A novel multipriority reservation protocol for plastic optical fiber access network

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In this paper, a novel multipriority reservation protocol for plastic optical fiber access network based on optical code division multiplexing access (OCDMA) technology is proposed. Conventional OCDMA system only allows finite units to transmit and access simultaneously according to the number of channels. The protocol is proposed to resolve this problem. By using the reservation scheme and a distributed arbitration algorithm, channel collision and destination conflict can be avoided. The protocol can efficiently support the transmission of multimedia messages that require the different time-delays. At the same time, each optical network unit is equipped with a fixed optical encoder/decoder that is always tuned to channel for control and the tunable optical encoder/decoder that is tuned to any of channel for data. The network throughput and average delay have been investigated by numerical analysis and simulation experiments. It is shown that the multipriority reservation protocol in this POF access network based on OCDMA technology is valid and efficient.

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Code-division multiplexing (CDM) is achieved by assigning different, minimally interfering code sequences to different user pairs. In this system, network units communicate by imprinting their message bits upon their own unique code, which they transmit asynchronously over a common channel. A matched filter at the receiver end ensures that data are detected only when they are imprinted on the proper code sequence. This approach to multi-access allows transmission without delay and handles multi-access interference as an integral part of the scheme. So code division multiplexing access (CDMA) is very suitable for multimedia access network, especially to real-time user pairs. Plastic optical fiber (POF) can offer high bandwidth[1], which can transmit data with high rate from 2.5 (polymethyl methacrylate based GI-POF) to > 10 Gb/s (perfluorinated polymer based GI-POF) over a 100-m-long distance[2]. As we know, the differential mode attenuation or mode coupling of POF makes the bandwidth much greater than that would be expected from their index profiles. In CDMA system, it must be afforded that the bandwidth is larger than that of signal being transmitted. So POF access network combined with CDMA gives us an effective solution to fiber to office (FTTO) or fiber to home (FTTH).

Optical access network comprises optical line terminal (OLT), optical distribute network (ODN) and optical network unit (ONU). A double star physical topology of OCDMA access network is shown in Fig. 1. In this access network, each ONU can make information exchange not only with any one at any time but also with more than one at the same time. To reach this aim, each ONU is equipped with a fixed optical encoder and a fixed optical decoder, also a tunable optical encoder and a tunable optical decoder. A multipriority reservation control

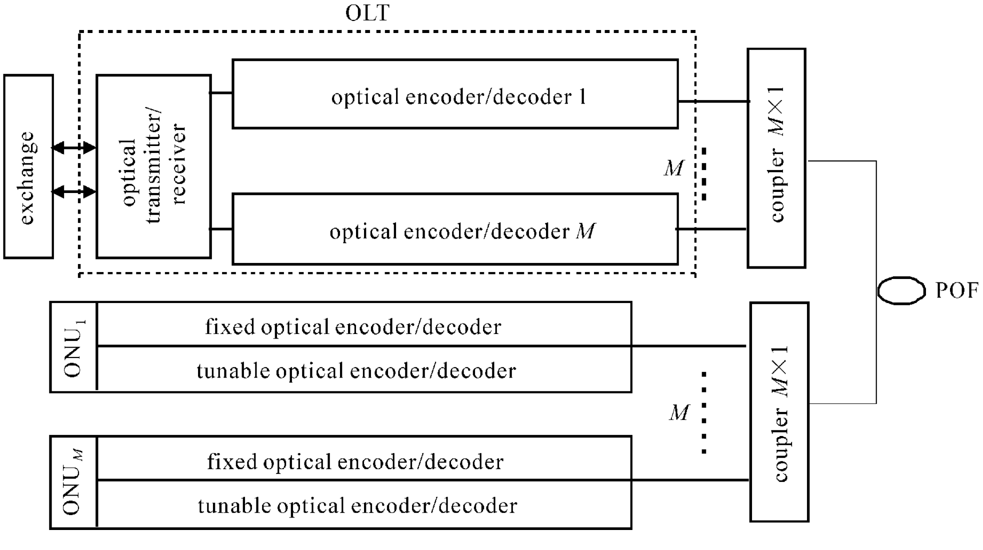

Fig. 1. The physical topology of OCDMA access network.

protocol that can efficiently support real-time multimedia communication is presented for the encoders and decoders to coordinate message transmission.

We assume that this POF access network, as shown in Fig. 2, possesses $(N+1)$ codewords and M ONUs $(M > N)$, each codewords operating with a different channel from the set $\{C_0, C_1, C_2, \cdots, C_N\}$. C_0 is used as a control channel for coordination of access among ONUs, and $\{C_1, C_2, \cdots, C_N\}$ are used as data channels for actual messages. All channels are slotted with the size of the transmission time of a fixed length data packet. One slot of the control channel is divided into L subslots, and the length of a control subslot equals the control packet transmission time. The control packet gives the information of the destination address and the priority of the data packet. The protocol operation is divided into two parts: reservation and data transmission. When a station has a packet to send, it performs reservation procedure first by sending a control packet on the control channel and then transmits the data packet on the data channel. We assume that the propagation delay from a station to the star coupler is zero. Therefore, if a station transmits a control packet in the Kth slot, it can obtain the result of the reservation at the end of the Kth slot, and if the reservation is successful, the station transmits the data packet in the $(K+1)$th slot.

In this protocol, the control slot has M subslots, where M represents the number of stations. Since each station has its corresponding control subslot, no collision occurs on the control slot. However, due to the limited number of channels and destination conflict, arbitration for selecting successful control packets is still needed. The algorithm of selecting successful control packets is as follows. Among the uncollided control packets, the successful ones are selected sequentially from the highest priority packets to the lowest priority ones. The scanning of the control slot always does not start from the fixed point in order to avoid that a station is more advantageous than the others. The scanning point can be obtained by the following rule. For each control slot, every station randomly selects an initial scanning point among the M control subslots. Each station has the same random number generator with the same seed. Consequently, they obtain the same initial scanning point for each control slot. Each station scans from the initial scanning point to the Mth control subslot and wraparound. If a control packet has the same destination address as the previously selected control packet, it is discarded to prevent destination conflict. The algorithm is completed when no more control packets are left or the number of selected control packets reaches that of data channels. The stations, whose control packets are successful, choose data channels sequentially from channel 1 through N in the order of their selection, and transmit data packets on the next slot. Figure 3 shows an example of the reservation algorithm of the slotted time-division multiplexing (TDM)-based protocol. In Fig. 3, priority 2 is higher than 1 and "blocking" control packet is the packet that fails due to the lack of available data channels. If the control packet is not successful, the station has to restart the reservation procedure on the next slot.

In the performance analysis of this POF access network, we make the following assumptions.

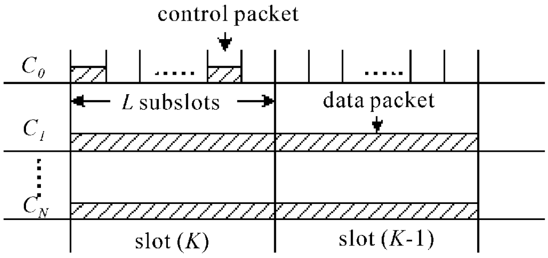

Fig. 2. Structure of control and data channels.

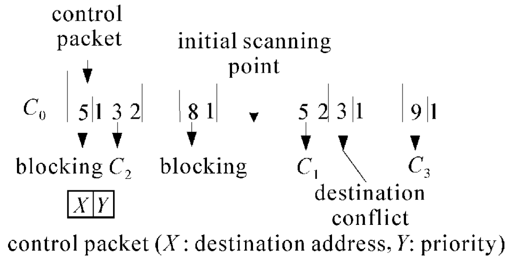

Fig. 3. Example of the reservation algorithm ($M = 10$, $N = 3$, $L = 10$, two priority traffics).

- The network can support m kinds of priority traffics, and 1-priority is the lowest priority; M_p is the number of the station that generate p-priority traffic, and $\sum_{p=1}^{m} M_p = M$.
- Each station belongs to either one of two states: empty or backlogged state. The empty station of priority p can generate a new packet with probability at the beginning of a slot, and a control packet is transmitted immediately. The backlogged station cannot generate a new packet but retransmits its old packet with probability 1. The new packet selects its destination address among $(M-1)$ stations with equal probability, and any backlogged station reselects the destination address of its packet.
- The tuning times of the tunable optical encoder/decoder are assumed to be zero.

With the assumptions stated above, we can construct a Markov chain by defining $X(i_1, i_2, \cdots, i_m)$ as the state where there are $\{1, 2, \cdots, m\}$ packets whose priorities are $1, 2, \cdots, m$-priority respectively in the network at the state transition probability from the state $X(i_1, i_2, \cdots, i_m)$ to $X(j_1, j_2, \cdots, j_m)$ during a slot time. We also define $\pi(i_1, i_2, \cdots, i_m)$ as the steady state probability of the state $X(i_1, i_2, \cdots, i_m)$, $\pi(i_1, i_2, \cdots, i_m)$ can be obtained by solving the linear equation

$$\begin{cases} \Pi = \Pi \cdot P \\ \sum\limits_{i_1, i_2, \cdots, i_m} \pi(i_1, i_2, \cdots, i_m) = 1 \end{cases}, \qquad (1)$$

where

$$\prod \triangleq \{\pi(i_1, i_2, \cdots, i_m)\},$$

$$P \triangleq \{P(j_1, j_2, \cdots, j_m / i_1, i_2, \cdots, i_m)\}.$$

To compute $P(j_1, j_2, \cdots, j_m / i_1, i_2, \cdots, i_m)$, we define several probabilities. Let $A_p(j/i)$ be the probability that

j new p-priority packets are generated at the beginning of a slot, given that there are i p-priority packets in the network at the end of the previous slot. Then $A_p(j/i)$ is given by

$$A_p(j/i) = C^j_{M_p-i} \cdot \sigma_p^j \cdot (1-\sigma_p)^{M_p-i-j}, \tag{2}$$

where $C^k_n = \frac{n!}{k!(n-k)!}$. Let $R(j/i, k_1)$ represent the probability that $(j-k_1)$ channels are reserved by the i uncollided control packets without destination conflict, given that k_1 channels are already reserved by the higher priority packets. To obtain $R(j/i, k_1)$, we define $\phi_M(k/i, k_1)$ as the probability of finding exactly k stations to which there are no packets destined among i packets, given that there are M stations in the system and k different destinations are already reserved by the higher priority packets. $\phi_M(k/i, k_1)$ can be calculated using the inclusion-exclusion principle[3] and is given by

$$\begin{aligned}&\phi_M(k/i, k_1)\\ &= \sum_{v=k}^{M-k_1} (-1)^{v-k} \begin{pmatrix} v \\ k \end{pmatrix} \begin{pmatrix} M-k_1 \\ v \end{pmatrix} \left(\frac{1-v}{M}\right)^i,\end{aligned} \tag{3}$$

where $\left(\frac{1-v}{M}\right)^i$ represents the probability that there is no packet destined to v specific stations among i packets, given that there are M stations. $R(j/i, k_1)$ is then given by

$$\begin{aligned}&R(j/i, k_1)\\ &= \begin{cases} \phi_M(M-j/i, k_1) & j < N \\ 1 - \sum\limits_{k=k_1}^{N-1} \phi_M(M-k/i, k_1) & j = N \end{cases}.\end{aligned} \tag{4}$$

Now $P(j_1, j_2, \cdots, j_m/i_1, i_2, \cdots, i_m)$ can be obtained by

$$\begin{aligned}&P(j_1, j_2, \cdots, j_m/i_1, i_2, \cdots, i_m)\\ &= \sum_{k_1=\max(0, i_1-j_1)}^{\min(i_1, N)} \sum_{k_2=\max(0, i_2-j_2)}^{\min(i_2, N-k_1)} \cdots \sum_{k_m=\max(0, i_m-j_m)}^{\min(i_m, N-\sum_{v=1}^{m-1} k_v)}\\ &\quad U(k_1, k_2, \cdots, k_m/i_1, i_2, \cdots, i_m)\\ &\quad \times A_1(j_1 - i_1 + k_1/i_1 - k_1)\\ &\quad \times A_2(j_2 - i_2 + k_2/i_2 - k_2) \times \cdots\\ &\quad \times A_m(j_m - i_m + k_m/i_m - k_m),\end{aligned} \tag{5}$$

where $U(k_1, k_2, \cdots, k_m/i_1, i_2, \cdots, i_m)$ is the probability that $\{k_1, k_2, \cdots, k_m\}$ control packets are successful, given that $\{i_1, i_2, \cdots, i_m\}$ control packets are transmitted in a slot.

Since there is no collision in the TDM scheme, the effect of destination conflict and insufficiency of data channels has only to be considered in the computation of $U(k_1, k_2, \cdots, k_m/i_1, i_2, \cdots, i_m)$, which can be obtained by

$$\begin{aligned}&U(k_1, k_2, \cdots, k_m/i_1, i_2, \cdots, i_m)\\ &= R(k_m/i_m, 0)\\ &\quad \times \prod_{a=1}^{m-1} R\Big(\sum_{b=m-a}^{m} k_b/i_{m-a}, \sum_{b=m-a+1}^{m} k_b\Big).\end{aligned} \tag{6}$$

Now we calculate the performance of the system. The system throughput of the priority p is given by

$$\begin{aligned}S_p = &\sum_{i_1=0}^{M_1} \sum_{i_2=0}^{M_2} \cdots \sum_{i_m=0}^{M_m} \sum_{k_1=0}^{\min(i_1, N)} \sum_{k_2=0}^{\min(i_2, N-k_1)} \cdots\\ &\sum_{k_m=0}^{\min(i_m, N-\sum_{v=1}^{m-1} k_v)} k_p(i_1, i_2, \cdots, i_m)\\ &\times U(k_1, k_2, \cdots, k_m/i_1, i_2, \cdots, i_m)\\ &\times \pi(i_1, i_2, \cdots, i_m),\end{aligned} \tag{7}$$

where $p = 1, 2, \cdots, m$. And the system throughput is

$$S = \sum_{p=1}^{m} S_p. \tag{8}$$

The average delay is defined from the arrival instant of a packet at a station to the instant that the packet successfully leaves the station. The average delay of the priority p packet can be written by

$$D_p = \left(\frac{M_p}{S_p} + 1 - \frac{1}{\sigma_p}\right) + 1, \tag{9}$$

where $p = 1, 2, \cdots, m$.

For the multipriority reservation control protocol of the POF access network, a large number of simulation experiments have been accomplished using various system parameters. Now a part of typical results are given below.

Figure 4 shows the throughput characteristics as the arrival rate of the low-priority packet (σ_1) increases and the high-priority packet (σ_2) is fixed. The maximum total throughputs are 3, and the maximum total throughput of the protocol is always N if the effect of destination conflict is negligible (i.e. M is larger than N). The throughput of the high-priority traffic does not change, though the input load of the low-priority traffic varies. The throughput of the high-priority traffic only depends on its own input load. Figure 5 shows the delay characteristics as the throughput of the low-priority traffic increases. For each curve, σ_2 is fixed and σ_1 varies from 0.01 to 1. The protocol has an optimal priority control,

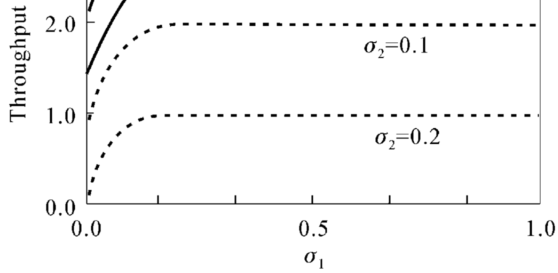

Fig. 4. Network throughput versus input load with two priority traffics ($M_1 = 10$, $M_2 = 10$, $N = 3$, $L = 20$).

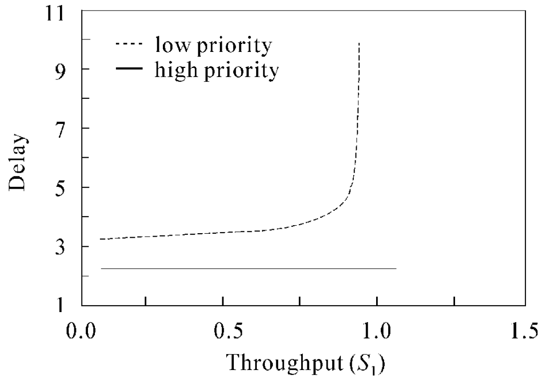

Fig. 5. Comparison of the delay characteristics of the two priority traffics ($M_1 = 10$, $M_2 = 10$, $N = 3$, $L = 20$, $\sigma_2 = 0.2$).

that is, the higher-priority packet in the system is always transmitted prior to the lower-priority packet and the lower-priority traffic does not affect the performance of the higher-priority traffic.

POF is a very attractive candidate for transmission media in access network based on OCDMA technology because of its low cost, larger core diameter, huge bandwidth, flexibility, higher endurance to repeated bending, easier installation and maintenance. OCDMA scheme is employed not only to efficiently exploit the huge bandwidth potential of POF, but also to simplify the control logic. To resolve the problem, a novel protocol is proposed in this paper. The number of data channels does not restrict the number of units in the network, and real-time traffic always is serviced before non-real-time traffic. The performance of the proposed multipriority control protocol using various system parameters has been investigated by numerical analysis and simulation experiments. It is shown that the control protocol is valid and efficient.

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