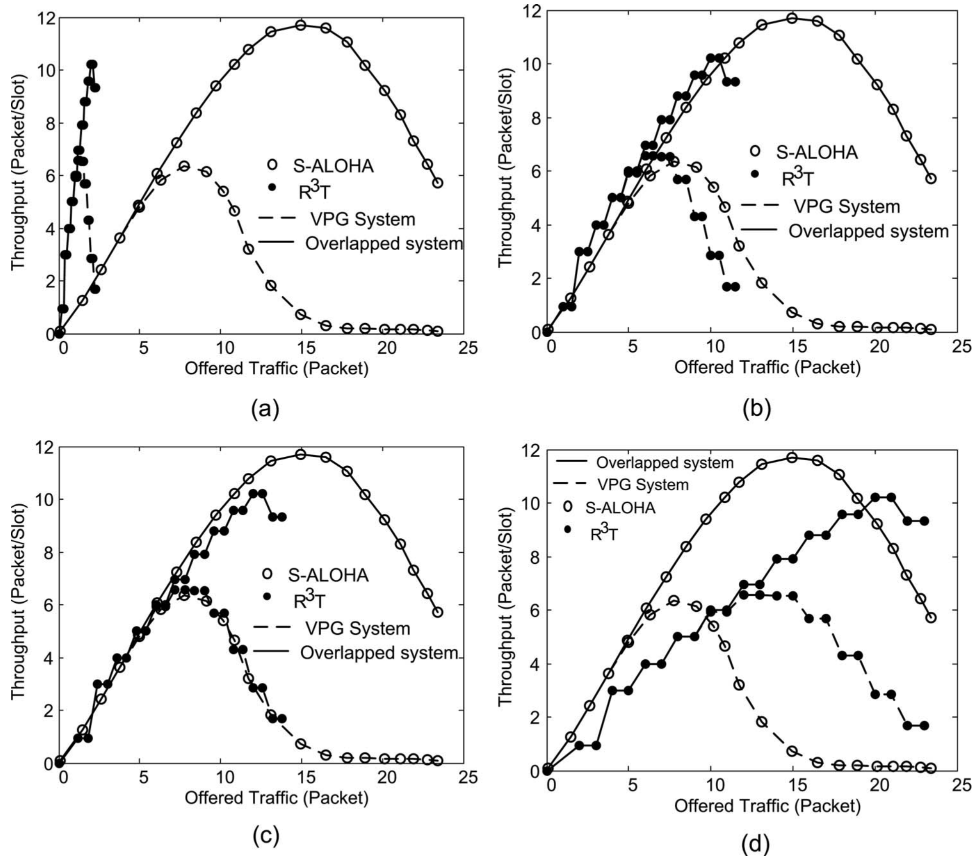

Fig. 6. Throughput versus offered traffic of the multirate systems under the two MAC protocols, S-ALOHA and R^3T, for a two-way propagation time of two time slots: (a) $A=0.1$, (b) $A=0.5$, (c) $A=0.6$, (d) $A=1$.

4.B. R^3T/OFFH-CDMA

The system throughput under R^3T is computed in Ref. [8] as

$$\beta(K,A,t,\tau_o,L) = \frac{P_c(K)Lr_o}{L+(1-P_c(K))(\min\{t,L\}-1)(L-\min\{t,L/2\})}, \tag{14}$$

where r_o can be obtained such that the following condition is satisfied:

$$K[L+(1-P_c(K))(\min\{t,L\}-1)(L-\min\{t,L/2\})] = r_o\left[2tL(1-P_c(r_o)) + (2t+2L-1)P_c(r_o) + \frac{P_c(r_o)}{\rho} + A(t-1)\frac{1-\rho}{\rho}P_c(r_o) + \left\{1-\left[1-\frac{\rho}{A(1-\rho)}\right]^{1/\tau_o}\right\}^{-1}P_c(r_o)\right],$$

where

$$\rho = \rho(r_o) = 0.5[\sqrt{u^2+4u}-u],$$

$$u = \frac{AP_c(r_o)\tau_o r_o}{K[L+(1-P_c(r_o))(\min\{t,L\}-1)(L-\min\{t,L/2\})]}. \tag{15}$$

The delay is given by

$$D = \frac{KA}{\beta(K,A,t,\tau_o,L)}, \tag{16}$$

where KA is the average offered traffic.

5. Results and Comparison

In this simulation we have assumed that the number of stations is $K=23$, the processing gain is $G=31$, the packet length under the S-ALOHA protocol is $L=300$ bits/time slot, and the message is one packet, whereas, equivalently, under the R^3T protocol, the packet length is one bit/time slot and $L=300$ designates the message length in the packets. Note that there is a correspondence between A and P_r. In S-ALOHA, when a terminal enters the backlogged mode, it cannot generate new packets until all the accumulated ones in the system's buffer are retransmitted. Consequently, the offered traffic varies according to the retransmission probability, P_r. Meanwhile, in R^3T, the terminal in the case of transmission failure retransmits the last unsuccessful t packets with the same transmission probability (user's activity) A, which varies the offered traffic. For S-ALOHA, we assume $P_r=0.9$, whereas for R^3T, we assume $A=0.1$, 0.5, 0.6, and 1; the time-out duration $\tau_o=1$ time slot and the two-way propagation delay $t=2$; and eight time slots in fiber lengths of 200 and 800 m, respectively. In addition, we consider that both multirate systems transmit at a normalized rate of $R_S=714$, which corresponds to an increase of the overlapping coefficient ε_s from 0 to 18 for the overlapped system and a reduction of the PG to 13 for the VPG system.

The throughput of both systems is presented in Figs. 6 and 7 for two-way propagation delays of two and eight time slots ($t=2$ and 8), respectively. Note that the propagation delay has remarkable influence on the throughput of the OCDMA systems. This is due to the degradation of the signal power over the long distance in the fiber, which yields the available offered traffic to be susceptible to the MAI.

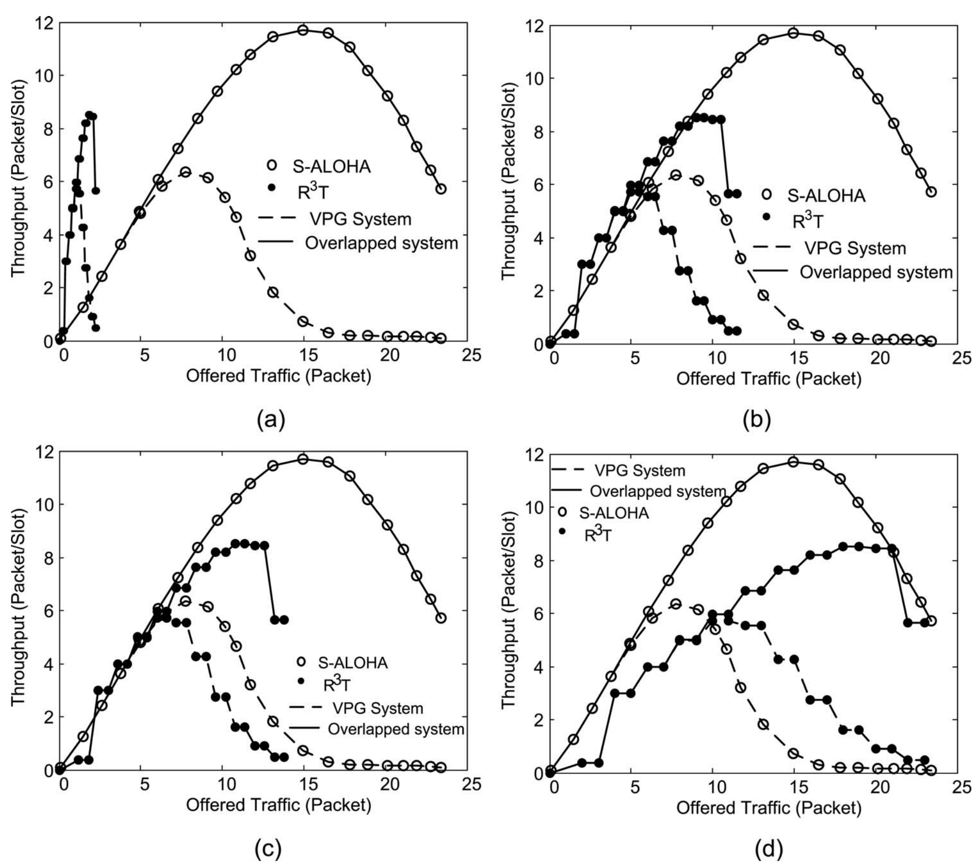

Fig. 7. Throughput versus offered traffic of the multirate systems under the two MAC protocols, S-ALOHA and R^3T, for a two-way propagation time of eight time slots: (a) $A=0.1$, (b) $A=0.5$, (c) $A=0.6$, (d) $A=1$.

In addition, for low offered traffic, we notice that in both cases the R^3T protocol exhibits higher throughput than the S-ALOHA protocol when the user's activity is $A < 0.6$, whereas the throughputs of both protocols match when $A=0.6$. It is clear that under the R^3T protocol the throughput curves of the overlapped system at a moderate transmission rate reach around 10.5 packets per slot and decrease to 8.5 for $t=2$ and 8, respectively; whereas those of the VPG system reach around 6 packets per slot, given that the maximum offered load is relative to A. This means that the R^3T protocol always ensures a successful transmission of its offered load when it is less than or equal to the maximum achievable throughput. In this case, this offered load is almost completely transmittable. As the offered load (KA) increases, at a certain level it exceeds the systems' capacities and becomes intolerable by such systems whose throughputs begin dropping off.

As A increases, the throughput of R^3T decreases compared to S-ALOHA. This is because more users are now transmitting and the offered traffic is increasing, which means that the MAI is intensifying. The packets facing such interference are susceptible to distortion, which, in turn, degrades the throughput. For $A=1$ all the users are transmitting at the same time, nevertheless the throughputs of both OCDMA systems undergoing R^3T are declining. This is because more users are now trying to transmit while other users are still busy transmitting their long messages, so that the interference significantly increases and any unsuccessful transmission is replaced by the retransmission of the last t packets and the optical channel is crowded by the retransmitted packets. This problem can be resolved in the S-ALOHA protocol by randomly delaying the distorted packets, which are then retransmitted with a probability P_r. By increasing this probability, the protocol gives higher priority to the retransmissions over the newly generated packets. In this way contention can be efficiently controlled and the throughput is optimized. On the other hand, for high offered traffic, the throughputs of R^3T decay faster than that of S-ALOHA, which means that R^3T has limited capacity. However, for a large value of A ($A=1$), the throughput of R^3T/VPG-OFFH-CDMA is better than that of S-ALOHA. This means that the VPG system undergoing R^3T can tolerate a higher load than when undergoing S-ALOHA. Also, under both protocols, the throughput of the overlapped system outperforms that of the VPG system.

In Figs. 8 and 9 we present the average packet delay versus the system throughput of both multirate OCDMA systems operating under the two mentioned protocols for $t=2$ and 8, respectively. We remark that the R^3T protocol exhibits higher delay, especially at low throughput even if the user's activity and the two-way propagation time are reduced as revealed by both figures. This significant delay is caused by two factors: the adoption of the go-back-n protocol for the retransmission of the distorted packets where $n=t$ and the signaling packets such as request, acknowledgement, and ask-for-retransmission, which, in the case of failure, place the system in the waiting mode for a period of time. Therefore, by minimizing the transmission activity of users ($A=0.1$) and the propagation time to $t=2$, the average system delay encountered by the R^3T when the throughput is low is still higher than that encountered by the S-ALOHA.

In addition, for both $t=2$ and 8, the average delay of the VPG system begins increasing as the throughput. This is because, as the load increases, the MAI level increases in the optical channel. Due to the reduction of the PG of the VPG system to $G_V=13$, the optical signal intensity of users gets reduced and it is unable to persist to the MAI. This in turn increases the likelihood of packet corruptions, and the erroneous packets will require a longer time to be successfully transmitted, whereas the delay of the overlapped system remains less affected as the traffic load increases since the PG is always preserved and hence so is the signal intensity. This makes the packets less susceptible to MAI and thus to failure. However, in the S-ALOHA/VPG-OFFH-CDMA system the delay is significantly increasing as the throughput increases because the excess load is not tolerable by the system; therefore, it is exposed to failure and equivalently to the retransmission.

By comparing the performance of both systems under both protocols, we notice that for low and moderate offered load, the S-ALOHA is better than the R^3T when A is high, whereas the R^3T is better when A is small. In addition, the throughputs of both protocols are matched when $A=0.6$. On the other hand, for high offered load, the S-ALOHA surpasses the R^3T. However, the VPG system under R^3T can provide

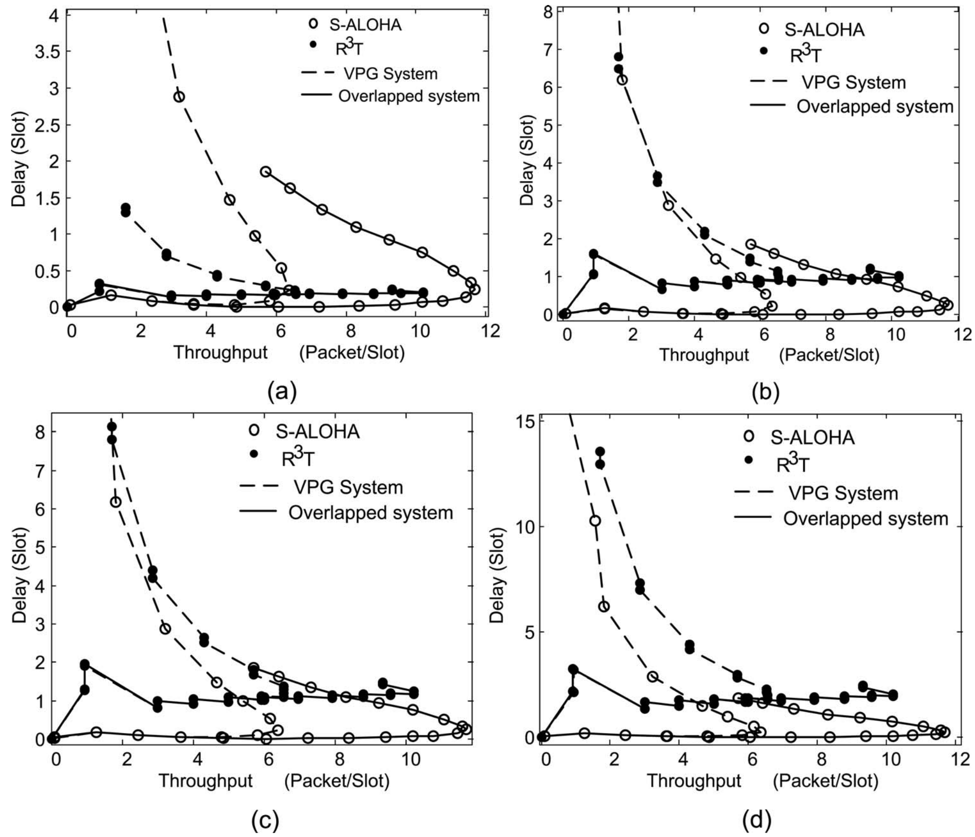

Fig. 8. Delay versus throughput of the multirate systems under the two MAC protocols, S-ALOHA and R^3T, for a two-way propagation time of two time slots: (a) $A=0.1$, (b) $A=0.5$, (c) $A=0.6$, (d) $A=1$.

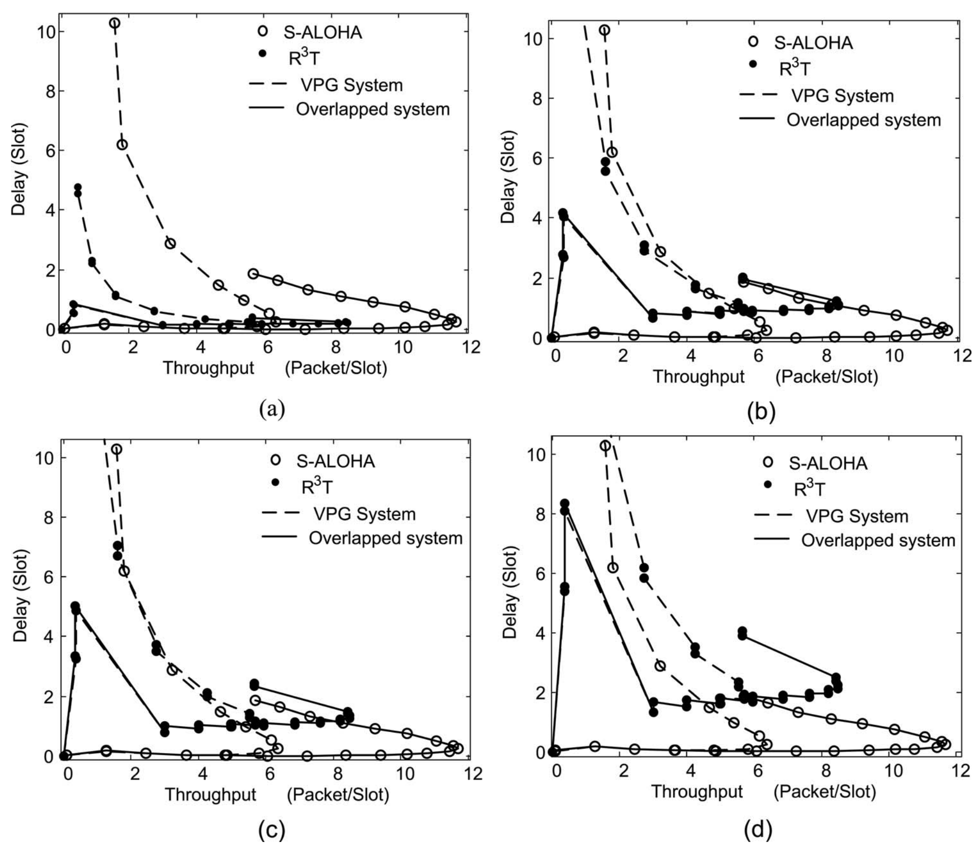

Fig. 9. Delay versus the throughput of the multirate systems under the two MAC protocols, S-ALOHA and R^3T, for a two-way propagation time of eight time slots: (a) $A=0.1$, (b) $A=0.5$, (c) $A=0.6$, (d) $A=1$.

improved performance over that under S-ALOHA when A is large and the offered load is relatively high. In addition, the S-ALOHA always outperforms the R^3T in terms of the average packet delay especially for large values of A.

6. Conclusion

A comparison of the performances of two multirate OCDMA systems under two different MAC protocols—the S-ALOHA and the R^3T—has been performed. It has been shown that the S-ALOHA is better than the R^3T when the user's activity A and the offered traffic are high, whereas the R^3T is better for smaller values of A and moderate traffic. In addition, both protocols can be competitive in terms of system throughput for moderate offered traffic by fitting the corresponding parameters to an appropriate setting. However, the R^3T protocol suffers a higher delay mainly because of the presence of additional modes (acknowledgement mode and requesting mode) that require a priority time setting for establishing a connection before data communication begins between the transmitting–receiving parties. Such modes are not available in S-ALOHA protocol. Finally, the overlapped OCDMA system always outperforms the VPG OCDMA system regardless of the protocol used.

References

1. S. Zahedi and J. A. Salehi, "Analytical comparison of various fiber-optic CDMA receiver structures," J. Lightwave Technol. **18**, 1718–1727 (2000).
2. A. Stok and E. H. Sargent, "Comparison of diverse optical CDMA codes using a normalized throughput metric," IEEE Commun. Lett. **7**, 242–244 (2003).
3. H. Ben Jaafar, S. LaRochelle, P.-Y. Cortes, and H. Fathallah, "1.25 Gbit/s transmission of optical FFH-OCDMA signals over 80 km with 16 users," in *Optical Fiber Communications Conference (OFC)*, Vol. 54 of OSA Trends in Optics and Photonics Series (Optical Society of America, 2001), pp. TuV3.1–TuV3.3.
4. P. Kamath, J. D. Touch, and A. J. Bannister, "The need for media access control in optical CDMA networks," in *Twenty-third Annual Joint Conference of the IEEE Computer and Communications Societies* (IEEE, 2004), pp. 2208–2219.
5. D. Raychauhuri, "Performance analysis of random access packet-switched code division multiple access systems," IEEE Trans. Commun. **COM-29**, 895–901 (1981).
6. C.-S. Hsu and V. O. K. Li, "Performance analysis of slotted fiber-optic code-division multiple-access (CDMA) packet networks," IEEE Trans. Commun. **45**, 819–828 (1997).
7. R. J. Raad, E. Inaty, P. Fortier, and H. M. H. Shalaby, "Optical S-ALOHA/CMDA system for multirate application: system architecture and performance evaluation," in *Global Communications Conference* (IEEE, 2005), pp. 1936–1941.
8. H. M. H. Shalaby, "Performance analysis of an optical CDMA random access protocol," J. Lightwave Technol. **22**, 1233–1241 (2004).
9. E. Inaty, H. M. H. Shalaby, and P. Fortier, "A new transmitter-receiver architecture for noncoherent multirate OFFH-CDMA system with optimal detection threshold," J. Lightwave Technol. **20**, 1885–1894 (2002).
10. E. Inaty, H. M. H. Shalaby, and P. Fortier, "On the cutoff rate of a multiclass OFFH-CDMA system," IEEE Trans. Commun. **53**, 323–334 (2005).
11. L. D. Wronski, R. Hossain, and A. Albicki, "Extended hyperbolic congruential frequency hop code: generation and bounds for cross- and auto-ambiguity function," IEEE Trans. Commun. **44**, 301–305 (1996).