Fiber-Optic Bus-Oriented Single-Hop Interconnections among Multi-Transceiver Stations

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***Abstract*—This paper explores the merits of the single-path selective-broadcast interconnection (SBI) implemented in fiber-optic technology. This is a static, passive, fiber-optic interconnection among a set of stations, each equipped with multiple, say c, transmitters and receivers. It employs c^2 buses, each interconnecting a subset of the stations, and provides a single optical path between any two stations. Thus, it succeeds in decoupling transmission rate from aggregate network throughput. It also offers substantial advantages in power budget and the maximum number of stations that can be connected without repeaters or amplifiers. When compared with c buses, each interconnecting all stations, this SBI is also attractive in terms of the required passive fiber-optic compnents such as fiber segments and star couplers. For a fixed power budget, the capacity of this SBI is optimal among bus-oriented single-hop interconnections for both a uniform traffic pattern and worst-case unknown skew.**

Key words and phrases: *single-hop interconnections, fiber-optic interconnections, bus-oriented interconnections, local area networks, FOLAN's, selective-broadcast interconnections.*

I. Introduction

We define a *single-hop interconnection* (SHI) to be one in which a message travels from the sender to the recipient without any intervention; i.e., no intermediate switches (as in multistage interconnections) and no need for forwarding by other stations (as in multihop networks). The interconnection network can thus be entirely passive. SHI's are often desired due to their inherent reliability, low latency, and simplicity in operation and maintenance. Extreme instances of SHI's are a network with dedicated point-to-point links between every pair of stations, and a single broadcast bus (SBB). Notable uses of the SBB are Ethernet [1], radio networks, and computer buses.

In the early days of local-area networks (LAN's), the required network speed was dictated by the peak single-user requirement. In recent years, however, both the number of stations attached to an LAN and its usage by each station have been increasing rapidly. The increased usage is due to proliferation of distributed services, shared storage with diskless workstations, information servers, distributed image-intensive applications, graphics terminals, etc., and is expected to grow even further. These changes are causing aggregate network throughput, not peak single-user requirements, to dictate the required transmission rate.

It would appear that many of the aforementioned applications could benefit from higher peak transmission rate, even if it is merely a by-product of the higher throughput requirement. However, the present bottleneck in effective transmission rate is inside the workstations, due in part to data copying and in part to long software paths for handling packets. An increase in transmission rate between network adapter boards would thus be of little benefit to the applications. Users would thus be forced to pay for expensive hardware that is of little benefit to them, making shared channels less attractive.

The increased number of users sharing the channel also reduces the average utilization of transmitters and receivers. In fiber-optic implementation of bus-oriented LAN's, power budget is an additional concern, and manifests itself as a limitation on the number of stations and/or the transmission rate. Alternatively, signals must be amplified and the network is no longer passive.

In view of the above, it is desirable to decouple the required transmission rate from the aggregate capacity of the network. Presently, this is achieved by partitioning the network into multiple LAN's, interconnected by routers and bridges which forward only packets whose source and destination are on different LAN's. This solution is viable but very expensive. Moreover, it places complex, active elements in the message path with negative implications on latency and reliability. This paper focuses on ways of attaining some decoupling of the transmission rate from aggregate throughput while retaining the simplicity of single-hop connectivity.

With conventional signaling techniques, in which a bus can carry at most one successful transmission at any given time, the constraint of single-hop connectivity among all stations through a passive medium implies that each station must be equipped with multiple transmitters or receivers if any decoupling is to be achieved. The most obvious way of interconnecting user stations, each equipped with c transmitters and receivers, is to construct c subnetworks (''buses''), each interconnecting all stations through one of their transmitters and receivers [2], [3]. We refer to this as the *parallel broadcasts interconnection*, PBI. This would achieve a c-fold decoupling of the transmission rate from the aggregate throughput, but offers no advantage in hardware utilization and limited advantage in power budget. In terms of adapter cost, there

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is a capacity beyond which PBI would be advantageous, since the cost of adapters eventually grows faster than their speed, making multiple slow adapters cheaper than a single fast one. As a by-product, fault-tolerance would also be enhanced.

For a uniform traffic pattern, one can do better than PBI. (By "uniform traffic pattern" we mean an equal amount of traffic between every pair of stations.) Specifically, a single-path, unidirectional *selective-broadcast interconnection* (SBI) comprises c^2 equally populated buses, providing a common bus to any pair of station [4]. In [5], this interconnection was described and compared with PBI in terms of capacity and delay under an assumption of fixed transmission rate per bus, i.e., ignoring power budget. For equal capacities, the delay with SBI was shown to be higher than with PBI, which in turn was higher than that with a single bus. Also, the delay disadvantage of SBI in this case is smaller if the hardware savings (compared with PBI) take the form of fewer transmitters and receivers per station, rather than an equal number of slower ones. With equal transmission rates and equal numbers of transmitters and receivers per station, SBI still exhibits higher delay at low load, but much lower delay than the other two at higher loads; this is due to its higher capacity in this case.

In [6], certain aspects of fiber-optic implementation were discussed. These included a method of using WDM to separate the various subnetworks, as well as an approach for combining WDM with space-division multiplexing. Also, a limited comparison of component requirements was carried out.

This paper focuses on the properties of SBI's in the context of fiber-optic implementations, extending the results of [6] and presenting new ones. It presents an extensive comparison between the single-path SBI, PBI, and SBB. Fiber-optic component requirements and the maximum number of stations that can be accommodated without repeaters are compared under various assumptions and physical implementations. Also included is a capacity comparison between the single-path SBI and other SHI's with fixed transmission power rather than fixed transmission rate. The single-path SBI is shown to dominate the others. (With fixed transmission rates, in contrast, the relative performance depends on the traffic pattern.)

The paper is organized as follows. In Section II, we briefly describe the single-path, unidirectional SBI along with two methods of "interpolating" between an SBI and a PBI. Section III explores fiber-optic aspects of SBI, Section IV discusses some of the results, and Section V concludes the paper.

II. Unidirectional SBI's

A. Construction of a Single-Path SBI

Consider a set of N stations, each with c_T transmitters and c_R receivers. For simplicity of exposition, let us split each station into a *transmitting station* (TS) and a *receiving station* (RS). Next, we divide the TS's into c_R groups of equal size, and the RS's into c_T groups. The idea is that an RS would use its ith receiver to listen to TS's in the ith group of TS's; likewise, a TS would use its jth transmitter to reach RS's in the jth group of RS's. (See Fig. 1.)

Viewed differently, the TS's and RS's are partitioned into c_R and c_T groups of equal sizes, respectively. Next, $c_T \cdot c_R$ subnetworks (buses) are constructed, such that subnetwork (i, j) connects the TS's of group i to the RS's of group j. As depicted in Fig. 1, each TS has exactly one subnetwork (bus) in common with any given RS. When $c_T = c_R = N$, this SBI comprises a point-to-point link from each TS to each RS; when $c_T = c_R = 1$, it is an SBB. (PBI, in contrast, never becomes a collection of point-to-point connections.) Finally, note that this can easily be generalized to the case of N_T transmitting stations and N_R receiving stations, respectively. In this case, however, one cannot view a (TS, RS) pair as two parts of the same station.

B. Uniform-Traffic Capacity and Station Hardware

Let B denote the data rate of an individual transmission and thus the capacity of a single bus; C denotes the capacity of an entire interconnection.

For a uniform-traffic pattern and single-destination transmissions:

$$C^{\mathrm{PBI}} = c^{\mathrm{PBI}} \cdot B^{\mathrm{PBI}} \tag{1}$$

$$C^{\mathrm{SBI}} = c_T^{\mathrm{SBI}} \cdot c_R^{\mathrm{SBI}} \cdot B^{\mathrm{SBI}}. \tag{2}$$

Letting $c_T = c_R = c$ and assuming that $N_T = N_R = N$ in both systems, the above expressions can be interpreted in several ways:

- With equal numbers of transmitters and receivers per station and equal transmission rates, the capacity of SBI is c times higher than that of PBI.
- With equal capacities and the same numbers of transmitters and receivers per station, SBI can use slower (by a factor of c) and probably cheaper transmitters and receivers for the same aggregate throughput.
- With equal capacities and transmission rates, the required number of transmitters and receivers per station for SBI is only the square root of that for PBI.

Since each subnetwork of SBI serves only N/c transmitting stations and N/c receiving stations, as compared with N in PBI, the average utilization of transmitters and receivers can be c times higher than that of PBI. In fact, this SBI is optimal in terms of uniform-traffic capacity, transmitter and receiver utilization, and power split (the number of receivers that hear a transmission, maximized over all transmitters) [4], [5].

When all the traffic is from one TS group to one RS group, however, only one of the c^2 buses can be used, so the capacity of the single-path SBI drops to B, whereas that of PBI remains $c \cdot B$. Also, for any given source-destination pair, the maximum instantaneous data rate with SBI is B, as compared with $c \cdot B$ for PBI. If the

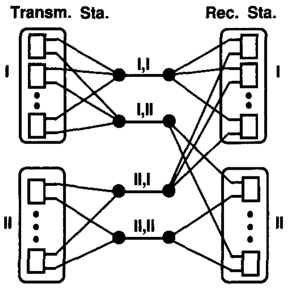

Fig. 1. Single-path, unidirectional, equal-degree SBI. Several stations are shown for each group. $c_T = c_R = 2$; two groups; four subnetworks.

traffic pattern is known and static, one can assign stations to groups so as to balance the load on the buses. Otherwise, our design goal is to maximize the uniform-traffic capacity C_{unif} subject to a guaranteed worst-case capacity C_{guar}. To achieve $C_{\text{guar}} = kB$, $(k \leq c,)$ an interconnection must provide k disjoint paths between any pair of stations.

C. k-Path, Unidirectional SBI's

In [3], it was shown that the maximum possible (relative) savings in transmitters and receivers without losing the flexibility of PBI is $(c + 1)/N$, which becomes negligible as the number of stations increases. Given c, there thus appears to be a trade-off between C_{unif} and C_{guar}; PBI and the single-path SBI are two extremes. Following are two parameterized compromises [4], [5].

Multiple single-path SBI's (MSP). k single-path SBI's are constructed, each of which utilizes $1/k$ of the transmitters and receivers of any station. Here

$$C_{\text{guar}} = k \cdot B; \quad C_{\text{unif}} = \frac{c_T \cdot c_R}{k} \cdot B;$$

$$\text{Power split} = k \frac{N_R}{c_T}. \tag{3}$$

A hybrid SBI-PBI interconnection. c' transmitters and c' receivers of each station are used for a PBI, and the remaining ones are used for a single-path SBI. See Fig. 2. Here

$$C_{\text{guar}} = (c' + 1) \cdot B; \quad C_{\text{unif}} = (c' + (c_T - c') \cdot (c_R - c')) \cdot B; \quad \text{Power split (worst case)} = N_R. \tag{4}$$

Using MSP terminology for the hybrid

$$C_{\text{unif}} = ((k - 1) + (c_T - k + 1)(c_R - k + 1)) \cdot B. \tag{5}$$

The hybrid outperforms the MSP, except for equality when $k \in \{1, c\}$ [4]. The hybrid has another advantage, namely the flexibility in allocation of hardware to the two components. On the negative side, the PBI part of the hybrid causes its utilization and power split to be no better than those of PBI.

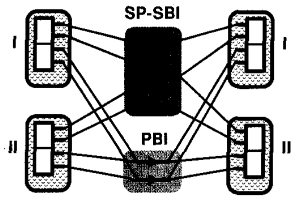

Fig. 2. Unidirectional hybrid SBI-PBI. $c = 4$, $c' = 2$. One station is shown for each group of $N/2$. $C_{\text{guar}} = 3$; $C_{\text{unif}} = 6$.

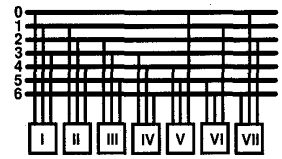

Fig. 3. Bidirectional single-path SBI. $c = 3$; $c^2 - c + 1 = 7$ subnetworks. Each group is represented by a single station.

D. Bidirectional SBI's

In a bidirectional SBI, unlike in a unidirectional one, a station's transmitters and receivers must be connected to the same buses. A bidirectional SBI interconnecting a set of N stations, each with c transceivers, can be derived from a unidirectional SBI with $c_T = c_R = c + 1$ by merging the (i, j) bus with the (j, i) bus for all $i < j$, removing all (i, i) buses, and reducing the number of transmitters and receivers by one. The total number of buses is $c(c + 1)/2$. One can, however, obtain better results by applying the theory of block designs and projective geometry [7]. Specifically, whenever $(c - 1)$ is a power of a prime, an SBI with $c^2 - c + 1$ buses can be constructed. For example, let $c = 3$; divide the stations into seven groups, numbered 0–6, and assign them to buses as follows: {0, 1, 3}, {1, 2, 4}, {2, 3, 5}, {3, 4, 6}, {4, 5, 0}, {5, 6, 1}, {6, 0, 2}. Fig. 3 illustrates the example. The design trade-offs and options are essentially identical to those of the unidirectional SBI. For further details, see [4], [5].

E. Operation

Bidirectional single-path SBI's can be operated using an LAN access scheme, with minor modifications for choosing the appropriate transmitter. In fact, many present LAN-based systems are already equipped with the ability to pick routes based on the destination and to pick alternate routes in case of failure. Similarly, unidirectional SBI's can be operated with access schemes that do not require sensing of the channel. Operation of the unidirectional SBI with schemes such as CSMA-CD [8], however, would be complicated by the fact that a station can only hear one of the c_T buses over which it may transmit. One solution would be to add a sensor to each transmitter, which also requires that the aggregate signal be brought back to the station. With a centralized-star implementation of a bus, this could be achieved by adding an output(s) to the star and returning the signal over a dedicated (additional) fiber for each transmitter, or by reflecting the signal at the output into the star, causing a fraction of the power to travel back to the transmitters over the existing fibers. Other options include the use of the (i, i) buses for coordination or the introduction of an extra bus for that purpose [4].

Multiple-path SBI's require a policy for bus selection. This is discussed in [4], where it is also shown that the use of nonideal access schemes has a positive effect on the performance of SBI relative to PBI.

III. Fiber-Optic SBI's

In this section, we focus specifically on fiber-optic implementations of SBI's. The various issues are all related to power budget; reciprocity of star couplers is also taken into consideration. We begin by comparing this SBI with PBI in terms of the requirements for fiber-optic components and the maximum number of stations that can be accommodated with a given power budget. We then prove that with fixed transmission power on all buses, the single-path SBI is capacity-optimal and there is no trade-off between C_{guar} and C_{unif}.

A. Passive Fiber-Optic Component Requirements

One might expect that the higher number of buses in SBI than in PBI would require more passive fiber-optic components, namely fiber segments and directional star couplers. In this section, we will show that this is not necessarily the case. We will assume that fibers and couplers can operate at any transmission rate. The comparison will be conducted for three sets of constraints: 1) equal B and C, 2) equal c and C, and 3) equal B and c. Two extreme configurations of an individual subnetwork will be considered: a linear bus with taps and a centralized star.

Linear bus with taps. As shown in Fig. 4, each subnetwork is implemented as a single fiber that goes among the stations. Each transmitter is connected to this fiber by means of a (2×2) star coupler, and the same is true of each receiver. The results are summarized in Table I.

Centralized star. This is the dual of the linear bus: a star coupler corresponds to a subnetwork, and a fiber corresponds to a transmitter or a receiver. Here, the comparison of the interconnection component requirements is complicated by the fact that the required star couplers are of different sizes. We solve this by assuming that large couplers are implemented using small ones as building blocks [9]. (An $(M \times M)$ coupler can be constructed using $M/P \cdot \log_p M$ couplers of size $(p \times p)$, where p divides M.)

Table II summarizes the comparison. Perhaps the most interesting result is that for equal B and c, (the case in which SBI has higher capacity for identical active hardware,) and a star configuration, SBI requires fewer couplers and the same amount of fiber.

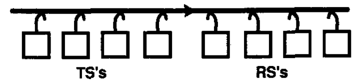

Fig. 4. Linear-bus implementation of a subnetwork.

TABLE I
FIBER-OPTIC COMPONENT REQUIREMENTS FOR A LINEAR BUS WITH TAPS

Conditions Equal:	Fibers		Couplers	
	PBI	SBI	PBI	SBI
C and B	C/B	C/B	$2N \cdot c_{\text{PBI}}$	$2N\sqrt{c_{\text{PBI}}}$
c and B	c	c^2	$2N \cdot c$	$2N \cdot c$
C and c	c	c^2	$2N \cdot c$	$2N \cdot c$

B. Maximum Number of Stations that Can Be Accommodated

Path loss is the ratio of the power at the output of a transmitter, P_T, and the power at the input of a receiver, P_R. Its constituents are

- **Power split.** With direct detection and low-impedance optical detectors like those typically used for FOLAN's at present, the reception of a signal "consumes" the power that is present at the receiver's input, requiring a certain power level for reception. If a signal can reach several receivers, the level at each one is only a fraction of the transmitted power. This is in contrast with the case of coaxial cables and high impedance detectors, which sense the voltage and draw minimal amounts of power, or coherent optical detection.
- **Inefficient fan-in.** If fibers of constant cross section are used, an $(m \times n)$ lossless coupler has a power split of max $\{m, n\}$. (The ratio of power at a single input to that at the output is max $\{m, n\}$.)[1]
- **Excess loss.** This represents the imperfection of the coupler and its connectors.

For a given transmitted power P_T, the maximum allowable path loss is $P_T/P_{R_{\min}}$, where $P_{R_{\min}}$ is the minimum amount of power required at the receiver. In studying the performance of existing optical receivers, one observes that over a wide range of transmission rates (100 Mb/s to 1 Gb/s), $P_{R_{\min}}$ is roughly proportional to the transmission rate [12]. This is consistent with a requirement of a minimal amount of energy per bit. As a result

$$P_{R_{\min}}(B) \approx B \cdot P_{R_{\min}}(1). \qquad (6)$$

[1]This is indirectly explained by the constant radiance theorem in optics [10], which states that when a narrow beam undergoes a linear lossless transformation, its radiance remains constant. A corollary of this is that the product of the cross-sectional area and the square of the numerical aperture of an optical beam must remain constant under any lossless linear transformation of that beam [11]. As a result, when several fibers are fused to form a single fiber, as is the case at the input of a star coupler, the cross-sectional area decreases and the numerical aperture increases. Unfortunately, the numerical aperture of the fiber is not any larger than that of the original one, so most of the power cannot propagate and is lost. The fact that the cross-sectional area again increases at the output of the coupler does not help.

TABLE II
FIBER-OPTIC COMPONENT REQUIREMENTS, STAR IMPLEMENTATION

Conditions Equal:	Fibers		Couplers	
	PBI	SBI	PBI	SBI
C and B	$2N \cdot c_{PBI}$	$2N\sqrt{c_{PBI}}$	$c_{PBI}\ (N \times N)$	$c_{PBI}\left(\frac{N}{c_{PBI}} \times \frac{N}{c_{PBI}}\right)$
c and B	$2N \cdot c$	$2N \cdot c$	$c\ (N \times N) = \frac{N \cdot c}{p} \log_p N\ (p \times p)$	$c^2\left(\frac{N}{c} \times \frac{N}{c}\right) = \frac{N \cdot c}{p} \log_p \frac{N}{c}\ (p \times p)$
C and c	$2N \cdot c$	$2N \cdot c$	"	"

Lemma 1. *The minimum power split for an* SHI *is* N_R/C_T.

Proof: C_T transmitters must jointly reach N_R stations. Thus, there must be a transmitter that reaches at least N_R/C_T receivers. The single-path unidirectional SBI provides proof that this limit can be attained.

The number of stations that can be accommodated by a passive fiber-optic interconnection is determined by the maximum path loss over all source-destination pairs. Since the subnetworks are disjoint, the first step in determining the maximum number of stations is to derive the maximum number per subnetwork (bus), N_b, as a function of the permissible path loss (*power margin*). Two configurations will be considered: a linear bus with taps, and a centralized star.

1) Linear Bus with Taps: A signal must first go through a sequence of up to N_b couplers that collect the signals of downstream stations onto the bus, and then through one coupler for every receiver on the bus.

Due to reciprocity of the couplers, the fraction of power that is coupled from a transmitter onto the bus is equal to the fraction that is taken off the bus to the dangling output of the coupler. This creates a trade-off in the selection of the coupling coefficient, and results in significant signal loss at each coupler [13]. This problem does not exist in the receiver couplers, each of which removes a small fraction of the signal from the bus. Nevertheless, the excess loss of a receiver coupler is compounded N_b times.

For simplicity of analysis, let us assume that all transmitter couplers have the same coupling ratio. Also, we take the effective transmitted power to be that which is actually coupled to the bus; finally, we lump the insertion loss of a receiver coupler together with the total loss of a transmitter coupler and the loss of signal that goes to the wrong output of each coupler and denote it L (>1). Thus, a signal traveling on the bus is attenuated by a factor L up to N_b times. The remaining loss is power split in receiver couplers and, if those are set to optimal ratios, is equal to N_b, the number of receivers on a bus.

The loss incurred by a signal from the first transmitter to the last receiver is thus

$$\frac{P_T}{P_R} \approx L^{N_b} \cdot N_b \tag{7}$$

and the maximum number of stations on any given bus is such that

$$N_b + \log_L N_b \approx \log_L\left(\frac{P_T}{P_{R_{\min}}}\right). \tag{8}$$

This expression is clearly quite crude. Moreover, typical values of L, N_b and the power margin are such that the logarithmic term on the left-hand side cannot be neglected. Nevertheless, (8) does offer some insight, telling us that for a linear bus with taps, the increase in N_b with an increase in power margin ($P_T/P_{R_{\min}}$) is sublinear. Indeed, the change of N_b with power margin suggested here closely matches the numerical results in [13], which are based on a more detailed model.

2) Star Configuration: The star configuration is logically an ($N_b \times N_b$) star. With the large star implemented using elementary ($p \times p$) stars as building blocks, the signal passes through $\log_p N_b$ couplers on its way from the transmitter to any receiver. The path loss is hence

$$\frac{P_T}{P_R} = N_b \cdot L^{\log_p N_b} = N_b^{(1+\log_p L)} \tag{9}$$

and the maximum number of stations on a bus is

$$N_b = \left(\frac{P_T}{P_{R_{\min}}}\right)^{1/1+\log_p L} \approx \frac{P_T}{P_{R_{\min}}} \approx \frac{P_T}{P_{R_{\min}}(1) \cdot B}. \tag{10}$$

3) Comparison Among SBI, PBI, and SBB: We assume equal capacity C for all three, and equal c for SBI and PBI. As a result, SBI can use a lower transmission rate.

- **Linear bus with taps.** Since we do not have a precise quantitative formula, let us consider the specific example of an LAN with an aggregate capacity $C = 900$ Mb/s; $P_T = 1$ mW; minimum energy per bit (at the receiver) is $1.5 \cdot 10^{-15}$ J (20 dB above the quantum limit); $c = 3$. Results for coupler losses of 0.5 and 1.0 dB are presented in Table III, which also depicts the maximum total number of stations. (Coupler loss includes connections, excess loss and fiber loss.) The results for 1 dB were taken from Fig. 6 in [13]; those for 0.5 dB were obtained using (8), with L chosen to

TABLE III
MAXIMUM NUMBER OF STATIONS—LINEAR BUS WITH TAPS
(Values of N_b and N marked with "*" are based on (8); the others are from [13], Figs. 6 and 7. ($c_T = c_R = 3$.))

Topology	B (Mb/s)	Power Margin (dB)	N_b 0.5 dB	N_b 1.0 dB	N (total)	
SBB	900	28.7	17*	11	17*	11
PBI	300	33.4	20*	13	20*	13
SBI	100	38.0	24*	15	72*	45
		40.0	27	16		

match the result in Fig. 7 [13] for a 40-dB power margin.

- **Star configuration.** Let N_0 denote the maximum number of stations that can be accommodated by the SBB with capacity C. It follows from (10) that

$$N_b^{\text{PBI}} \approx c \cdot N_0 \tag{11}$$

$$N_b^{\text{SBI}} \approx c^2 \cdot N_0. \tag{12}$$

4) Maximum Total Numbers of Stations:

- **Linear bus with taps:** Numerical results are presented in Table III. For $c_T = c_R = 3$, SBI offers an advantage by more than a factor of three. Moreover, since the benefit is due primarily to the fact that $N = c \cdot N_b$ (for SBI), the results would remain similar if we used equal transmission rates.
- **Star configuration:**

$$N^{\text{PBI}} = c \cdot N_0 \tag{13}$$

$$N^{\text{SBI}} = c^3 \cdot N_0. \tag{14}$$

The maximum number of stations which can be accommodated by SBI is thus always higher than the corresponding numbers for the single bus or PBI by at least a factor of c, due to the fact that $N^{\text{SBI}} = c \cdot N_b^{\text{SBI}}$. An additional advantage of up to c^2 over the single bus and up to c over PBI is a by-product of the reduced transmission rate.

C. Capacity with Fixed Transmission Power

Our discussion of ways of accommodating variable or unknown traffic patterns in Section II was based on an assumption of fixed transmission rate on a bus, and identified a trade-off between guaranteed worst-case capacity and uniform-traffic capacity. For fiber-optic implementations, however, a more realistic assumption is fixed transmission power. We now revisit the proposed compromises under this assumption. The analysis will first be carried out for a star implementations of each subnet, and then for a linear bus with taps.

With each subnet (bus) implemented as a star, the power at each receiver is inversely proportional to the number of receivers on the bus. (This remains true for lossy components, since the number of those in any given path is logarithmic in the number of receivers.) For fixed transmission power, the maximum transmission rate is therefore inversely proportional to the number of receivers on the bus.

Let B_0 denote the maximum transmission rate on a bus with N stations. We now recompute the capacities of the different configurations.

***k*-path SBI with equally populated buses.** (E.g., MSP.) The number of receivers on each bus is $N/c/k$, so the permissible transmission rate is $c/k\, B_0$. Thus

$$C_{\text{guar}} = k \cdot 1 \cdot \frac{c}{k} B_0 = c \cdot B_0 \tag{15}$$

$$C_{\text{unif}} = k \cdot \left(\frac{c}{k}\right)^2 \cdot \frac{c}{k} B_0 = \frac{c^3}{k^2} \cdot B_0. \tag{16}$$

Hybrid SBI-PSI. The permissible data rate on each bus of the SBI portion is $(c - c') \cdot B_0$, but that on the PBI buses is only B_0. Thus

$$C_{\text{guar}} = 1 \cdot (c - c') \cdot B_0 + c' \cdot 1 \cdot B_0 = c \cdot B_0 \tag{17}$$

$$\begin{aligned} C_{\text{unif}} &= (c - c')^2 \cdot (c - c') \cdot B_0 + c' \cdot 1 \cdot B_0 \\ &= ((c - c')^3 + c') \cdot B_0. \end{aligned} \tag{18}$$

Surprisingly, C_{guar} is identical to all cases, so we are free to optimize for C_{unif}. This is attained with $k = 1$ or $c' = 0$, both of which correspond to the single-path SBI. Moreover, while we implicitly permitted different transmission rates on different buses, the optimal topology does not exploit this! We conclude that the inclusion of the interplay between the number of stations on a bus and the allowable transmission rate strongly favors the SBI. For example, the uniform-traffic capacity of a single-path SBI with $c = 2$ would be (at least) four times higher than that of a PBI with $c = 2$ and the same power budget. (The worst-case capacities are equal.)

In any other implementation of a bus, such as a linear bus with taps, power budget (and thus transmission rate) is even more sensitive to the number of stations on a bus than in the star implementation. (The main contributor is actually the number of transmitters, since reciprocity of couplers dictates a compromise in coupling factors.) Since the optimal solution for the star was the one with the fewest stations per bus, it is clearly optimal for any other implementation.

Theorem 2. *Given N stations, each with c_T transmitters and c_R receivers, fixed transmission power and required energy per bit, and a required guaranteed capacity (over the entire range of traffic skews), the single-path SBI has the highest uniform-traffic capacity of all static, passive, single-hop, bus-oriented fiber-optic interconnections. Moreover, the capacity of this SBI is greater than or equal to that of any other SBI, PBI or combination thereof for any traffic pattern.*

Note. The careful wording of the theorem reflects the fact that for a known sparse traffic pattern, one can sometime construct a single broadcast bus (to guarantee single-hop connectivity) along with a collection of point-to-point links between pairs of stations that communicate extensively, thereby achieving a very high capacity for that specific pattern.

Linear bus with taps. In determining the maximum number of stations on a bus, we noted that a three-fold increase in power margin did not substantially increase N_b. In other words, a huge difference in power margin would be required to change N_b by even a small integral factor.

In the present discussion, N (total number of stations) and c are equal for all interconnections, so the number of stations on each of the SBI buses is smaller than those of SBB and PBI by a factor of c. Thus, we expect a very large change in the power margin, which in turn would result in a similarly large change in maximum transmission rate (based on (6)) and thus capacity. As an example, we again use numbers from Fig. 6 in [13]. (Unfortunately, we cannot use the same example as before because the numbers fall off the curves.) Reducing N_b from 20 to 10 (corresponding to $c_T = c_R = 2$) changes the required power margin from 48 to 28 dB. Under these conditions, the permissible transmission rate with the single-path SBI would therefore be 100 times higher than with PBI or SBB. Thus, even if only one of its four buses could be used due to traffic skew, the SBI's capacity would still be 50 times higher than that of PBI. With $c = 3$ the results would be even more dramatic.

IV. Discussion

Having established various advantages in SBI, in this section we revisit some of the costs and apparent disadvantages. Also, a number of issues that are outside the main thrust of this paper but may be of interest to the reader are discussed briefly.

The cost of multiple transmitters and receivers. We have shown that the single-path SBI offers substantial advantages over a single broadcast bus or even multiple broadcast buses. However, one may still wonder about the cost of multiple transmitters and receivers per station. Although each station requires several network adapters, these adapters can be much slower (for equal capacities) and cheaper. In fact, there is always a speed beyond which several slow adapters would cost less than a single fast one. The break-even point for SBI is lower than that for PBI due to the sharp increase in capacity with an increase in the number of adapters. (This increase is at least quadratic in c, but can be much higher for fixed power budget. For example, a 20-station network with two transmitters and receivers per station whose individual buses are implemented as linear buses with taps, would have a capacity on the order of 100 times higher than that of a single-bus LAN.) If one were willing to design special multi-adapters, further substantial savings would be attained.

Peak instantaneous rate. A perceived disadvantage of SBI relative to PBI is that PBI can make its entire capacity available to a single pair of stations whereas SBI cannot. However, the reduced number of stations on an SBI bus permits a transmission rate that is at least c times higher than on a single PBI bus. Stated differently, the capacity of a single SBI bus under an equal-power constraint is equal to or even greater than that of the entire PBI. The same is true for a comparison of SBI with SBB with equal transmission power per station. It is also worth noting that using the entire capacity of PBI for a single message complicates the protocols and requires packet reassembly at the destination.

Fault tolerance. The single-path SBI, unlike PBI, provides only a single path between any pair of stations. This path constitutes a single point of failure. However, multihop communication could be used in case of failure. With 2-hop routing, the interconnection can tolerate any $c - 1$ faults, like PBI.

A. Alternative Implementations

- **Rings.** High-speed LAN's are often implemented as rings rather than buses. While power-budget advantages are no longer relevant, SBI retains some of its other advantages. A similar observation applies to systems with other forms of signal amplification or coherent detection.
- **Spatial/spectral subnetwork separation.** Figs. 1 and 3 imply a spatial separation between the subnetworks, and call for c_T transmitters and c_R receivers per station. Nevertheless, separation can also be achieved in the frequency domain, polarization, angle [14] (when relevant) and others, and the actual number of transmitters per station can sometimes be as low as one. It is also possible to combine different separation methods. For example, one could combine spatial and spectral separation so that any two subnetworks are separated in space, wavelength, or both. The reader is referred to [15], [6], and [4] for a detailed discussion if this issue, including an algorithm for assigning wavelengths to subnetworks and the possible savings in fiber-optic components.
- **Spread-spectrum.** Decoupling of transmission rate from aggregate throughput was one of the goals of SBI. Further decoupling can be attained through the use of code-division multiple access [16]–[18] in the implementation of the individual buses. Thus, CDMA should be viewed as complementing SBI rather than competing with it.
- **The impact of using real channel access schemes.** Channel access schemes were not discussed in any depth. This is because the bidirectional SBI's, in which $c_T = c_R = c$ and each station has its transmitters and receivers on the same buses, can be operated using any existing LAN protocol. Moreover, most channel access schemes operate more efficiently at lower transmission rates [8]. Consequently, the fact that the total network capacity is divided among more buses makes those access schemes operate more efficiently. The use of real access schemes thus has a favorable effect on SBI's merits relative to those of SBB or PBI.

V. Conclusion

Equipping every station on an LAN with a small number of transmitters and receivers and interconnecting the stations through a collection of buses such that any two stations have a single bus in common can result in a sharp increase in total network capacity, especially with a fixed power budget, as well as other important benefits.

SHI's cannot compete with multistage interconnections or with multihop ones in terms of performance; nevertheless, this paper helps demonstrate that their performance can be extended quite dramatically beyond that of a single bus while retaining the simplicity and reliability of single-hop communication through a purely passive communications fabric. It is also worth noting that a much higher capacity can be attained by using frequency-agile transmitters; the interconnection, however, would no longer be static.

For facility of exposition, we focused on unidirectional SBI's, in which a station's transmitters and receivers were not connected to the same buses. However, with the exception of a small reduction in the number of buses ($c^2 - c + 1$ instead of c^2), all the results are also valid for bidirectional SBI's, which can be operated using any LAN protocol.

Our discussion was restricted to bus-oriented SHI's. While the capacity of these increases with c, it does not grow with an increase in the number of stations. With unidirectional media, such as fiber optics with directional star couplers, more general SHI's can be constructed [4], whose capacity can also grow with N [19].

In summary, we have shown that equipping stations with multiple transceivers and using multiple buses is not merely a necessary evil; it may actually be cost effective.

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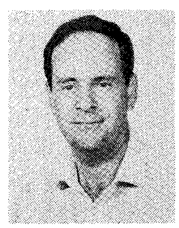

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