A Multi-Gbit/s Optical LAN Utilizing a Passive WDM Star: Towards an Experimental Prototype*

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Abstract

STARNET is an optical broadband local area network based on a physical passive star topology. Over a single physical network, STARNET offers all users both a moderate-speed packet network and a high-speed WDM circuit interconnect. Based on these two data transport facilities, several topological and protocol solutions are available to the users. As a result, STARNET supports traffic of widely different speed and continuity characteristics. This paper describes an ongoing experimental effort aimed at the realization of a STARNET prototype at the Optical Communication Research Laboratory of Stanford University. The prototype nodes are FDDI and SONET OC-48 data format compatible. The first four network layers will be fully implemented and the nodes will serve high performance workstations.

1 Introduction

Future Local Area Networks (LANs) are expected to provide a wide variety of services, such as distributed multimedia, file transfer, remote logins, etc. Packet switching and circuit switching have both been considered for LANs. Currently, the prevailing approach is that of packet switching, because packet switching seems to be more effective in handling very different data rates and permits a more efficient processing of bursty data.

As far as physical implementations of optical LANs are concerned, the Wavelength Division Multiplexing (WDM) passive star solution seems to be a promising option. WDM offers a potentially very large number of independent optical channels that can be used to ensure *concurrent* access to the network by many users. This results in high overall network throughput. However, realizing a packet mode of transmission in this intrinsically circuit switched environment represents a challenging task. To this end, different media access strategies and node configurations have been devised.

Some of these proposals rely on the use of very fast tunable receivers [1, 2, 3]; others impose strict requirements on the node ability to maintain synchronization with the other nodes and/or to operate in a time-slotted environment [4, 5, 6, 7]; still others are based on the use of multihop logical topologies [8, 9, 10, 11, 12], where each node performs some routing functions. Some of the above proposals require that each node have many transmitters and/or receivers [7, 5]. From these proposals it is clear that implementing fast packet switching optically is not yet a viable option.

In this paper we describe the implementation of a new optical LAN architecture, STARNET, based on a passive WDM star, designed to take advantage of the multiple channels without requiring extreme hardware and protocol complexity. This result is achieved by giving up the attempt to deliver all kinds of traffic through a single packet network. Instead, two logical networks, a packet subnetwork and a circuit subnetwork, are put together on the same physical medium. In addition, the circuit subnetwork design enables arbitrary subsets of STARNET end-users to set up, beside one-to-one links, more advanced multihop logical subnetworks, in case the amount and type of their traffic requires it. STARNET was first proposed in [13].

STARNET has been designed with the objective of an experimental realization, which is currently in progress. The initial prototype will be a 2-node LAN, serving RISC workstations. To build such a prototype, the first four network layers (from the physical layer

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upward) have to be developed. This paper contains a description of this experimental effort.

The paper is organized as follows. In Section 2 we discuss the characteristics of the different types of traffic, and envisage suitable network solutions. The goals of STARNET, and in particular the idea of implementing both a packet network and a broadband circuit interconnect on the same physical star, are established. In Section 3 the node structure is described and the basic network architecture is introduced. Section 4 describes the implementation of the physical layer of the node (transmission optics and electronics). The current status of the physical layer implementation is reported on in Section 5. Section 6 describes the approach taken at the realization of the electronic interface between the physical layer and the computer bus. In Subsection 6.3 topological and optimization issues are discussed.

2 STARNET Goals

A LAN should handle different types of traffic having diverse speed and continuity characteristics. Traffic can be broadly grouped into three categories:

1. low speed, bursty or continuous;
2. high speed, continuous;
3. high speed, bursty.

Packet transmission is an adequate solution for category 1. A circuit-switched network is suitable to handle continuous streams of data (category 2), especially when the duration of the connection is relatively long. This is the case, for instance, of video-conferencing or transfer of big files (images, books, movies, magazines). These services are often referred to as "connection oriented". For this kind of traffic, switching time does not need to be extremely small.

One example category 3 is supercomputer interconnections. One-to-one connections can be handled on a circuit-switched basis, but when many supercomputers need to communicate simultaneously, *broadband* (multi-Gbit/s) packet communication may be necessary. This last scenario is bound to a very specific application, most likely involving only a small subset of nodes in the LAN.

Taking into account the above observations, our proposal, STARNET, offers to all nodes *both* a packet subnetwork for low and moderate speed services (category 1) *and* a broadband circuit subnetwork for call-oriented services (category 2). These two entities operate independently and simultaneously over the same physical network.

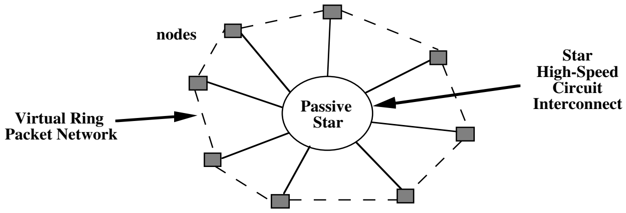


Figure 1: Each STARNET node has a two-fiber connection with the star: one carries the node signal to the star and the other brings from the star the signals of all the nodes.

The merit of this approach is that one does not need to push the performance of the packet network because it is devoted to low speed traffic. At the same time, the circuit interconnect implementation is greatly simplified by the relaxed switching time requirements of call-oriented traffic. Also, all the signaling and protocol management for the circuit interconnect is easily handled through the packet network.

Finally, *arbitrary subsets* of STARNET nodes can be upgraded so that a broadband packet network can be built among them. The upgrade involves only the electronics, *not the optics*, of the nodes. The broadband packet network can be set up without interfering with the lower speed packet network or the circuit interconnections of the other nodes in the network. This feature enables STARNET to cover category 3 of traffic, thus making it capable of supercomputer interconnections.

As a result STARNET meets the goal of dealing with the different kinds of traffic effectively, while avoiding extreme constraints on network parameters or hardware and protocol features. A comparison between the STARNET architecture and other experimental WDM networks can be found in [14].

3 The Basic Node Configuration

Each node of STARNET is optically connected to all the other nodes through a passive optical star, as shown in Fig. 1.

The basic node configuration is shown in Fig. 2. Each node is equipped with *one* transmitter. Its light source is tunable, but tunability is required for network flexibility and fault tolerance only, rather than wavelength switching. In normal operation the light source is kept at a fixed wavelength. Each node keeps

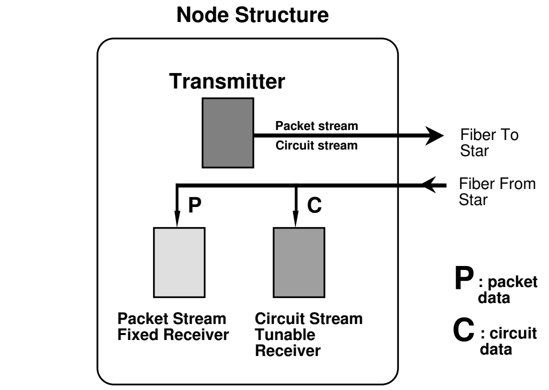


Figure 2: Block diagram of the basic node configuration.

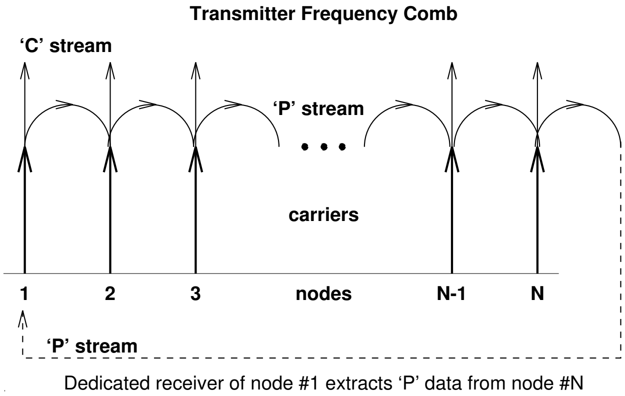


Figure 3: Each transmitter multiplexes the 'C' stream and the 'P' stream onto the outgoing light signal; the 'P' stream is looped from node N to node 1, forming a logical ring

its source tuned to a different wavelength, so that a *comb of light carriers* is formed.

Using a suitable multiplexing strategy (discussed in the next Section), the node transmitter transmits *two independent data streams*, stream 'P' and stream 'C'. Letters 'P' and 'C' are mnemonic for 'Packet' and 'Circuit', and this distinction will become clear shortly.

Every node has a *tunable* receiver that can be tuned to any transmitter and decodes the 'C' stream only. 'C' stream transmission and tunable receivers are used to implement a circuit interconnect among all the nodes.

In addition, each node is equipped with a *fixed receiver* which is permanently tuned to the *previous node* in the frequency comb and receives the 'P' data stream only.

Therefore each node receives 'P' data from the previous node and transmits 'P' data to the following

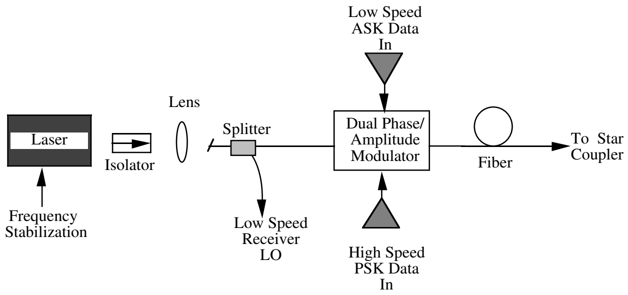


Figure 4: Schematic of the transmitter.

one. Exploiting this feature, STARNET builds a logical 'chain' along the frequency comb. Through this chain packet information flows as depicted in Fig. 3, provided that the data received by the previous node is relayed towards the next.

To close this unidirectional chain, the first node of the chain (the one whose transmitter is the first in the frequency comb) is equipped with a receiver that decodes the 'P' stream of the last node in the chain. Then, it relays this information down the chain, by retransmitting it through its 'P' data stream. This way, a logical unidirectional ring along the frequency comb is created as shown in Fig. 3.

The fact that the transmitters are capable of multiplexing the 'P' and 'C' data streams onto the same carrier not only avoids the need for another optical transmitter, but also eliminates the need to form a second comb of carriers, which would waste optical bandwidth.

Throughout the paper, the node structure will be referred to as Basic Node Configuration (BNC).

4 Node Implementation

The experimental STARNET prototype will interconnect RISC workstations. The network operates around a center wavelength of 1319 nm over single mode fiber. BNC, as outlined in the previous section, has three different subsystems: a fixed-wavelength transmitter, a tunable receiver for the 'C' stream, and a fixed-wavelength receiver for the 'P' stream, permanently tuned to the previous node in the frequency comb. We discuss these subsystems one by one.

4.1 The Transmitter

Fig. 4 shows the schematic of a STARNET node transmitter. The laser source is a 25 mW, 1319 nm Nd:YAG laser. The laser is kept at a fixed frequency.

The laser light passes through an isolator and is then coupled into a conventional single mode fiber. Subsequently, a splitter sends half of the optical power to an external optical modulator. The other half is used as Local Oscillator (LO) light for the 'P' stream receiver.

As shown in Section 3, the transmitter has to multiplex two independent data streams, the 'C' stream and the 'P' stream. To achieve this goal, we exploit a new multiplexing strategy called 'combined modulation': the 'C' stream is PSK-encoded while the 'P' stream is transmitted *on the same light carrier* using low-modulation-index ASK. Combined modulation is obtained through a custom-made (now commercially available) dual phase/amplitude $LiNbO_3$ optical modulator. The 'C' stream can run at up to 2.488 Gb/s. The 'P' stream is made up of packet data coming from FDDI electronic hardware installed in the workstation. As a result, packet data is 4B/5B encoded and its line rate is 125 Mb/s. After modulation, the optical signal is sent to the star.

4.2 The Tunable 'C' Stream Receiver

The tunable 'C' stream receiver (Fig. 5) is a synchronous PSK heterodyne receiver with a thermally tunable Nd:YAG laser as Local Oscillator (LO). The polarization of the LO light is manually aligned with the incoming signal. Signal and LO are combined with a 3 dB coupler. The mixed optical signal is applied to a PIN photodiode with a low-impedance front-end. The resulting electronic signal is centered around an intermediate frequency (IF) of 8 GHz. The signal is then mixed with a 8 GHz RF local oscillator to bring it to baseband. A portion of the baseband signal is used to maintain phase lock of the receiver [15]. The remainder of the baseband signal is low-pass filtered to recover the 2.488 Gb/s data.

4.3 The Fixed Receiver

The fixed receiver is permanently tuned to the transmitter of the previous node in the frequency comb.

This task could be carried out by another independent tunable receiver, which would remain permanently locked on the previous node carrier. However, the additional receiver in our experiment is built in such a way that it does *not* require another tunable laser and at the same time permits frequency stabilization of the comb of carriers [13].

The fixed receiver extracts the 125 Mbit/s ASK-modulated packet stream by eliminating the concurrently present PSK modulation through a squarer (Fig. 5). The data is then decoded by FDDI electronic hardware in the workstation.

4.4 Frequency Stabilization

Like any coherent receiver, the fixed receiver must keep its LO tuned so that reception of the desired channel takes place. Since the LO of the fixed receiver is also the node transmitter laser, the frequency control operated by the fixed receiver to keep its LO locked on the previous node carrier also provides relative frequency stabilization between the two nodes. Since this is done by all the nodes in the comb, each node is frequency locked to the previous node and overall network frequency stabilization is achieved.

This scheme is made possible by the use of coherent communications and is an important advantage over direct detection systems.

The above idea needs experimental confirmation, since it is not clear what the effect of propagation of random frequency fluctuations along the comb will be.

However, Nd:YAG lasers are known to be extremely stable laser sources [15]. In the STARNET prototype, once the network has been set up, a very slow digital control, requiring updates less than once per second, is believed to be adequate to keep them at their nominal frequencies. A distributed control scheme will be implemented in software: it will trigger and control the necessary tuning adjustments, and information on the overall stability of the comb will be exchanged through the packet network.

Finally, the first node in the comb is locked to an absolute reference. This reference needs to be *one stable spectral line only*, which would establish the "origin" of the frequency comb and prevent it from drifting.

4.5 Combined ASK-PSK Modulation

As described in Section 4.1, the transmitter has to multiplex two independent data streams, the 'C' stream and the 'P' stream, *on the same light carrier.* In the prototype this is done by PSK-encoding the 'C' stream while using low-modulation-index ASK to transmit the 'P' stream. This technique is discussed in detail in [16].

In the STARNET prototype, we use combined ASK-PSK modulation because although it has a contained (3 dB) power penalty, it proves simpler to implement and requires less receiver bandwidth than other multiplexing options such as Subcarrier Multiplexing (SCM), or Time Division Multiplexing

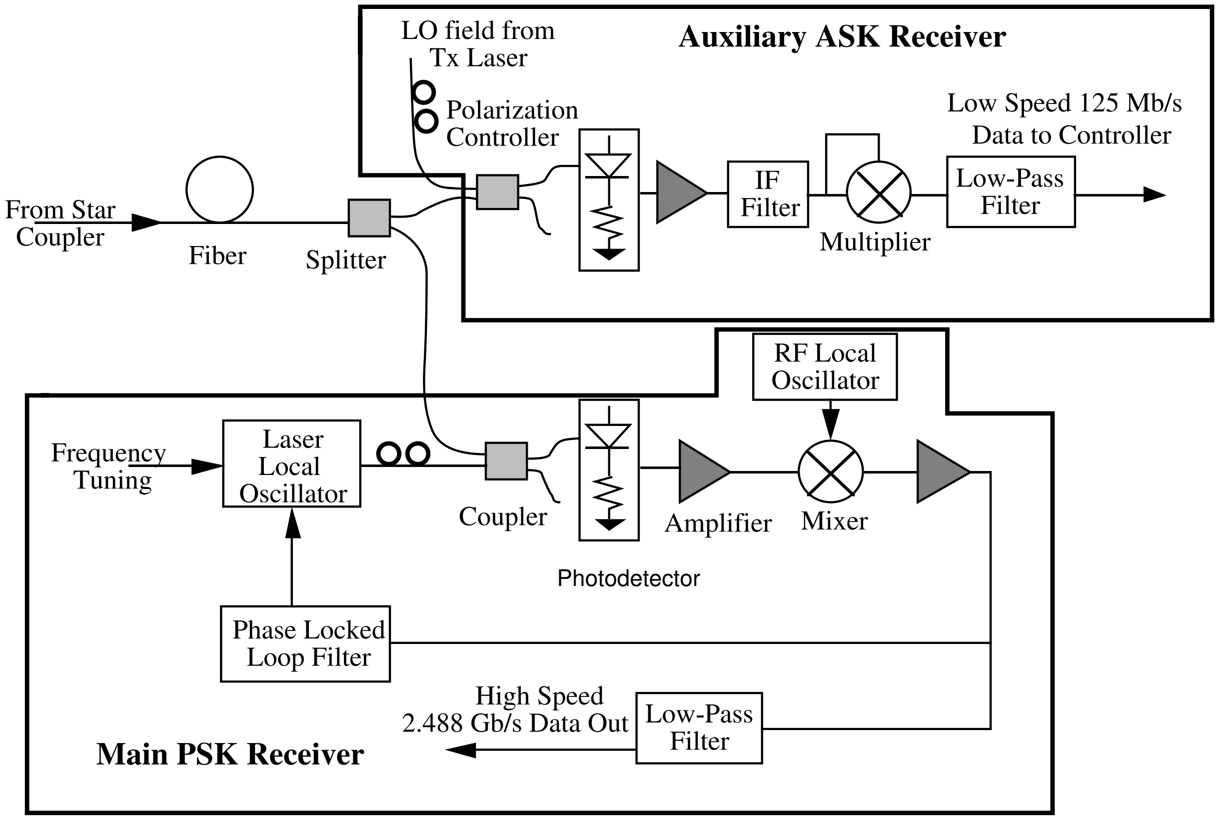


Figure 5: Schematic of the receivers.

System Power Budget	
Laser Power	14.8 dBm
Transmitted Power	5.0 dBm
Node Receiver Sensitivity	-25.0 dBm
Power Margin	30.0 dB

Table 1: System power budget according to experimental data, without additional ASK modulation.

(TDM), which would also require complex frame synchronization.

5 Current Status of the STARNET Prototype

The experimental realization of STARNET is currently underway. A STARNET node transmitter, 'C' stream PSK synchronous heterodyne receiver and 'P' stream ASK nonsynchronous heterodyne receiver have been designed, constructed and tested at various bit rates. Their schematics are shown in Figures 4 and 5 and their structure was discussed in Section 4.

The PSK receiver has been demonstrated with pseudo-random bit streams at 2.488 Gb/s. The ASK receiver has been demonstrated with FDDI data at 125 Mb/s. A complete node receiver has been characterized with with 125 Mb/s ASK data and 2.488 Gb/s PSK data on the same lightwave. These measurements show that the system power budget is 30 dB. (Table 1).

The work in progress at this point is a continuing investigation of the dual ASK-PSK modulation format discussed in the previous section. In the ASK heterodyne receiver, the phase modulation is canceled during the squaring process in the IF demodulator. The IF filter bandwidth is set at 5 Ghz to pass the complete ASK/PSK IF spectrum to the squaring circuit, avoiding conversion of the phase modulation into amplitude fluctuations, that could impair the ASK stream.

An amplitude modulation depth of 0.6 caused both receivers to operate with the same 10^{-9} bit error ratio, with a received optical power of -28 dBm. The amplitude modulation caused a PSK receiver sensitivity penalty of 5 dB. The ASK receiver operated with a sensitivity penalty of 12.6 dB. The resulting node transceiver sensitivity is -25 dBm.

Results on the performance of the ASK-PSK stream multiplexing are presented in [16].

6 Network Interface Issues

6.1 Workstation/STARNET Interface

The interconnection of two workstations using STARNET prototype optics and electronics is shown in Fig. 6. Each experimental STARNET node is attached to a DECstation™ 5000/240 RISC workstation. Each workstation connects to a STARNET transceiver via electronic hardware modules which are installed in the DECstation's TURBOchannel™ I/O bus. Real-time voice and video functionality is provided by additional TURBOchannel modules in the workstation. Moreover, built-in functionality in the workstation provides connections to SCSI storage devices, and to an Ethernet port. Consequently, a rich environment of high and low bandwidth sources/sinks of bursty and continuous traffic is available for the study of the performance of the STARNET architecture.

Two I/O bus interface modules are used to provide datapath connections from the workstation to the STARNET transceiver. One interface module is custom designed for receiving and transmitting data over the 2.488 Gbps circuit switched subnetwork. The other interface uses off-the-shelf FDDI electronics to interface to the 125 Mbps STARNET packet switched subnetwork.

The following section details some of the important issues that are addressed in the experimental implementation of the STARNET architecture.

6.2 Channel Bandwidth Allocation

The STARNET high speed network transceiver provides *full-duplex* communication at a sustained rate of 2.488 Gb/s. The workstations' TURBOchannel I/O bus, however, provides *half-duplex* data transfer at a *burst* rate of 800 Mb/s. A typical application would consist of the interchange of stored images from CD, and real-time audio and video. This data would have to be transferred *twice* over the TURBOchannel bus (once for input to the workstation's main memory and once from main memory to the network for transmitted data, vice versa for received data). Furthermore, the I/O bandwidth must be shared with other devices on the bus (e.g. FDDI packet subnetwork,

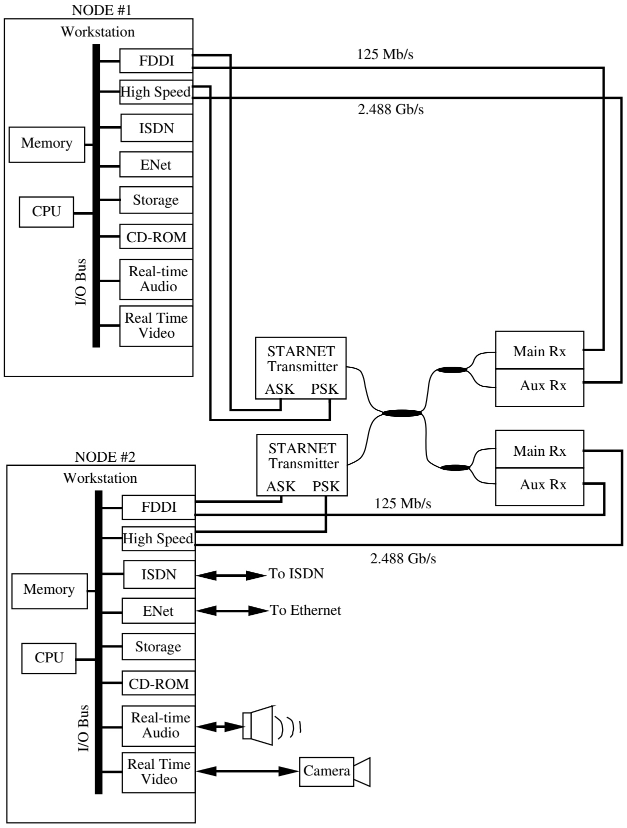


Figure 6: Interconnection of two STARNET nodes.

Ethernet, SCSI, etc.). A conservative estimate of the I/O bandwidth available to the high-speed subnetwork that can be *sustained* is 200-250 Mb/s *full-duplex*. Therefore, the STARNET transceiver is capable of sending/receiving at a rate 10-12 times greater than that which the TURBOchannel can sustain. Therefore, in order to take advantage of the remaining bandwidth of the STARNET transceiver, the high speed circuit switched sub-network interface is also capable of multihop *packet switching*. In Section 6.3 we explain how this additional capability will be used in order to fully exploit the high speed link 2.488 Gb/s capacity.

Routing of incoming packets is done on-the-fly on a packet by packet basis. The headers of incoming packets are checked if they are destined for the receiving node, in which case they are placed in a receive FIFO. Packets which are not destined to the workstation are forwarded to the node's output link without being seen by the node's local bus. The result is a high-speed 2×2 multihop packet switch architecture over the circuit switched subnetwork.

There are two bottlenecks associated with the high-speed network interface: the TURBOchannel and the

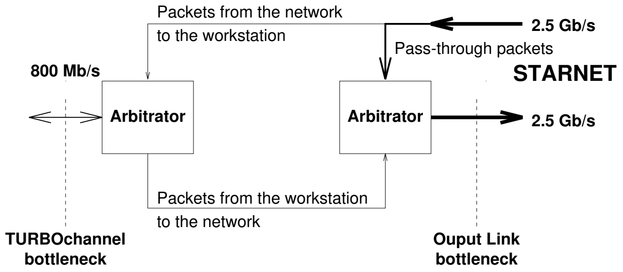


Figure 7: Bottlenecks in the high-speed network interface.

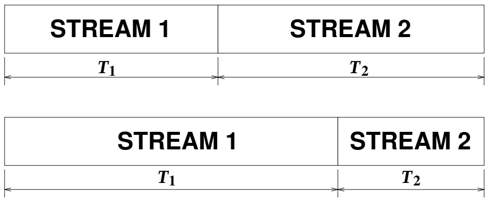


Figure 8: Dynamic bandwidth allocation in the high-speed network interface.

2.488 Gb/s output link. The TURBOchannel bandwidth must be shared between the workstation's input and output data streams; the output link must be shared between the workstation's output stream and the pass-through traffic. The allocation of bandwidth at each bottleneck is done in hardware by two arbitrators, as shown in figure 7. The arbitrators operate as follows: a two-slot cycle is formed, and each of the time slots is allocated to one of the competing streams. By adjusting the time slot sizes, it is possible to control the amount of bandwidth allocated to each stream; this adjustment can be done dynamically by software. The process is illustrated in figure 8. The granularity in the time slot sizes (T_1 and T_2 in figure 8) is one packet, and if one stream is idle, then the whole bandwidth is available to the other stream.

This node interface architecture will enable us to implement an arbitrary bandwidth allocation policy between the multiple streams; research is still ongoing in this aspect.

6.3 Network Control, Routing and Reconfiguration

In STARNET the high speed 2.488 Gb/s PSK links of the circuit interconnect are supported by *tunable* receivers. Therefore the connection pattern that can be established among the nodes is fully reconfigurable. As a result, STARNET belongs to the class of WDM reconfigurable networks.

In a WDM reconfigurable network, control, reconfiguration and routing have to be performed in an integrated fashion to achieve the best performance. Since STARNET uses thermally tuned lasers, and has extra capacity on the 2.488 Gb/s links that cannot be fully utilized by the individual nodes due to computer bus bandwidth limitations, it naturally lends itself to operate in multihop fashion.

In its simplest instance, the virtual topology of a multihop arrangement is a single ring. Notice however that this ring can be formed using the *tunable* receivers and therefore it is completely independent of the lower-speed ASK ring packet network that utilizes the *fixed* receivers. Also, depending on traffic requirements, more than one of these rings can be established among *different* subsets of nodes. Not *all* the nodes need to be hooked up to one of these multihop virtual subnetworks.

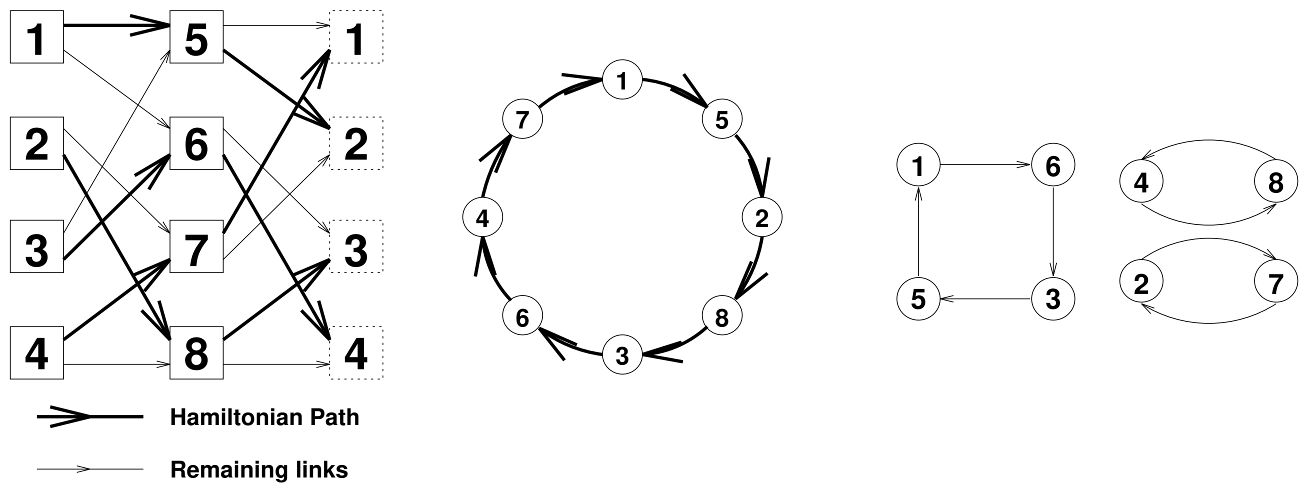
The data on the high-speed 2.488 Gb/s reconfigurable links will be composed of packets belonging to multiple virtual circuits. Each node can be seen as a small fast packet switch which will extract the packets destined to the local node and forward all other packets to the output link, without intervention from the node's CPU.

In a more general picture, the multihop virtual subnetworks need not be confined to the use of the high speed links only: they can take advantage of the lower speed packet network to realize more complicated virtual topologies.

From this point of view, STARNET can implement any mesh topology where a ring Hamiltonian Path[1] can be identified. This mesh is then mapped onto STARNET by mapping the Hamiltonian Path onto the ring packet network, and using the circuit interconnection to map the remaining links. In general, the circuit interconnection will be composed of a series of subrings; in the particular case of a 2-dimensional torus, the circuit interconnection will also form a single link. In Figure 9 we show how to map [18] the ShuffleNet onto the STARNET topology.

At the transport layer, the model of operation of the network will be virtual circuits, which will provide reliable end-to-end data streams. Multiple virtual circuits will be multiplexed over each physical link. To avoid the need for resequencing buffers, all packets from a given virtual circuit will follow the same route. A bandwidth reservation scheme will be used to ensure that the packet loss probability, due to buffer overflow, is held at an acceptable value.

[1] A *Hamiltonian Path* is a path that visits each node of the network exactly once.



(a) ShuffleNet (b) Circuit Subnetwork (c) Packet Subnetwork

Figure 9: Mapping the ShuffleNet onto STARNET.

The challenge is to design and investigate the proper reconfiguration/routing algorithms to maximize the network throughput, given the current traffic requirements. Those algorithms will identify the network topology (i.e., the tuning of the PSK receivers) and the virtual circuit routing. As indicated before, a virtual circuit can go through several hops until it reaches its destination. Depending on its bandwidth requirements, it can use either the lower-speed ring packet network or the circuit interconnection on its trip from the source to the destination. Note, however, that removing a packet from the high-speed "circuit" stream and forwarding it onto the lower speed "packet" stream will require intervention from the node's CPU.

The reconfiguration/routing problem can be formulated as:

GIVEN:	Traffic Requirements
OPTIMIZE:	<*objective function*>
WITH RESPECT TO:	Network topology
	Virtual circuit routing
SUBJECT TO:	Hamiltonian path is a ring
	channel bandwidth

The technique used to solve this problem will depend on the form of the <*objective function*>. If it is a linear function of the required bandwidth, like the average path length, then this problem can be solved by a combination of integer programming (which solves the routing problem for a fixed topology) and a random search (which searches in the topology space); if it is a non-linear function, like the queueing delay, then the problem becomes too difficult for an analytical solution, and one has to resort to random search methods like the *simulated annealing* method [17]. For a high-speed network with limited buffering, where the propagation delays are not negligible when compared to the queueing delays, minimizing the average path length is roughly equivalent to minimizing the average delay. We are currently evaluating such algorithms.

Another issue to be dealt with is the time scale for the topological reconfiguration. Since STARNET uses thermally tuned lasers, the reconfiguration process is relatively slow. Since the channels carrying active virtual circuits cannot be re-allocated because this action would disturb the communication, a link is reconfigured only when it is idle. Moreover, the reconfiguration process has to respond to the average traffic pattern, which must be measured from the data; the actual topology will be an approximation of the optimum identified above.

7 Conclusions

STARNET is a new optical broadband LAN based on a physical passive star topology. STARNET offers all users two data transport facilities: a moderate-speed (100 Mb/s) packet network and a high-speed (2.488 Gb/s per node) WDM circuit interconnect, both running on the same physical network.

The moderate-speed packet network is used for control, reliability, rearrangeability, optimization, maintenance and exchange of low and medium speed data. The WDM circuit interconnect provides the users with high speed links that can be used for high speed node-to-node connections, broadcasting, or to build virtual broadband multihop topologies among arbitrary subsets of nodes.

A STARNET prototype is being built at the Optical Communication Research Laboratory of Stanford University. The network operates at FDDI and SONET OC–48 data rates (the packet subnetwork and the circuit subnetwork, respectively). The first four network layers will be built, including both (optical and electronic) hardware and software. The nodes will serve high-performance DECstation 5000/240 workstations.

Preliminary results are now available on the node optical communication subsystems, confirming the viability of the combined ASK-PSK modulation approach.

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