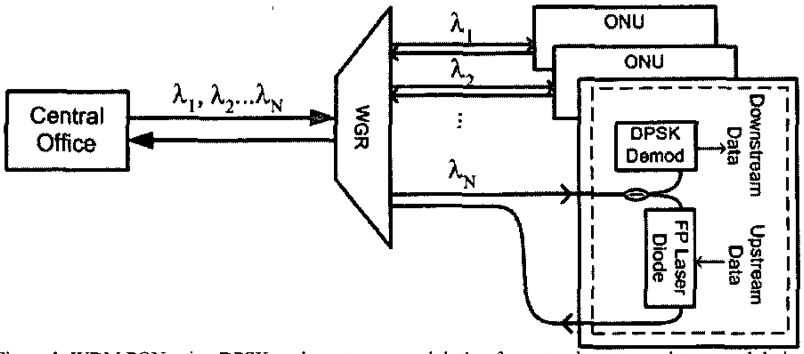

Figure 1. WDM PON using DPSK as downstream modulation format and upstream data remodulation using injection locked FP laser.

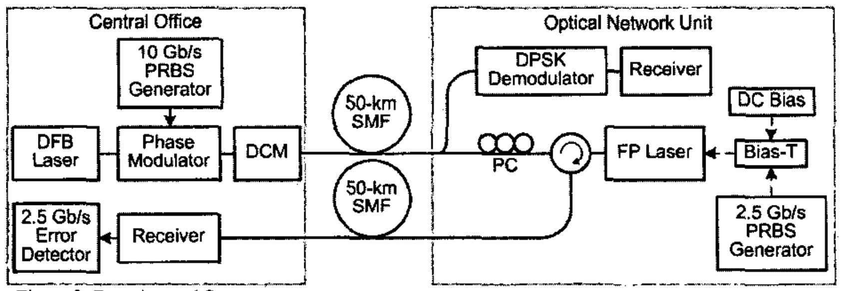

Figure 2. Experimental Setup

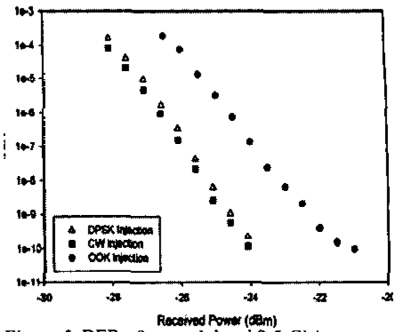

Figure 5. BER of re-modulated 2.5-Gb/s upstream data stream for CW, DPSK and OOK injection measured at central office.

direct detection. DPSK demodulators based on fused-fiber are commercially available, thus it can be potentially low-cost and suitable for access applications.

3. Experimental Demonstration

Figure 2 shows the experimental setup to demonstrate our proposed upstream data re-modulation scheme. At the central office, a DFB laser at 1546.73 nm was externally modulated by an $LiNbO_3$ phase modulator with a 10-Gb/s NRZ 2^{31}-1 pseudorandom bit stream (PRBS) to form the downstream DPSK signal. Normally, a differential pre-coder is necessary for DPSK transmission. However, it can be omitted when a PRBS sequence is used. The optical DPSK signal (at a launched power of 0 dBm) was transmitted over a fiber span of 50 km to the ONU. A matching dispersion compensation module (DCM) was placed in CO to pre-compensate the phase-to-intensity conversion caused by chromatic dispersion.

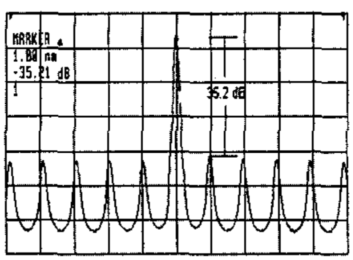

Figure 3. Output optical spectra of the injection-locked signal by downstream wavelength (1546.73nm) with an SMSR of 35.2dB

At the ONU, 40% of the received signal was injected into a FP laser diode biased 1.4 times above threshold, which was simultaneously directly modulated with a 2.5-Gb/s NRZ 2^{31}-1 PRBS upstream data. An optical circulator was used to separate the reflected upstream signal from the downstream signal. Injection locking improved the side mode suppression ratio (SMSR) from 1.4 dB to 35.2 dB as shown in Figure 3 and the output power from the laser was about -4 dBm. The re-modulated upstream signal was then transmitted over another 50 km fiber span and was received back at the central office. Figure 4 (b) shows the received eye diagram of the re-modulated upstream signal at the CO. It showed a clear eye opening, though the 'one' level was thicker when compared with the eye diagram with CW injection as shown in Figure 4 (a). This could be attributed to the effect of phase-to-intensity conversion during injection locking. As can be seen in Figure 5, the performance of injection locking re-modulation scheme using DPSK downstream signal was very close to that of CW injection, with only a power penalty of about 0.25 dB. As a reference, we also measured the BER of the injection locking data re-modulation using OOK as the injection signal, where the phase modulator in Figure 2 was replaced by an intensity modulator. The extinction ratio of the modulated signal was 3 dB. The result, as shown in Figure 5, indicated a 2 dB power penalty when compared with the CW injection case. This shows the improvement of our proposed scheme over the OOK injection scheme.

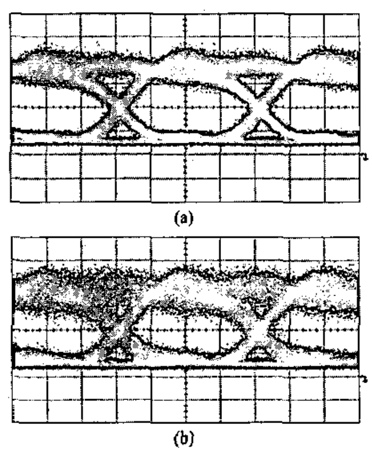

Figure 4. Eye diagram of re-modulated 2.5-Gb/s upstream data with (a) CW- injection and (b) DPSK-injection measured at central office.

4. Summary

The use of injection locked FP laser as an upstream transmitter is an attractive solution for low cost implementation of WDM PON with centralized light source. The crosstalk caused by the amplitude-modulated downstream data degrades the performance of the upstream data transmitter. In this paper, we have proposed and experimentally demonstrated the use of DPSK as the downstream modulation format to alleviate the induced power penalty. A 1.8 dB performance gain was achieved for upstream transmission when DPSK was used in place of OOK as the downstream signal modulation format.

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TuR3 **5:15 PM**

FULL-RCMA: A High Utilization EPON

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This paper proposes a novel medium access control protocol for Ethernet passive optical networks. Its efficiency is evaluated by simulations that demonstrate that 95% utilization can be achieved under heavy load conditions.

1. Introduction

Ethernet passive optical networks (EPONs) [1] are reliable high bit-rate point-to-multipoint optical access networks. They will provide a wide range of services to end-users.

This paper extends the *Request Contention Multiple Access* (RCMA) [2] medium access control (MAC) to suit upstream traffic in an EPON access

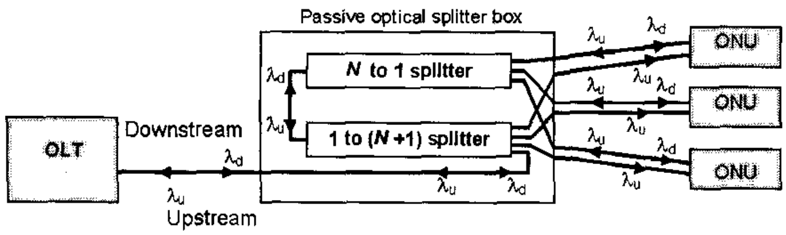

Fig. 1. Network Architecture of FULL-RCMA

Parameter	Value
Data rate	1Gb/s
Maximum distance between an ONU and the optical splitter	1km
Number of active ONUs	16 and 32
Guard time between transmissions from different sources, t_g	0.032μs (32 bits)
Request frame transmission time, t_r	0.128μs (128 bits)
Request contention period (for 32 request timeslots), T	$32\times(t_r+t_g)=5.12\mu s$
Maximum number of Ethernet frames in a frame burst	4
Maximum data period	2ms

Table 1. Protocol parameters

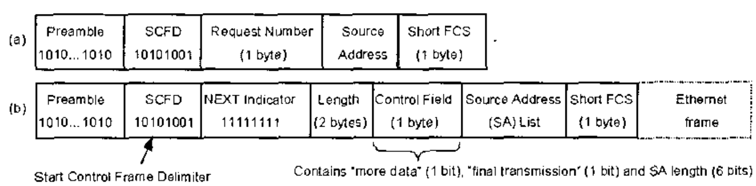

Fig. 2. The frame format (a) FULL-RCMA request frame (b) FULL-RCMA NEXT frame

network. The extended protocol, *Full Utilization Local Loop* RCMA (FULL-RCMA) features a short access delay under light load and efficient behavior under heavy load, similar to time division multiple access (TDMA) of the active users. It also has a very simple priority mechanism, allowing service differentiation, and does not require a complex initialization procedure. Moreover, it achieves this without centralized control. Instead, it uses the synchronizing effect of passing all data through a common passive optical splitter. This allows time to be divided into separate request and data periods, each with its own method of avoiding collisions of packets.

After a description of the FULL-RCMA protocol in Section 2, its performance is evaluated in Section 3.

2. The FULL-RCMA Protocol

2.1 Network Architecture

A fiber to the home (FTTH) EPON solution optically connects a central office (CO) to optical network units (ONUs) in individual houses. An optical line termination (OLT) in the CO is connected by a long fiber to a passive optical splitter near the ONUs. This connects to the ONUs by short runs of fiber (see Fig. 1). This avoids using unreliable active components away from the network edges.

Data transmitted on the point-to-multipoint connection from the OLT to ONUs can simply be broadcast by the OLT. Each ONU identifies its packets by the MAC address, and privacy is maintained by scrambling users' data.

The multipoint-to-point upstream connection from ONUs to the OLT can suffer contention. FULL-RCMA can relieve this. FULL-RCMA requires that the splitter echo upstream data back to all ONUs, including the sender. This requires two fibers per ONU, as depicted in Fig. 1, as the transmitted and echoed data use the same wavelength. The returned signals provide a method for senders to detect collisions of their transmissions. This is the key to FULL-RCMA. Collisions occur at the OLT if and only they occur at the splitter. Thus, by scheduling data transmissions not to collide at the splitter, data collisions can be eliminated.

2.2 The FULL-RCMA Protocol

FULL-RCMA enhances the RCMA Local Area Network protocol [2] to allow (almost) full channel utilization, even for networks with long links. RCMA divides time into request and data periods. During the request period, stations contend to submit reservation requests. Short request packets yield low utilization, and few collisions. Based on the reservation requests, transmissions in the data period are synchronized which again avoids collisions. FULL-RCMA differs from RCMA in the scheduling of transmissions during the data period, to minimize the guard times needed between transmissions.

The start of a request period is announced by the final transmission of the previous data period. It has a fixed duration, T. When a formerly idle ONU has data to transmit, (i.e., becomes a "*ready ONU*"), it prepares a request frame, whose format is shown in Fig. 2(a). This frame is very short compared with T. At a random time in the next request period, it broadcasts the request packet by which it makes a reservation for further data transmission.

Throughout the request period, each ONU monitors the echoes from the splitter and sorts the successful requests in decreasing order of the random 8-bit *request number* (RN), using the ONU's MAC address (SA) to break ties. Note that request collisions at the splitter are detected by all ONUs, and the requests involved are ignored. Each ONU, i, whose request did not collide measures the propagation time, R_i, between itself and the passive optical splitter, which allows it to determine the times of events at the common reference point, the splitter.

The ONU with the largest RN (with SA tie breaks) is called the *winner*. After the maximum round trip time, R, it broadcasts a NEXT header (Fig. 2(b)) containing the sorted list of SAs in the order in which the remaining ONUs will transmit. (Strictly, this can be determined by each ONU, but broadcasting improves reliability in the case of imperfect collision detection.) Immediately following the NEXT header, the winner transmits its Ethernet frame. If it has more than one frame to transmit, then it sets the "more data" bit of the control field. The length field of the NEXT header is the length of both the header itself and the Ethernet frame. The control field indicates the number of SAs in the SA list.

ONUs, other than the winner, listen to the NEXT header. Each ONU whose MAC address is in the SA list knows the order of transmission. When its turn to transmit comes, it will know when the last bit of the previous transmission will leave the splitter. This is because it knows the length of the transmission (from the NEXT header), the time that the first bit arrived, and its own RTT. It can then compute when it can transmit without overlapping the current transmission on the upstream fiber to the OLT and without wasting any time. This pipelining of transmission, similar to that of [3], is the key to achieving high utilization. However, FULL-RCMA does not require the OLT to interleave precisely timed grants with its downstream transmission, as [3] does. The subsequent ONUs must also transmit NEXT headers, but these do not repeat the SA list, indicated by a zero SA length field.

The ONU whose address was listed last in the previous SA list is responsible for constructing a new SA list based on the "more data" field in the NEXT headers it received during the data period. If none of the ONUs set the "more data" bit, then it is the last ONU in this data period. It indicates this by setting the "final transmission" bit in the control field of its NEXT header. When the "final transmission" bit is detected by a free ONU, it knows that a request period will follow immediately after the data transmission. Free ONUs include those which either suffered a collision when transmitting request frames or became ready during the data transmission period.

If there has been no request period for a set time, say 2 ms, then one is initiated, even if the SA list contains further entries. This is done by setting the "final transmission" bit and including the SA list in the NEXT header. This ensures that real-time services have prompt access to the network, even under heavy load. Ready ONUs that are not listed on the SA list may perform a request transmission to obtain the transmission right, as usual. The winner automatically adds the ONUs in the old SA list to the newly formed SA list. Since these ONUs need not re-contend, the probability of request collision is reduced. (Note that this response to a "final transmission" bit subsumes that described in the previous paragraph as a special case, with an empty SA list.) If no stations contend, then the station at the head of the most recently broadcast SA list declares itself the winner.

The initialization procedure for FULL-RCMA is simple. As well as at start up, it is invoked to avoid deadlocks if the normal operation of FULL-RCMA is disrupted by, for example, equipment failure. ONUs monitor channel idle time. During a normal data period, the idle time will remain below threshold, small compared with R and T. If this threshold is exceeded, a request period is started. Unlike a request period that is initiated by a "final transmission" bit, this request period does not have a fixed duration, but continues until an ONU makes a request. This mode is also entered when there are no requests made in a request period following the broadcast of an empty SA list.

3. Performance Study

Test networks of 16 and 32 active ONUs were studied. The distance between the splitter and an ONU is 1km. The traffic model was similar to one used in [3]; each ONU is modeled as an ON/OFF source, with Pareto distributed ON and OFF periods. The shape parameter of the Pareto distribution function was 1.4, producing long range dependent traffic with Hurst parameter of 0.8. During the ON period, each source generates traffic into its (infinite) local buffer at 100Mb/s data rate. Table 1 summarizes the parameters used in the simulation.

The effect of frame bursting was also studied. With frame bursting, the ONU with the channel transmission rights may transmit up to four

Ethernet data frames before releasing the channel to the next ONU. The "more data" bit was not used, and so these results underestimate the true achievable throughput.

Fig. 3 presents the channel utilization of FULL-RCMA versus offered load for several cases. Cases 1 and 2 use frame bursting, while ONUs in cases 3 and 4 do not implement frame bursting. In cases 1 and 3, there are 32 active ONUs, and in cases 2 and 4 there are 16. The traffic intensity was increased to full load by reducing the OFF periods. In all cases, over 87% channel utilization can be achieved when the channel is fully loaded. When frame bursting is implemented, over 95% of the time is spent carrying payloads on the broadcast channel. These results confirm the full utilization property of FULL-RCMA.

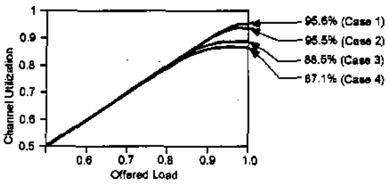

Fig. 3. Channel utilization versus offered load for FULL-RCMA

4. References

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A Distributed Collision Avoidance Protocol using Pilot Tone-based Carrier Sense Mechanism for Passive Optical Networks

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A distributed collision-avoidance scheme employing pilot-tone based carrier sensing mechanism is proposed for the upstream multi-access in PONs. Simulation results show the proposed algorithm outperforms the conventional CSMA/CD scheme in terms of network throughput and delay.

I. Introduction

Carrier sense multiple access with collision detection (CSMA/CD) scheme has been used as an effective multiple access control for Ethernet built with bus topology for many years. Recent research interest on the first/last mile problem led to the development of packet-based passive optical network (PON) technology. In PON, the downstream channel is broadcast in nature while the upstream channel uses multi-access. One difficulty in upstream multi-access is that data frames sent from one ONU are only received by the optical line terminal (OLT), but not the other ONUs. Thus, different ONUs may transmit simultaneously and may lead to collision of data at the aggregation point of the remote node (RN). Media access control (MAC) used by IEEE802.3ah task force provides an efficient approach that allows request-and-grant mechanism to coordinate the multi-access of data [1]. Nearly 95% channel utilization and quality of service (QoS) can be achieved by controlling the granted data size and priority. However, synchronization is needed among all ONUs and global knowledge of distance from each ONU to the OLT should be known by the OLT in order to process the request and grant.

A recent multiple access research on tree topology network tried to eliminate the use of MAC message by optical CSMA/CD [2]. A small part of the optical power was fed back to the ONUs such that every ONU could know the data transmission status of the others. In this paper, we propose to use pilot tones, which are permeable to optical data, to enable optical signaling (carrier-sensing) and achieve collision avoidance (CA), instead of CD. Similar to the optical CSMA/CD scheme in [2], some of the optical power is fed back to the ONU and carrier-sensing is performed by detecting the presence of the distinct pilot tones in the reflected optical power. Unlike the case in 802.3ah, the OLT is not responsible for the multiple access in the uplink. It is shown that channel utilization of over 90% is possible when there are 32 ONUs in the network, compared with only 70% by using the conventional CSMA/CD scheme.

II. Protocol Description

In our proposed scheme, each ONU is assigned with a distinct pilot tone frequency for signalling, which will be multiplexed to the baseband data as in [3]. The spectra for the data and the pilot tone are regarded as the data channel and the tone channel, respectively. The pilot tone is sent by the ONU before they transmit data and is reflected at the congregation point of the RN back to every ONUs. Whenever there is data collision at the RN, the ONU will sense there is more than one pilot tone in the reflected signal. Based on this signaling information, a proposed collision avoidance algorithm will then be preformed. Figure 1 presents the state diagram when an ONU has a data packet to send. In order to assure fairness for all ONU nodes with different distances from the RN, the algorithm will go into "sleep" mode after sending a pilot tone for transmission request. This sleep time, T_s, should be set at least larger than the round-trip time of the ONU that is farthest from the congregation point at the RN.

Figure 2 shows an example of tone sending and

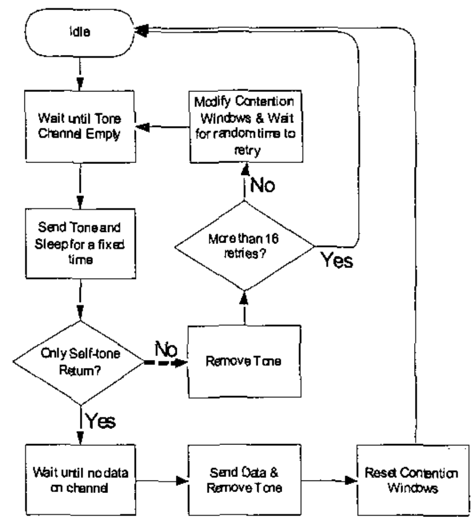

Fig. 1 Algorithm of the Collision Avoidance Protocol Pilot Tone-based carrier sense mechanism

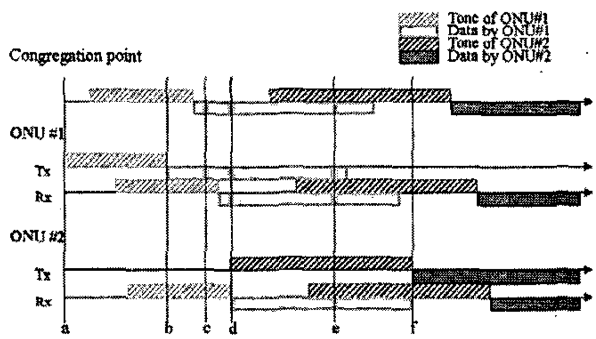

Figure 2. An Example showing the case when there is no contention occurs.

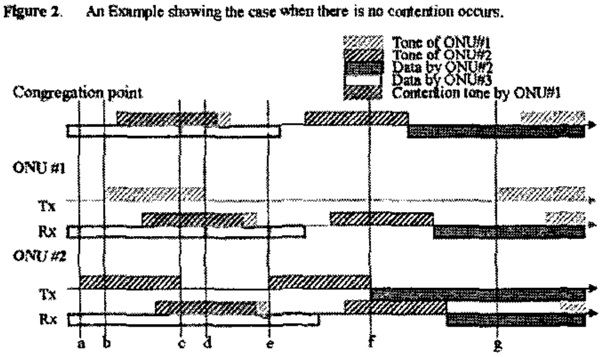

Figure 3. An Example showing the case when there is contention.