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Tunable-Channel Multi-Access (TCMA) Networks: A New Class Of High-Speed Networks Suitable For Multimedia Integrated Networking

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Abstract

Tunable-channel multi-access (TCMA) networks are a new class of multi-channel networks that employ local channel tuning to reduce the node complexity. These networks are hybrids of switching networks and multiaccess networks and are very suitable for high-speed multimedia integrated networking. Various distributed network protocols for these TCMA networks based on star, bus and ring topologies are discussed, including two particularly promising protocols, ACTA and EQEB. Both are based on bus/ring topologies, compatible to ATM, have simple design, high throughput, low delay and a performance that is independent of the round-trip delay. Various multiplexing strategies (space-division, wavelength-division, time-division and subcarrier) employing regenerative and non-regenerative implementations are also discussed.

1 Introduction

This paper is abóut a new class of distributed networks based on fast packet switching that is suitable for providing an integrated services platform for multimedia applications. The class of networks being considered, called *Tunable-Channel Multi-Access (TCMA) Networks*, are multi-channel networks employing local channel tuning to reduce the processing complexity of the nodes. Below we shall discuss the motivation, the protocols, and the implementation issues of these networks, in particular, those with a bus/ring topology.

1.1 Multimedia Network Protocols

An ideal network protocol for high-speed multimedia applications should have the following desirable characteristics:

1. low delay at lightly loaded traffic, high throughput and fair access at overloaded traffic,
2. throughput performance independent of round-trip delay time, e.g. high network utilization even when only a single node is transmitting,
3. supports multimedia integrated traffic,
4. allows reservation for performance guarantee,
5. scalable bandwidth capacity and access bit-rate,
6. low node complexity,
7. simple processing and implementation.

Many network protocols have been proposed in the past [1] - [10] but they did not have all of the desirable characteristics above. The major problems seem to be their limited bandwidth capacity and high node complexity.

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1.2 Access bandwidth utilization factor ($ABUF$)

The node complexity can be measured by the access bandwidth utilization factor (*ABUF*) [11]:

$$ABUF = \frac{\text{ave available BW per node at peak load}}{\text{peak access BW}}. \quad (1)$$

$ABUF$ is a good measure of the cost effectiveness of the node complexity and is optimal when it is ≈ 1. For all of the proposed networks referenced above, $ABUF$ is $\approx 1/N$, where N is the number of nodes in the network, thus the node complexity is less than optimal.

1.3 Tunable-Channel Multi-Access (TCMA) networks

To overcome the limited capacity and node complexity problems, a new class of multi-channel networks employing local tunable-channel access have been proposed [12]-[17]. Instead of putting the entire bandwidth onto one single channel, the bandwidth is segmented into multiple smaller bandwidth channels and each node only communicates with one or a few of the channels at a time. Thus, the nodes are spared from having to process the information of all channels simultaneously — each node only has to tap out and process the information from the appropriate channel intended for itself. Similarly, it is only necessary to write back to the appropriate channel where the destined node attaches to. Equivalently, the $ABUF$ is increased by a factor of M, where M is the number of channels a node can tune to. This generic class of multi-channel networks that employs local tunable channel access is called Tunable Channel Multi-Access (TCMA) networks. It features increased network capacity and reduced node complexity, and is the hybrid of the purely multiaccess network and the purely switching network.

2 Physical Network and Node Structure

TCMA networks are a very general class of networks. They include any network that satisfies the above criteria, whether they are based on star, bus, ring or other topology.

TCMA networks with a star topology are mostly studied in the context of wavelength-division multiplexed (WDM) networks employing a transparent fabric or star couplers for interconnection. The multiple channels are realized by different wavelength carriers and local channel tuning is realized by using wavelength-tunable components at the nodes (see e.g., Ref. [18]-[22]). Due to the round-trip delay time among the network nodes, it is rather difficult to design protocols with a high throughput that simultaneously have a processing complexity low enough for practical implementation.

TCMA networks that are based on bus or ring topologies are more attractive for high-speed distributed networking because the sequential arrangement of nodes allows many high performance protocols to be implemented distributively which results in easier network management and reduces the difficulty of congestion control. The linear topology also allows scheduling of reserved services to guarantee the quality of services whereas distributed packet switching avoids the technical difficulties associated with building large centralized switches of terabit/sec capacity (such as the high power dissipation in the switch fabric).

In Fig. 1 is shown a simple representation of a dual-bus TCMA network. The physical network is assumed to be a dual-bus looped back to itself forming a ring. Fixed-sized empty slots are continuously generated from the Head-of-Bus nodes in opposite directions.

Figure 2 shows the node structure of the TCMA network. The node structure and complexity are very similar to those of the traditional single-channel dual bus/ring network, the major difference being the addition of some local switches for the media access control (MAC) unit to selectively access one of the channels. The multiple channels shown in Fig. 2 are space-division multiplexed channels for clarity of presentation. In practice, they can also be wavelength-division multiplexed channels, subcarrier multiplexed channels, time-division multiplexed channels ... etc., or combinations of them.

Each node consists of two receiving modules and two transmitting modules, one for each bus. The receiving modules are almost identical to the transmitting modules, with the exception that the receiving modules are permanently connnected to designated channels whereas the transmitting modules can be tuned to any output channel. As an illustration, a simple round-robin channel assignment for the receiving nodes is shown in Fig. 3. In general any receiving node can be assigned to any channel. The only recommendation for node assignment is that the channels should carry roughly the same traffic load to optimize the utilization.

Each module has two packet buffers. The INBUF reads in the packet from the current time slot of the bus channel that the module is connected to, and the OUTBUF stores the outgoing packet or data bits that should be written back onto the bus. There is also a single output queue at each node for the outgoing packets.

3 Protocols For TCMA Networks

Many existing network protocols can easily be adapted to work with TCMA networks, such as Fasnet and its derivatives [3, 23]. The only change required is that part of the destination address must become the channel address, which has to be decoded for channel tuning before the media access. However, these protocols and many others that employ a cycle mechanism have a performance dependent on the round-trip delay time of the network. Thus, the channel efficiency at light traffic can be quite low and delay can be excessive for physically large networks. Later we shall describe a novel protocol ACTA that overcomes this difficulty by varying the cycle length according to the network loading. For this type of networks, it is not necessary to make a request before accessing the media, simplifying the media access procedure.

Another possibility is to use distributed queueing. This method requires service request to be made in a distributed manner before media access. However, the IEEE 802.6 standard DQDB [8] cannot be used for TCMA networks because of the channel tuning requirement. In DQDB, there is a local request counter at every node that monitors all the upstream requests and performs the task of distributed queueing. The counter has to monitor the channel at all time for the protocol to work properly. When channel tuning is required from packet to packet, this becomes impossible. To overcome this problem in DQDB, a generalization known as EQEB (Estimated Queue Expanded Bus) [13, 14] will be described. It uses global counters to replace the local counters in DQDB, thus can be used for TCMA networks.

3.1 Media Access Control (MAC)

For reception, each node simply monitors its own channel and reads in a slot whenever the packet's destination address matches its own. There is no channel tuning required.

For transmission, the MAC cycle consists of two phases:

1. channel tuning;
2. channel access.

The MAC unit will start a MAC cycle whenever there is an outgoing packet waiting in the queue.

In the first phase, the packet destination and its receiving channel are determined from an address table. The transmitting module is then tuned to the channel that the destination node is connected to. In the second phase, intermediate nodes will try to write onto the available slots. The second phase is essentially identical to a single-channel media access, provided they do not require the node to constantly monitor the channel (as in DQDB). Each channel also operates independently.

3.2 Adaptive-Cyle Tunable Access (ACTA) Protocol

ACTA is based on adaptive variation of cycle-lengths according to network loading. It requires only two control bits per slot in the media access, thus can be made slot-compatible to many other protocols, such as DQDB and ATM. The major advantages of this protocol are:

1. simplicity —
   (a) no request registration is required;
   (b) local processing is kept to a minimum – media access can be decided from simple state transitions based on slot information from a single bus;
   (c) each slot requires only two access-control status bits (*Cycle-Start* and *Slot-Occupied*), thus the protocol can be made slot-compatible to many other protocols such as ATM or DQDB;
   (d) consecutive slots going to the same destination can be transmitted together, thus the reassembly processing for large packets is simplified;

2. performance independent of the round-trip delay time —
   (a) the normalized throughput can be ≥ 0.9 and the fairness can be maintained fairly well even under heavily overloaded conditions;
   (b) network utilization is high even when only a single node is transmitting.
3. adaptive to different traffic — since ACTA is based on an adaptive cycle mechanism, it can adapt itself to different traffic conditions. In particular, it is very well-behaved under non-uniform traffic conditions and does not have pathological problems such as lock-out in 2-node competition situations that affect many other protocols [8].

3.2.1 Channel Access Procedure For ACTA Protocol

The channel access procedure can be described as follows:

1. Fixed-sized empty slots are continuously generated from the Head-of-Bus nodes in opposite directions. Each slot has two control-status bits: *Cycle-Start* and *Slot-Occupied*.
2. Variable-length cycles are continuously generated from the Head-of-Bus with a length set by a cycle-length counter.
3. At the start of a cycle, *Cycle-Start* of the first slot is set by the Head-of-Bus.
4. Any intermediate node can write consecutively onto the *first* N_q available slots immediately after it has seen *Cycle-Start*. N_q is an arbitrary quota decided for each node in advance according to priority. For simplicity it can be taken as a constant.
5. *Slot-Occupied* is set after a slot has been written onto.
6. When a node encounters one of the following conditions during transmission, it must stop and wait for the next *Cycle-Start* for any further transmission:
   (a) the node has used up its quota of N_q slots in the current cycle;
   (b) the node encounters a packet going to a different channel;
   (c) the outgoing queue has been depleted.

   The transmission quota is reset to N_q for the new cycle.
7. The End-of-Bus computes the new cycle-length according to the utilization of the current cycle using an adaptive algorithm (see next section). The cycle-length is always bounded by a minimum and a maximum. The new cycle-length is stored into the cycle-length counter.
8. After the current cycle has been completed, the Head-of-Bus node initiates a new *Cycle-Start* with a cycle-length given by the cycle-length counter. If an open dual-bus is used instead of a looped bus, the information about the new cycle-length can be sent back from the end-node to the Head-of-Bus via the opposite bus.

It can be seen that the media access is extremely simple and requires nothing more than a few state transitions and counting the number of packets sent in a cycle.

3.2.2 Cycle Utilization & Adaptive Algorithm

The following simple adaptive algorithm has been found to work very well for ACTA:

$$\textit{new cycle length} = \frac{\textit{current cycle length} \times \textit{cycle utilization}}{\textit{controlled load } L_c}, \qquad (2)$$

where *cycle utilization* is the number of slots used in the cycle divided by the cycle-length, and *controlled load* is a parameter specifying the desired throughput under heavily overloaded condition.

To understand the adaptive behavior of ACTA, consider the network in steady state: the new cycle length is equal to the old cycle length and so the network utilization is clamped at the controlled load level. When the network load deviates from steady state, the cycle would expand or contract accordingly, trying to maintain the network utilization close to the controlled load.

Even though it is tempting to try to get the largest possible throughput by setting the controlled load very close to unity, it must be prevented because the adaptive mechanism would lose its ability for cycle expansion. Furthermore, the response time required by the network to adjust itself to the new equilibrium is proportional to the ratio of the new cycle length to the old cycle length, thus it would take a long time for the network to adapt to a higher network load when the controlled load is set too close to unity. Finally, the cycle-length is bounded by a minimum CL_{min} and a maximum value CL_{max}.

Network simulations have been performed which demonstrate that normalized throughput ≥ 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. Further details of the protocol and simulation results can be found in [16, 17].

3.3 The EQEB Protocol

In this section, the EQEB protocol will be described. EQEB can be regarded as a multi-channel extension of the Distributed Queue Dual Bus (DQDB) protocol that is slot-compatible to it. Because of channel tuning, DQDB cannot be used for the TCMA networks since the local request counters must continuously keep track of the requests. In EQEB all local request counters are replaced by global request counters which continuously estimate the total number of requests and broadcast them to all nodes. Individual nodes then compute the estimated delay from the instantaneous value of the global request counters before accessing the transmission media.

An EQEB slot is essentially identical to a DQDB slot, the only difference being that the two unused, reserved bits in the Access Control Field (ACF) of DQDB is used by the *GRC* field in EQEB. *GRC*, which stands for Global Request Count, is a new access control field that represents the total number of requests made by the downstream nodes in a fixed period of time. It is broadcasted from the Head-of-Bus station for every new slot generated on each channel.

Functionally, the local request counters are used to keep track of the queueing sequence of the requests (*REQ*) from downstream nodes so as to establish some priority for transmission. *GRC*s replace all the local request counters in DQDB and free the nodes from having to keep track of the upstream requests. Ideally, *GRC* should be a large integer (say 1-2 octets) to accurately represent the changing number of requests, but due to the compatibility requirement with DQDB (only 2 bits are available in the ACF octet), *GRC* has to be quantized to 4 levels according to the traffic load. It has been shown in [14] that even under such a constraint, the performance is still quite satisfactory and is comparable to the results obtained with a large *GRC*.

Network simulations have been performed [13, 14] which demonstrate that a throughput of ≥ 0.8 per channel could be achieved even under heavily overloaded conditions. Fairness of access has also been demonstrated by proper selection of local parameters controlling the media access at each node.

3.3.1 Channel Access Procedure for EQEB Protocol

For EQEB, a MAC cycle consists of the following four phases:

1. channel tuning;
2. delay estimation;
3. request registration;
4. slot access.

The first phase has been discussed in the section describing the MAC for TCMA networks. The last three phases are for channel access.

In the second phase, the estimated delays for the last two phases are determined from the traffic loading. The transmitting module of the MAC unit reads in the current value of *GRC* from INBUF and multiplies *GRC* with the *GRC*Fairness parameters that have been determined for each node in advance. The estimated delays for the last two phases are different because the *GRC*Fairness parameters for the two directions are different for each node.

The operational procedures for the last two phases are identical, but the objects involved are different. Both procedures are similar to those in DQDB, with the exception that the MAC unit must idle for a certain period of time before making the request or accessing the slot.

In the third phase, the transmitting module of the MAC unit must make a request to the opposite-direction bus channel. No other request can be made until this segment has been sent and another MAC cycle is initiated by the next segment waiting in the queue. First, the transmitting module idles for a period equal to the estimated delay computed from above. Then the transmitting module can capture the first available empty request bit in any slot on the opposite bus channel. Request registration is completed after a request has been successfully written onto an empty request bit. A bandwidth balancing algorithm (BWB) should also be implemented to prevent lock-out.

In the final phase, the transmitting module can access the available slots. The procedure for accessing the slots is the same as that for making the request. After the module has idled for a period equal to the estimated delay, it can capture any available slot and send out the segment. BWB should also be implemented.

3.3.2 Global Request Counts (GRC) and Requests (REQ)

GRC works as follows. The Head-of-Bus maintains a linked list of N records for each channel. Each list holds the history of the requests made during the most recent N slot periods from the downstream bus. The list is updated for every slot period, with the oldest request record released and the new one linked in. The sum of all the requests in the list is then computed and the GRC vaule representing the instantaneous network load is estimated and broadcasted downstream. Each channel operates independently of one another. Figure 4 shows the spatial and temporal relationship of REQ, GRC, and the time slots for one channel. When the round-trip delay is large, N can be chosen such that the history covers all the requests made in one round-trip time. When the round-trip delay is small, N can simply be chosen to be the number of nodes in one channel.

Since GRC is a 2-bit field, it is quantized to 4 levels according to the network load as follows.

$$GRC(t, \overline{L}(t)) = \begin{cases} 00 & \overline{L}(t) \leq L_z \\ 01 & L_z \leq \overline{L}(t) \leq L_z + (1 - L_z)/3 \\ 10 & L_z + (1 - L_z)/3 \leq \overline{L}(t) \\ & \leq L_z + (1 - L_z)2/3 \\ 11 & L_z + (1 - L_z)2/3 \leq \overline{L}(t) \leq 1, \end{cases} \tag{3}$$

where

$$\overline{L}(t) = \frac{1}{N} \sum_{i=1}^{N} REQ(t - i) \tag{4}$$

is the normalized traffic load measured for the most recent N slot periods back from the current time t, and is directly proportional to the number of requests made during this period. $\overline{L}(t)$ is 1 if all the request bits were set for all N slots. L_z is the normalized zero-delay load. When $\overline{L}(t) \leq L_z$, $GRC(t, \overline{L}(t))$ is set to be zero, so the computed delay will also be zero. L_z is the upper limit of normalized bandwidth from a fixed channel that a single node can occupy assuming there are no other nodes competing. Thus L_z should be chosen as large as possible. However, if L_z is too large, the reaction time for the node taking up all the bandwidth to adjust to the traffic demand from others could be very large. A good compromise value for L_z is 0.7.

3.3.3 Delay Estimation and Fairness Parameters

The estimated delay is the time that the node must wait before it can access the bus channel, either during request registration (Phase III) or slot access (Phase IV). Since there is only 1 request bit per slot, there is a possibility that the downstream nodes may lock out the upstream nodes by reserving all the available slots. Thus, the estimated delay procedures and bandwidth balancing are applied during both Phase III and Phase IV.

The computational procedure for Phase III and Phase IV are the same, and the estimated delay is computed as a function of the network load and node position relative to the direction of object flow. Since the flow direction for Phase III is opposite to that of Phase IV, which means that the relative positions of the node with respect to the Head-of-Bus is different for the two cases, the estimated delay for Phase III and Phase IV are usually different.

There are some side benefits for making the operational procedure the same for both Phase III and Phase IV. First the design of the node is simplified. Second, because the request and access are made in opposite directions, the symmetry of the dual bus with respect to the node position improves tremendously, thus improving the fairness of the network. It should also be mentioned that in the earlier version of EQEB [13], REQ can take on values greater than one. That is, multiple nodes can make requests in the same slot at the same priority level up to a maximum of $MaxReq$ per slot. In that case, it would not be necessary to employ the estimated delay procedure or bandwidth balancing during Phase III.

3.3.4 Functional representation of estimated delay

In general, the estimated delay can be a complicated function of the node position and the traffic load. However, it has been found that a very simple functional representation is sufficient for practical purposes. In this representation, the positional dependence of the estimated delay is decoupled from the traffic load dependence. Algebraically,

$$\text{Est\_Delay}[GRC(\overline{L}), X_i] = F[GRC(t_0, \overline{L}(t_0))]GRC\text{Fairness}(X_i), \tag{5}$$

where $F[GRC(t_0, \overline{L}(t_0))]$ is a function of the current GRC read from INBUF, t_0 is the time when the GRC field of the current slot was written at the Head-of-Bus, and $GRC\text{Fairness}(X_i)$ is the fairness parameter that depends only on the positional parameter X_i. X_i is the relative position of $Node_i$ from the Head-of-Bus, i.e., $X_i = Node_i/N_{total}$, where N_{total} is the total number of nodes on one channel.

The functional dependence of GRCFairness with respect to the node position is:

$$GRC\text{Fairness}(X_i) = B(1 - X_i)N_{total}/2, \tag{6}$$

where B is a constant of proportionality which can be taken to be unity for simplicity. The functional dependence on GRC (and hence the network loading) is:

$$F[GRC] = \begin{cases} 0.00 & GRC = 00 \\ 0.25 & GRC = 01 \\ 0.50 & GRC = 10 \\ 1.00 & GRC = 11. \end{cases} \tag{7}$$

Thus, the explicit functional form of Est_Delay is:

$$\text{Est\_Delay}[GRC(\overline{L}), X_i] = F[GRC(\overline{L})]B(1 - X_i)N_{total}/2. \tag{8}$$

The performance of such a simple choice of Est_Delay actually works out very well. The throughput and delay are quite similar to those of ACTA, but the fairness is a little different. Further details of EQEB including the issue of single-node bandwidth utilization and bandwidth balancing can be found in [14].

4 Implementation Issues

There are many ways to implement TCMA, namely, by employing space-division multiplexing (SDM), wavelength-division multiplexing (WDM) [15], subcarrier multiplexing (SCM) [12] or time-division multiplexing. To take the best advantage of TCMA for complexity reduction, the implementation should be a non-regenerative (or passive) one. But even a regenerative scheme using time-division multiplexing can also benefit because the amount of processing is reduced.

4.1 Regenerative and Non-regenerative Implementations

In general, regenerative implementations have extra delays due to processing at each node, and are susceptible to node failures, i.e., any failed node could sever the dual bus/ring. An advantage of regenerative implementation is that time slots can be reused to improve the throughput efficiency.

Non-regenerative implementations have to deal with the problems brought by physical constraints such as fiber dispersion, accumulated amplifier noise, and fiber non-linearities. Roughly speaking, these factors impose severe limits on the number of nodes, number of channels, bitrate-distance product, channel separation, and signal synchronization (clock recovery) for all non-regenerative implementations, and can significantly affect the choice of implementation under different circumstances.

To increase the total capacity of the system, the optical power should be maintained as high as possible using optical amplifiers. However, due to fiber non-linearities (such as the Stimulated Brillouin Scattering, Stimulated

Raman Scattering and fiber four-wave mixing) and the output saturation power limit of the optical amplifiers, this maximum power is typically much less than 20 dBm, limiting the maximum capacity that can be achieved.

Fiber dispersion limits the physical size of the network and the maximum transmission bit rate. Among various proposed schemes to overcome fiber dispersion, the use of dispersion shifted fibers together with external modulators is one of the most effective and practical solutions at present. Assuming a dispersion of 2.7 $ps/nm.km$ and a bit rate of 1 Gb/s, it is possible to have a bus length running over several thousand kilometers for sources with very low chirp or with external modulators. In the future, soliton transmission may become a viable and attractive option.

Fiber dispersion also affects bit and frame synchronization for different wavelength channels. Even with dispersion shifted fibers, the relative time delay between two wavelength channels 30 nm apart can be as large as 100 ns for a distance of several thousand kilometers! Certainly the clock recovery circuitry and the control signalling would be affected. These factors must be fully considered when designing a non-regenerative network.

The tuning speed t_{tun} of wavelength-tunable devices or photonic switches can also affect the performance of the protocols. For packet switching applications, the slot time t_{slot} must be much larger than t_{tun}. Various fast switching devices have been proposed but their polarization dependency, temperature stability and relatively narrow tuning range have been an impediment to system applications.

Despite all the difficulties mentioned, non-regenerative implementations are attractive because:

1. node failures can be protected at no extra cost;
2. medium transparency allows unused bandwidth to be exploited for other uses, e.g., subcarrier multiplexing can be used to provide circuit connections, broadcasting etc... on top of the TCMA protocol;
3. it has great potential to reduce the node complexity by channel tuning as compared to regenerative schemes.

Further details can be found in [15].

4.1.1 Complexity of SDM/WDM Implementation

The TCMA dual bus/ring network is basically a self-routing distributed packet switching network. It is interesting to compare the complexity of this network with one built by centralized switches. The complexity of the network is usually measured by the total number of basic switching elements required. Here we shall use the 2 x 2 space-division photonic switch (SDS) as a basic unit (BU). A 1 x M SDS is assumed to be equivalent to (M - 1) BUs.

In Fig. 5 is shown an abstraction of a TCMA node employing SDM/WDM. Assuming the SDM/WDM dual bus has M fibers, and each fiber has M WDM channels, each node would require two 1 x M SDS per module, or four 1 x M SDS per bus. The total capacity of the dual bus is $M^2 \cdot BW$, where BW is the access bandwidth of each node. If there are N nodes in total, the average bandwidth per node is $M^2 \cdot BW/N$. Thus, $ABUF$ is $\approx M^2/N$. To make a easier comparison with a centralized switching network, we shall make $ABUF = 1$ for the SDM/WDM dual bus, so M is equal to $\sqrt{N}$. Thus, the complexity (BU count) of the SDM/WDM dual bus, which is equal $4(M-1) \cdot N$, is $\approx 4N^{3/2}$.

Compared to an N x N centralized switching network whose complexity is typically $N \log_2 N$, the TCMA SDM/WDM dual bus/ring may appear to have a higher complexity. However, it must be remembered that the congestion control and management issues of centralized packet switching networks are still unresolved, whereas for the TCMA dual bus/ring networks, these issues are easier to tackle. Thus, the slightly higher hardware complexity may have reduced the software complexity a lot more in return.

4.1.2 SCM Implementations

SCM takes advantages of the commercial availability of microwave electronic components which has a very mature technology base. To implement TCMA using SCM [12], each channel is allocated one microwave frequency band and channel tuning is accomplished by a tunable local oscillator. SCM is simple and inexpensive, but impelmentation for very high bit-rate systems ($\geq$ 10 Gb/s) would be quite unlikely due to the bandwidth limitation of laser diodes. The capacity of a SCM multiaccess system is also limited by the beat noise from various transmitters and the aggregated shot noise from different lasers in addition to those discussed above.

4.1.3 High-speed TDM Implementations

In this section, a novel non-regenerative implementations for TCMA networks using time-division multiplexing (TDM) will be described. The bit-rates we are interested in are those beyond 10 Gb/s. To overcome difficulties in dispersion, synchronization, intersymbol interference etc., a centralized pulse generation and destructive writing scheme is proposed. This scheme can be implemented using solitons and nonlinear optical loop mirrors (NOLM).

In Fig. 6 is shown a TDM frame. Each channel occupies one single bit in every frame. Thus, each frame contains a total of M bits, where M is the number of channels. To read a time slot of S bits from any channel, S contiguous frames must be read. Compared with SDM/WDM, TDM transmitters and receivers require a much higher bit-rate operation but with fewer components. Since electronic multi/demultiplexing may become impossible at very high bit rate (say beyond 10 Gbit/s), optical multi/demultiplexing may be required.

Several methods have been proposed for high speed optical multi/demultiplexing or switching, including electrooptic switches, four-wave mixing, NOLM, electro-absorption modulator gate, etc... The electro-absorption modulator gate can only be used as a demultiplexer since unwanted slots or bits will be gated and destroyed. NOLM's, on the other hand, is suitable for both switching or demultiplexing. Successful demonstration of 100 Gb/s demultiplexing has been shown using NOLM's [24].

To employ very high-speed optical TDM in non-regenerative TCMA networks, several difficult issues need to be resolved:

1. Dispersion must be overcome.
2. Frame and slot boundaries must be detected and synchronized. In particular, two sources of timing jitters must be controlled:
   (a) timing jitters due to the timing accuracy of various transmitters during pulse generation and media access,
   (b) timing jitters caused by differential dispersion for transmitters with slightly different carrier frequencies.
3. The signal amplitude variation from various nodes must be compensated. This is known as the "near-far problem".

4.1.4 Centralized Pulse Generation and Destructive Writing

To overcome these difficulties, we propose here a novel high-speed TDM scheme based on centralized pulse sources and a destructive writing mechanism (Fig. 7).

A centralized pulse source using CPM (colliding-pulse mode-locked) laser or mode-locked fiber ring lasers is used to generate short soliton pulses ($\approx$ ps) from the Head-of-Bus/Ring. Soliton transmission is a very attractive way for overcoming dispersion for very high-speed optical TDM networks. These pulses are multiplexed with delayed replicas of their own to produce a much higher bit-rate pulse train with repetition rate equal to the system bit rate. These pulses are to be regarded as "0"s in the complementary format.

At each node, there are a transmitter module and a receiver module. The transmitter module consists of a NOLM and a phase-tunable phase-locked loop (PLL) that can be tuned and lock onto a particular channel. NOLMs are used because Mach-Zehnder modulators are not very suitable for very high bit-rate operations. The receiver module is similar to the transmitter module, but the receiver is permanently locked onto a fixed channel using the PLL.

The destructive write mechanism works as follows. The NOLM has two states in its operation: the "reflect" state and the "forward" state. These states can be controlled by a local probe pulse generator (LPPG). The LPPG will adjust its probe pulse power according to whether a "0" or a "1" is to be sent.

To transmit a "0" bit, no power is launched by the LPPG to the NOLM, so the NOLM remains in the forward state and the pulse from the centralized source is forwarded to subsequent nodes as a complementary "0". To transmit a "1" bit, a probe pulse is launched by the LPPG and the NOLM becomes a reflector. The pulse is reflected back and thus no pulse is forwarded to the subsequent nodes. This becomes a "1" according to the complementary format. In addition, the reflected pulse can be use to reassure or confirm that correct data has been sent. Since the probe pulse does not have to be very precise in its timing (as long as it covers the selected pulse), the synchronization requirement is very much relaxed.

An additional advantage of this scheme is that a high extinction ratio can be achieved using the destructive write mechanism. Since 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.

In summary, the combined centralized pulse generation and destructive writing scheme has the following advantages:

1. relaxes the stringent requirement of carrier frequency alignment for all high-speed laser transmitters,
2. relaxes the synchronization requirement among the nodes for tracking one another,
3. provides an easy way for carrier recovery and clock extraction,
4. resolves the timing jitter problem for a multiaccess network,
5. resolves the near-far problem,
6. maintains a high extinction ratio for detection.

5 Conclusions

In conclusion, tunable-channel multi-access (TCMA) networks are a very attractive new class of networks for providing an integrated service platform for high-speed multimedia applications. They are multi-channel networks that employ local channel tuning to reduce the node complexity. These networks are hybrids of switching networks and multiaccess networks. Various distributed network protocols for these TCMA networks based on star, bus and ring topologies have been discussed, including two particularly promising protocols, ACTA and EQEB. Both are based on bus/ring topologies, compatible to ATM, have simple design, high throughput, low delay and a performance that is independent of the round-trip delay. Various multiplexing strategies employing regenerative and non-regenerative implementations have also been discussed, showing the versatility of these networks. A novel non-regenerative optical TDM implementation has also been proposed using a centralized source and a destructive writing mechanism to overcome many difficult problems in a high-speed TDM network.

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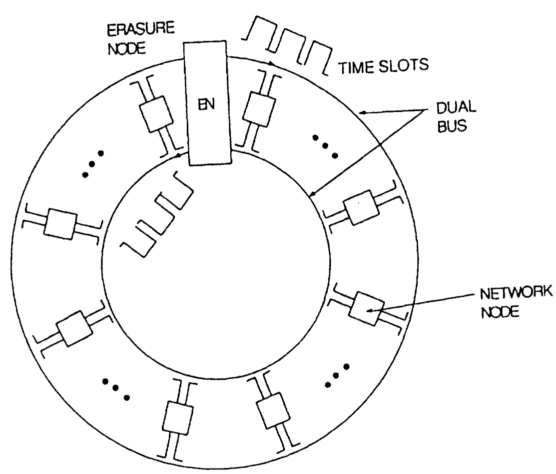

Fig.1 A dual-bus TCMA network looped back to itself.

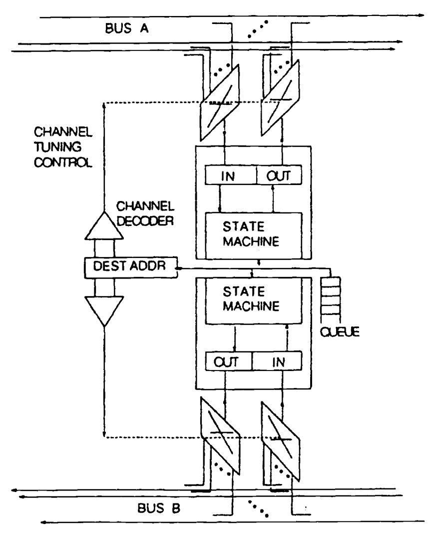

Fig.2 Node structure of a TCMA network.

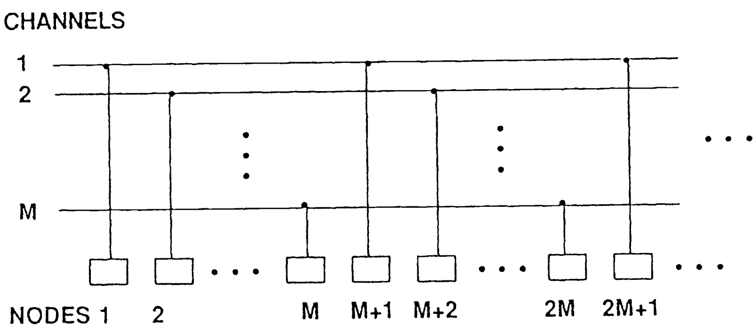

Fig.3 Round-robin channel assignment for the receiving nodes. Each node can only receive from one designated channel, but can send to any of the available channels. The transmitters are not shown.

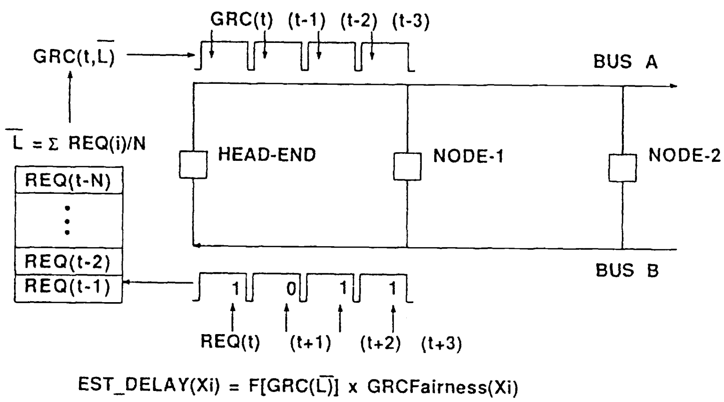

Fig.4 Spatial and temporal relationship of *REQ*, *GRC*, and the time slots for a single channel in EQEB.

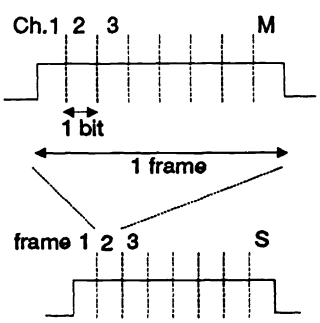

Fig.6 A TDM frame. Each channel occupies one single bit in every frame. Each frame contains M bits, where M is the number of channels.

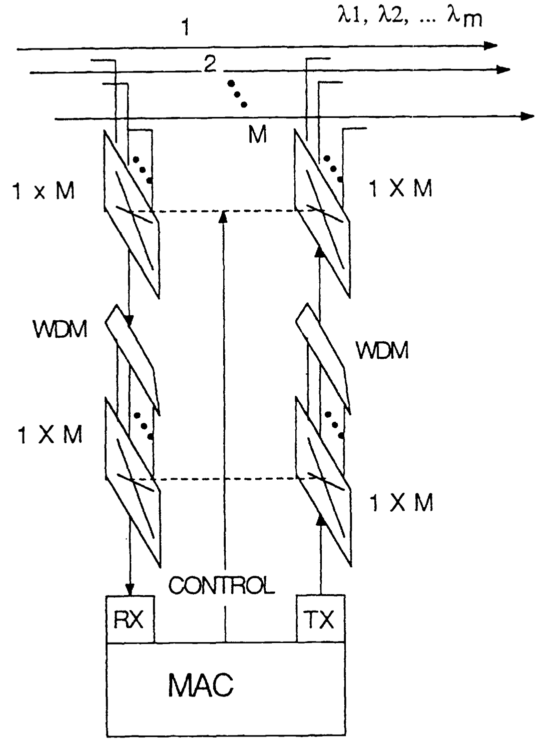

Fig.5 A TCMA node employing SDM/WDM.

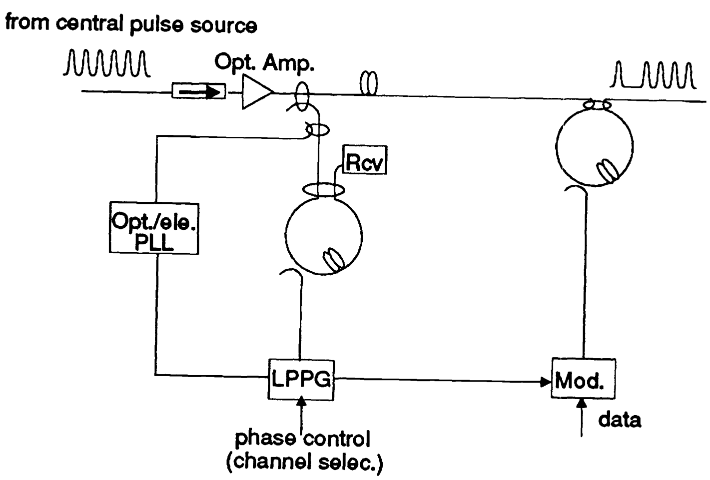

Fig.7 A novel high-speed TDM implementation of TCMA using a centralized pulse sources and a destructive writing mechanism. PLL: Phase-Locked Loop; LPPG: Local Probe Pulse Generator; PC: Polarization Controller.