EXPERIMENTAL DEMONSTRATION OF A HIGH-SPEED ALL-OPTICAL TUNABLE-CHANNEL MULTI-ACCESS (TCMA) NETWORK

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Abstract-This paper presents the experimental demonstration of an ultrahigh-speed all-optical tunable-channel multiaccess (TCMA) network based on novel ideas and technologies that could surmount the difficulties in ultrahigh- speed optical time-domain-multiaccess (TDM) networking. The demonstration includes: simple and fast channel-tuning capability with channel switching time < 5ns, high speed optical multiplexing & demultiplexing (16Gb/s) with a potential of reaching 100Gb/s, and relaxed synchronization requirement for multiaccess packet networks. To achieve these goals, two novel ideas in lightwave technologies and network architecture, namely fast channel-tunable transmitters and destructive-writing scheme, are implemented. We believe these schemes have great chance to overcome the asperity of realizing ultrahigh-speed (~ 100Gb/s) optical TDM networks.

I. INTRODUCTION

High-speed networking allows speedy access and dissemination of knowledge and information that is often critical in gaining competitive advantages. It is expected that services that required volume data exchange on the network will be pervasive in the future. One of the driving forces of course is the delivery of video information, such as video conferencing, video-on-demand, and database retrieval involving video clips, that can provide more vivid and direct impact to the users. Even at present, computer network traffic has increased substantially due to the usage of some browsing programs like "mosaic on World Wide Web (WWW)" that allow viewing images and video database at a remote site. To accommodate this requirement, it is essential to have a network with efficient network protocol and architecture to support timely and high bit-rate services as well as technologies that allow high speed data processing and transmission.

Tunable-channel multi-access (TCMA) networks are a new class of multi-channel networks that employ local channel tuning to reduce the node complexity. Implemented with ACTA [1] or EQEB [2] protocol, of which both are based on bus/ring topologies and compatible to ATM, TCMA is shown to have good characteristics such as simple design, high throughput, low delay and a performance that is independent of the round-trip delay. We attempt to implement ACTA protocol in our TCMA network prototype.

To implement ultrahigh-speed networks, it is imperative to use lightwave technology due to the limited bandwidth of electronic components. Lightwave technologies that can transmit more than 100 Gbit/s of data point-to-point using time-division-multiaccess (TDM) [3] or wavelengthdivision-multiaccess (WDM) [4] have been demonstrated. However, in order to realize a practical multi-access network, three key issues need to be considered:

- 1. channel-tuning capability & complexity
- 2. multiplexing and demultiplexing capability & complexity
- 3. timing and synchronization

Either transmitters or receivers have to be tunable in a network. The channel-tuning time should be small compared to a data packet duration. Optical data need to be multiplexed or demultiplexed at the precise channel (time slot for TDM and wavelength for WDM). At the receiver side, optical data generated from different transmitters are susceptible to dispersion, and need to be synchronized. For ultrahigh-speed TDM networks [5], timing and synchronization become a even greater task since the clock rate is much higher than WDM network's. On top of these considerations, solutions for these issues should be cost-effective to make the network feasible.

To achieve these goals, two novel ideas in lightwave technologies and network architecture, namely (1) destructivewriting scheme, and (2) fast channel-tunable transmitters and receivers, have been proposed [6]. In this paper, a lightwave network prototype based on TCMA and the two proposed schemes are demonstrated and experimental results of components testing are presented. We believe these schemes have a great chance to overcome the asperity of realizing ultra-high speed optical TDM networks, probably up to 100Gb/s.

II. TUNABLE-CHANNEL MULTI-ACCESS (TCMA) NETWORKS

To achieve high speed networking, both scalable capacity and low node complexity are the desirable critical design issues. Tunable-channel Multi-Access (TCMA) network is a generic class of multi-channel networks which meets these two requirements. Each node receives information from a designated channel. It can also send information to the other nodes by writing to the appropriate channel where the destined node attaches to. Since each chcannel operates at a lower data rate whereas the multiplexed data stream has a much higher data rate, the node complexity is much reduced while the network capacity is increased by a factor of M, where M is the number of channels. The Adaptive-Cycle Tunable-Access (ACTA) protocol [1], which has been shown to be a very efficient protocol, has been propsed for media access control of such high-speed all-otpical networks [6]. ACTA can be made compatible to ATM. Network simulations have been performed which demonstrate that a normalized throughput of ≥ 0.9 per channel can be achieved (with a controlled load equal to 0.95) and the fairness can be maintained to within a factor of two even under heavily-overloaded conditions. Therefore, TCMA network with ACTA protocol provides a flexible and efficient platform for ultrahighspeed networking.

III. PHYSICAL NETWORK AND NODE STRUCTURE

The novel TCMA networks can be implemented using ring or bus topologies. The physical network is assumed to be a dual-bus looped back to itself. Fixed-sized empty slots are continuously generated from the Head-of-Bus nodes in opposite directions. Each node consists of two receiving modules and two transmitting modules (see Figure 1), one for each bus. The receiving modules are permanently connected to designated channels whereas the transmitting modules can be tuned to any output channel. The multiple channels can be multiplexed by several common multiplexing schemes such as time-division-multiplexed (TDM) [1], wavelength-division multiplexed (WDM) [7] or subcarrier multiplexed (SCM) [8]. In our prototype, we have chosen TDM as the multiplexing scheme to achieve the novel high-speed TCMA network using photonic technologies and the implementation issues will be discussed in the following sections.

IV. PROPOSED HIGH-SPEED PHOTONIC TDM IMPLEMENTATION

In this section, a novel non-regenerative implementations for TCMA networks using time-domain-multiaccess (TDM) will be described. In a TDM frame. Each channel occupies one single bit in every frame. Thus each frame contains a total of M bits when there are M channels in the system. ATM packets can be sent on each individual channel. Figure 2 shows the photonic configuration of a node. A centralized pulse source is used to generate the pulses with width less than the system bit interval. Ultrafast Optical channel multi/demultiplexing is achieved by nonlinear optical loop mirror (NOLM) [9] which acts as an ultrafast optical switch to 'forward' or 'reflect' the centralized pulses according to the injected control pulses. Nonlinear amplifying loop mirror (NALM) [10], which is similar to NOLM but having an EDFA inside the loop, may be used alternatively for its lower switching power needed. Both NOLM and NALM have the merits that they provide ASE reduction [11], pulse shaping, compression and pedestal suppression [12]. Also, better timing jitter tolerance can be acheived by the walkoff characteristics of such novel all-optical switching devices [13].

At each node, there are two pairs of channel-tunable transmitters and fixed-channel receivers. In the receiver module, the centralized pulse stream is tapped and the

pulses on a particular channel is demultiplexed and detected by a photodiode. The detected data pattern can be recovered in NRZ format by using a decision circuit. In the transmitter module, the modulated optical pulse stream is channel-tuned to the destined time slot and then it is injected into the NOLM as the control pulse stream. The optical pulses in the destined time slot in the centralized pulse stream will be forwarded to the subsequent nodes or reflected according to the proposed destructive writing scheme which will be described later. Clock recovery [14;15] can be done by using optical or electrical phaselocked loop and the recovered clock can be used to control the channel-tunable delay line to achieve more accurate channel tuning. The design of the major functional modules of the proposed architecture are discussed in details in the followings.

A. Fast Channel Tuning for Transmitter

For channel tuning, one of the previous methods was to use optical delay lines with expensive optical switches/ modulators [16] to route optical pulses through different lengths of fiber delay line. Tuning with time slot interval of 156.25ps has been demonstrated. However, the tuning speed is about 50 MHz. This type of tunable delay line usually is polarization-dependent and also suffers from a high insertion loss and thus a degraded power budget. Thus we propose a novel channel-tuning method using relatively low speed electronic components to generate channel-tunable optical short pulses for high speed optical TDM systems. The tunable optical pulse source is fairly simple. An electrically tunable RF delay circuit is implemented with a switching time < 5ns. A sinusoidal signal is delayed by this channel-tunable delay circuit and the delayed signal is used to drive a gain-switched DFB laser to generate tunable optical pulses. Data is superimposed on the electronic short pulse from the comb-generator. Since only the electrical clock (1 GHz) is delayed, not the comb generator output (18 GHz) or the optical pulses (> 40GHz), the bandwidth requirement of the tunable delay circuit is much reduced and so is the cost. The simplicity of this channel-tuning scheme also helps the feasibility to realize the true networking. Also, the generated optical pulse stream will be modulated according to the data. This provides a better alternative for high-speed optical modulation than using optical modulator which has high insertion loss.

B. Destructive Writing Scheme for High-Speed Channel Multiplexing

In optical TDM systems or ATM networks, writing high speed data and multiplexing the data to a specific channel with channel-tunability is a great challenge. This can be achieved by a proposed multiplexing scheme called *destructive writing*. In this scheme, a centralized optical pulse train is generated from the head of network nodes. The modulated optical stream is injected into the NOLM of the transmitter module as the control pulse stream. To transmit a '0' bit, the NOLM will switch to 'forward' state and the corresponding optical pulse in the centralized pulse stream will be forwarded. Conversely, to transmit a '1' bit, the NOLM will switch to 'reflect' state. The corresponding optical pulse in the centralized pulse stream will be reflected and thus no pulse is forwarded to the subsequent nodes. So, the central pulse stream carry transmitted data in complementary format. It can be interpreted as destroying an optical pulse when transmitting a '1' bit and this is why the scheme is called 'destructive writing'.

An additional advantage of the destructive writing mechanism is that a high extinction ratio can be achieved. In particular, when soliton pulses are used, after a destructive write, the remnant of the pulse that is forwarded will be below the critical soliton power and hence will fade out as it propagates along the link. It was reported recently that using NOLM, the spacing between optical amplifiers can be increased in a soliton transmission. This can further reduce the cost of implementing the high speed network.

By employing the destructive writing scheme, together with NOLM and the fast channel-tunable delay circuit, a channel-tunable multiplexer for the destructive writing or a channel-tunable demultiplexer for receiving can be realized.

C. High Speed All-Optical Demultiplexing

Ultrafast all-optical demultiplexing at the receiver module has been demonstrated by using NOLM [9] or fourwave-mixing (FWM) [17]. In our design, the receiver modules are locked to designated channels, we can simply use an unmodulated optical pulse stream at frame rate as the control pulses to a NOLM to demultiplex the optical pulse stream of the designated channel.

D. Timing and Synchronization

As for the timing and synchronization problems, several difficult issues need to be resolved. First, dispersion must be overcome. Second, frame and slot boundaries must be detected and synchronized. Third, the signal amplitude variation from various nodes, which is known as the "nearfar problem", must be compensated. In particular, two sources of timing jitters must be controlled:

- 1. timing jitters due to the timing accuracy of various transmitters during pulse generation and media access, and
- 2. timing jitters caused by differential dispersion for transmitters with slightly different carrier frequencies.

A simple calculation would reveal the problem in the latter case. Assuming two transmitters with wavelength separation of 5 nm are used at two nodes, two data streams multiplexed with perfect alignment would have a relative pulse delay of about 20ps after transmitting through a 20-km fiber with dispersion slope of $0.08ps/(nm^2 \cdot km)$. This severely limits the total network capacity to be much less than 100Gb/s.

In view of the above problems, we proposed to use a centralized pulse source with repetition rate equal to the system bit rate. By using the destructive writing scheme mentioned above, the near-far problem and the timing jitters that arise from using multiple laser sources can be overcome. The timing jitter problem can also be relaxed by using the walkoff effects in the NOLM [13]. The dispersion problem can be solved by using solitons or using dispersion-shifted/compensated fibers.

In summary, the illustrated high-speed photonic implementation schemes have the following advantages:

- 1. allows ultrahigh speed channel-tunable multi-access $(\sim 100Gb/s)$,
- 2. relaxes the stringent requirement of carrier frequency alignment for all high-speed laser transmitters $(\sim \pm 2 nm)$,
- 3. relaxes the synchronization requirement among the nodes for tracking one another,
- 4. relaxes the timing jitter problem (± 0.5 bit time),
- 5. eliminates the near-far problem,
- 6. maintains a high extinction ratio for detection,
- 7. provides network scalability

V. EXPERIMENTAL RESULTS

Several key components, including fast channel- tunable transmitter, destructive-writing nodes and demultiplexing modules have been implemented and the experimental characterization of these components are illustrated in this section.

A. Pulse Generation

The ultrashort optical pulse generation technique we employed is gain-switching [18] which is simple and has relatively lower cost as compared to other techniques such as mode-locking. 1-GHz comb generator is used to generate short electrical pulse to drive the DFB laser diodes. The pulse width of the 1Gb/s gain-switched optical pulses obtained is about 30ps as shown in Figure 3. The pulses are then multiplexed to 16Gb/s by optical fiber delay lines.

- B. Channel-Tunable Channel Multiplexer
- (i) Channel-Tunable Delay Circuit

The delay circuit is designed for a 16 - Gb/s and 16channel optical TDM systems. Each TDM frame has 16 time slots, each slot being a single bit of interval $\tau = 62.5ps$. The channel-tunable delay circuit consists of four stages of 1X2 RF switches. These switches are controlled by a computer to select between the upper (longer) paths or the lower paths that have relative time delays of 1τ , 2τ , 4τ and 8τ respectively in the four stages. Thus, the delayed clock gives delayed electrical pulse train and in turn gives delayed gain-switched optical pulse train.

The maximum aggregated error in the time delay of the optical pulse train has been measured to be less than 3ps, which is below the oscilloscope's resolution. This corresponds to less than 5% of a bit period in a 16 - Gb/s network. Figure 4 shows the waveforms of the gain-switched optical pulses that are tuned to different time slots. The typical channel-tuning or switching time is 3ns, less than 1% of an ATM packet (53 bytes) transmission time at 1Gb/s per node, which is sufficiently fast.

(ii) Optical Pulse Stream Modulation

1Gb/s NRZ data is generated from pattern generator (HP 70941B) and it is added to the comb generator output, as shown in Figure 5, before driving the $1.55\mu m$ DFB laser diode [19]. The output waveform of the modulated gain-switched pulse stream (data pattern: <111011011>) after being detected by a 2.4Gb/s photodector is shown in Figure 6.

(iii) Destructive Writing Scheme

Figure 7 shows the waveform of the modulated optical pulses @1551nm using NALM with 6.6km dispersionshifted fiber loop using a 1Gb/s 1555nm modulated gain-switched optical pulse stream (data pattern: < 010001>) as control stream. Note the complementary representation of the optical pulse stream. The extinction ratio between '1' and '0' is about 8 dB. The pulse width of the demultiplexed optical pulse is 27ps.

C. All-Optical Channel Demultiplexer

All-optical demultiplexing at 1Gb/s is done by using NALM with 6.6km fiber loop of dispersion-shifted fibers @1 Gb/s. An unmodulated gain-switched optical pulsestream as control stream. The extinction ratio between '1' and '0' is about 8 dB. The pulse width of the demultiplexed optical pulse is 27ps. The extinction ratio is about 18dB.

VI. CONCLUSION

In conclusion, we have demonstrated the operational features of a high-speed all-optical TCMA network. Despite the fact that the currently demonstrated individual channel speed is only 1Gb/s with a total network capacity of 16Gb/s, we believe the ultimate network capacity can reach 100Gb/s with our current approach. We have demonstrated the functional blocks of the network, including the tunable transmitters, receivers, the channel-tuning mechanism which is accurate to within 3ps, and the destructive writing mechanism using the NOLM implementation. We believe this scheme has a great chance to overcome the asperity of realizing ultrahigh-speed (~ 100Gb/s) optical TDM networks.

References

 K. W. Cheung, "Adaptive-Cycle Tunable-Access (ACTA) Protocol: A Simple, High-Performance Protocol for Tunable-Channel Multi-Access (TCMA) Networks," *ICC'93*, paper 16.1, pp. 166–171, Geneva, Switzerland, May 1993.

- [2] K. W. Cheung and V. W. Mak, "EQEB A Multi-Channel Extension Of the DQDB Protocol With Tunable Channel Access," *GLOBECOM'92*, paper 47.01, pp. 1610–1617, Orlando, Florida, Dec. 1992.
- [3] M. Saruwatari, "All-Optical Signal Processing in Ultrahigh-Speed Optical Transmission," *IEEE Commun. Mag.*, vol. 32, pp. 98-105, Sept. 1994.
- [4] A. R. Charplyvy, A. H. Gnauck, R. W. Tkach, and R. M. Derosier, "160-Gb/s(8x20 Gb/s) 300-km Transmission With 50-km Amplifier Spacing and Span-by-Span Dispersion Reversal," OFC'94, paper PD-19, pp. 92–93, San Jose, CA, 1994.
- [5] D. M. Spirit, A. D. Ellis, and P. E. Barnsley, "Optical Time Division Multiplexing: Systems and Networks," *IEEE Commun.* Mag., vol. 32, pp. 56-62, Dec. 1994.
- [6] K. W. Cheung, L. K. Chen, C. Su, C. T. Yeung, and P. T. To, "Tunable-Channel Multi-Access (TCMA) Networks: A New Class of High-Speed Networks Suitable for Multimedia Integrated Networking," SPIE Multigigabit Fiber Communication Systems, vol. 2024, pp. 122-133, San Diego, CA, July 1993.
- [7] K. W. Cheung, "Design and Implementation Considerations for Wavelength-Division Multiplexed (WDM) Photonic Dual Bus," *ICC*'92, paper 330.6, pp. 848-854, Chicago, 1992.
- [8] K. W. Cheung, "A Subcarrier-Multiplexed Photonic Dual Bus With Tunable Channel Slotted Access For Local/Metropolitan Area Network Applications," *OFC'92*, paper FD5, pp. 300, San Jose, CA, Feb. 1992.
- [9] K. Uchiyama, S. Kawanishi, H. Takara, T. Morioka, and M. Saruwatari, "100Gbit/s to 6.3Gbit/s Demultiplexing Experiment Using Polarization-Independent Nonlinear Optical Loop Mirror," *Electron. Lett.*, vol. 30, pp. 873–874, May 1994.
- [10] M. E. Fermann, F. Haberl, M. Hofer, and H. Hochreiter, "Nonlinear Amplifying Loop Mirror," Opt. Lett., vol. 15, pp. 752-754, July 1990.
- [11] E. Yamada and M. Nakazawa, "Reduction of Amplified Spontaneous Emission from a Transmitted Soliton Signal using a Nonlinear Amplifying Loop Mirror and a Nonlinear Optical Loop Mirror," *IEEE J. Quantum Electron.*, vol. 30, pp. 1842–1850, Aug. 1994.
- [12] K. Smith and N. J. Doran, "Pulse Shaping, Compression, and Pedestal Suppression Employing a Nonlinear-optical Loop Mirror," Opt. Lett., vol. 15, pp. 1294-1286, Nov. 1990.
- [13] K. Uchiyama, H. Takara, T. Morioka, S. Kawanishi, and M. Sawarutari, "Effects of Control-Signal Pulse Walk-off on BER Performance of Nonlinear Loop Mirror Demultiplexer," *Electron. Lett.*, vol. 29, pp. 1313–1314, July 1993.
- [14] K. Smith and J. K. Lucek, "All-optical Clock Recovery Using a Mode-locked Laser," *Electron. Lett.*, vol. 28, pp. 1814–1815, Sept. 1992.
- [15] S. Kawanishi and M. Saruwatari, "10GHz Timing Extraction from Randomly Modulated Optical Pulses using Phase-Locked Loop with Travelling-wave Laser-Diode Optical Amplifier using Optical Gain Modulation," *Electron. Lett.*, vol. 28, pp. 510–511, Feb. 1992.
- [16] P. R. Prucnal, M. F. Krol, and J. L. Stacy, "Demonstration of a Rapidly Tunable Optical Time-Division Multiple-Access Coder," *IEEE Photon. Technol. Lett.*, vol. 3, pp. 170-172, Feb. 1991.
- [17] S. Kawanishi, T. Morioka, O. Kamatani, H. Takara, and M. Saruwatari, "100Gbit/s, 200km Optical Transmission Experiment Using Extremely Low Jitter PLL Timing Extraction and All-optical Demultiplexing Based on Polarization Insensitive Four-wave Mixing," *Electron. Lett.*, vol. 30, pp. 800-801, May 1994.
- [18] M. Nakazawa, K. Suzuki, and Y. Kimura, "Transform-limited Pulse Generation in the Gigahertz Region from a Gain-Switched Distributed-Feedback Laser Diode using Spectral Windowing," Opt. Lett., vol. 15, pp. 715-717, June 1990.
 [19] Y. C. Lu, P. Zhou, and J. L. Cheng, "A Directly Modulated
- [19] Y. C. Lu, P. Zhou, and J. L. Cheng, "A Directly Modulated Pulse-Compressed and Time-Multiplexed Optical Source for High Speed Multiple-Access Networks," *IEEE Photon. Tech*nol. Lett., vol. 5, pp. 905-907, August 1993.







Fig. 2. A novel high-speed TDM implementation of TCMA using a centralized pulse source and destructive writing scheme. ISO: Isolator, G: Optical Amplifier, F: Optical Bandpass Filter, PD, Photodiode, PLL: Phase-locked Loop, CS: Channel Selection, CT: Channel Tuning, C: Control Pulse, PC: Polarization Controller



Fig. 3. Waveform of gain-switched optical pulse @1Gb/s, Pulse width = 30 ps



Fig. 4. Optical pulse waveforms after being tuned to different channels



Fig. 5. Optical pulse stream modulation scheme



Fig. 6. Detected optical pulse stream modulation with a 2.4GHz photodiode, data pattern: '111011011' @1Gb/s



Fig. 7. Detected optical pulse stream with a 40 GHz photodiode after destructive writing, data pattern: '010001' @1Gb/s

1765