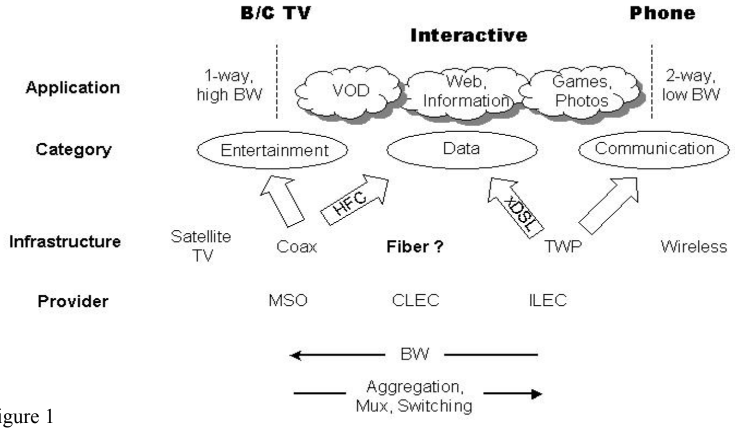

Figure 1

cost in a monopoly situation. Costs for today's services are well known and markets are competitive for new entrants. Thus, new providers would have no pricing power and lenders or financial markets will not permit stranding capital in the new (post telecom-crash) sensibility. This favors greenfield approaches in which the FTTH build can be justified on costs and the fiber's capacity would dissuade a competitor from trying to overbuild. (A second network would presumably cap the take rate at 50% for both.) Thus, tied to low capital turnover rates, it would take 30 to 50 years for FTTH to become prevalent. Even then, a monopolist owner must subsume his competitor's business, a challenge for businesses as disparate in technology and practices as entertainment and telecommunications are.

Second, the calculations assume the existence of a "killer app" in video and/or data. HDTV, a slow starter so far, is unlikely to fill the bill: spectral efficiency and node splitting will permit MSOs to carry it over HFC networks (although it may motivate ILECs !), especially if the HDTV were primarily used only for new movies. Data applications in the form of, say, 80 kB web pages, are unlikely to strain either network because of statistical multiplexing, and recent communications trends (messaging) place more value on mobility than bandwidth. Thus, no application is visible which *demands* FTTH.

Third, the capital constraints on new builds will likely be tight. It is unlikely that large amounts of money will be sunk into infrastructure that has an unproven "killer app." That is, it is more likely that carriers will attract capital to defend their turf and incrementally improve their network than to build a network that might be able to serve an unproven service: the "Field of Dreams" approach ("If you build it, they will come.") is unlikely to attract capital.

While we have argued that massive FTTH deployment is unlikely in the near future, there are several ways that the situation could change to increase the chances for its deployment.

First, a killer app could emerge. The best example of such an application would be personal video, such as video-phones, that requires significant continuous upstream bandwidth. While earlier trials of this application have failed, more people have experienced streaming audio and video clips in recent years, which could stimulate this application. In a similar vein, the emergence of "Ethernet appliances" and home networking with 100 Mb/s interfaces might stimulate a demand for more symmetrical and higher bandwidth.

Second, the Government could decide to form an initiative that supports broadband to the home. This would be an economic policy, motivated by the correlation between communication infrastructure and GDP. As for electricity, for instance, applications which were unthought of or insufficient to justify an initial buildout would, after a buildout occurred, become potent economic drivers.

Third, an independent third party could eschew vertical integration by separating the network from the infrastructure, build a network capable of efficient delivery for all services, and offer it at "arms length" from the services. By relinquishing the hold of an existing service, such a player would enable a whole suite of services to be delivered by other providers. Each major service player would then be forced to either join the network or watch other players (entering through the central data space in Fig.1) move into his core business. In order to avoid stranding capital, such a player would probably have to be a utility who does not need to negotiate rights of way.

Summary

We have argued that the basis for the original vision of FTTH has been overtaken by technological, regulatory, and economic changes. The realities of today make it unlikely that the major players will build out a network without having demonstrable demand for it. The current climate suggests that only be greenfield developments can be sustained. On the other hand, there are service and societal changes that could accelerate the process, government intervention or subsidization that could motivate investment, or business strategies (coming from players without a telecom embedded base to protect) that could emerge that would realize the promise that FTTH holds.

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TuR2 **5:00 PM**

An Optical Network Unit for WDM Access Networks with Downstream DPSK and Upstream Re-modulated OOK Data Using Injection-Locked FP Laser

W. Hung, C. K. Chan, L. K. Chen, F. Tong, *Dept. of Information Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong Special Administrative Region of China, Email: whung1@ie.cuhk.edu.hk.*

We propose and demonstrate an upstream data re-modulation scheme for a WDM access network using downstream optical DPSK traffic. A 2.5-Gb/s upstream data transmitter is realized by directly modulating an FP laser, injection-locked with a 10-Gb/s downstream optical DPSK signal.

1. Introduction

The application of wavelength division multiplexing (WDM) in access networks is a promising approach to meet the increasing bandwidth demand from enterprises and households. An access network architecture utilizing a centralized light source at the central office (CO) and with data re-modulation using the downstream wavelength received at the optical network unit (ONU) [1-4] is an attractive solution for low-cost implementation of the upstream transmitter as it requires no wavelength management.

In [3], a low-cost data re-modulation scheme using injection locked FP lasers was proposed. An Fabry-Perot (FP) laser diode located at an ONU was injection-locked by partial received optical power of a 10-Gb/s NRZ downstream wavelength and was also simultaneously directly modulated to produce the upstream traffic at 1.25-Gb/s. Injection locking greatly enhances the side mode suppression ratio (SMSR) of the light generated by the FP laser and thus enables long-reach transmission for the upstream data. However, this scheme required large injection optical power and sacrificed the extinction ratio of the downstream data. In [4], binary phase shift keying (BPSK) was employed as the modulation format for the downstream signal, which was up-converted to a higher carrier frequency, leaving the baseband spectrum for the upstream data re-modulation at the ONU.

In this paper, we propose and demonstrate the use of optical differential phase shift keying (DPSK) modulation format for the downstream data traffic. It is found that the use of DPSK modulated signal as an injection light source for the FP laser substantially suppresses the crosstalk between downstream signal and the re-modulated data. A 2.5-Gb/s upstream data transmitter is experimentally demonstrated by directly modulating an FP laser, injected-locked with a 10-Gb/s downstream optical DPSK wavelength.

2. System Configuration and Proposed Scheme

Figure 1 illustrates the architecture of a WDM passive optical network (PON) with our proposed upstream data re-modulation scheme at the ONU. Downstream data modulated in DPSK format are carried by the wavelength channels from the CO to the ONUs through a wavelength grating router (WGR) at the remote node. Each ONU receives downstream data on a specific wavelength channel. At each ONU, a majority of the received power is fed into a DPSK demodulator to recover the downstream signal while the rest of the received power is used to injection lock an FP laser diode. It is found that, under a certain operating condition, injection locking can largely suppress the downstream DPSK data content at the FP laser's output. By directly modulating the injection-locked FP laser diode with the upstream data simultaneously, the FP laser-based upstream transmitter can be realized with largely enhanced side-mode suppression ratio and with the same wavelength value as that of the downstream signal. The upstream wavelength can then be routed back to the CO.

The major power penalty caused by the OOK injection scheme in [3] was that the upstream traffic suffered from severe crosstalk with the downstream data, particularly when the extinction ratio of downstream traffic was high. The use of DPSK alleviates this problem to a large extent due to the constant intensity property of the injected signal. Furthermore, with this method, a small injection power (around -14dBm) is required for FP laser to stay locked whereas in the OOK case, a higher average power was needed to guarantee locking for both '1' bits and '0' bits. Although phase-modulated injection may manifest itself as intensity fluctuation at the output of the laser [5], this can be suppressed by careful polarization control of the injection light. We have successfully demonstrated re-modulation of 2.5-Gb/s data using this scheme for upstream transmission. Note that a DPSK demodulator, which usually consists of a Mach-Zehnder interferometer with 1-bit delay, is needed at the ONU to facilitate

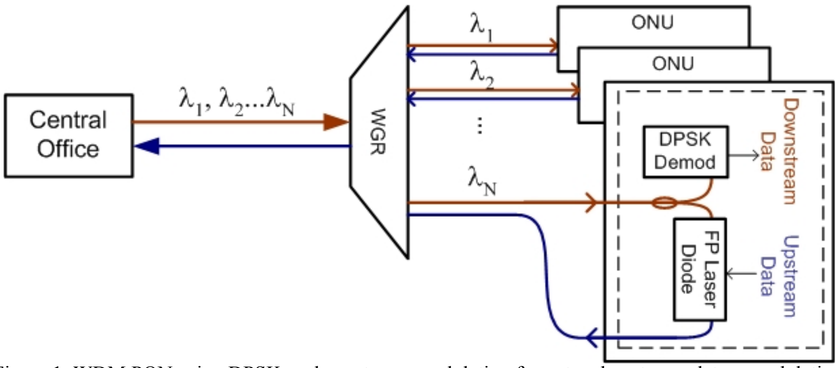

Figure 1. WDM PON using DPSK as downstream modulation format and upstream data remodulation using injection locked FP laser.

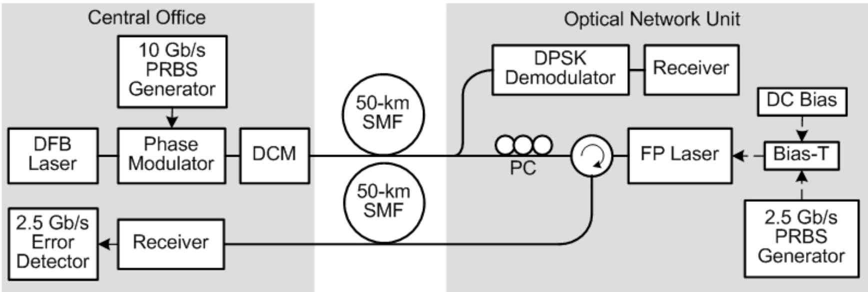

Figure 2. Experimental Setup

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.

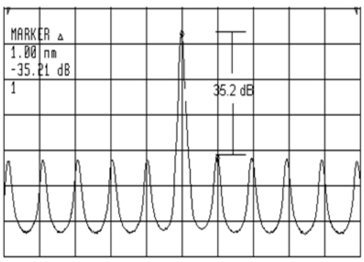

Figure 3. Output optical spectra of the injection-locked signal by downstream wavelength (1546.73nm) with an SMSR of 35.2dB

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.

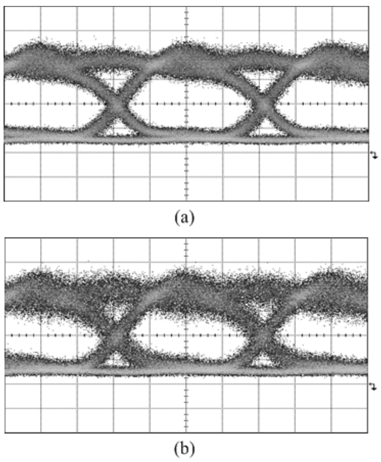

Figure 4. Eye diagram of re-modulated 2.5-Gb/s upstream data with (a) CW- injection and (b) DPSK-injection measured at central office.

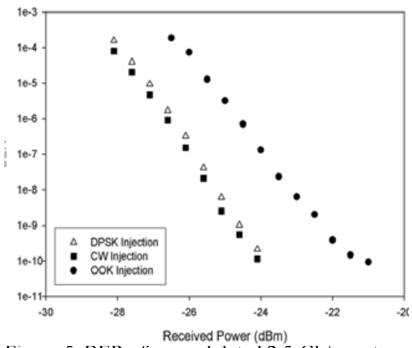

Figure 5. BER of re-modulated 2.5-Gb/s upstream data stream for CW, DPSK and OOK injection measured at central office.

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

C. Foh, *School of Computer Engineering, Nanyang Technological University, Singapore;* C. Foh, L. Andrew, M. Zukerman, *ARC Special Research Center for Ultra-Broadband Information Networks, University of Melbourne, Australia;* E. Wong, *Photonics Research Laboratory, Australian Photonics CRC, University of Melbourne, Australia, Email: chuanhf@yahoo.com*.

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