The Past, Present, and Future of Inverse Multiplexing

Aggregating channels so applications can readily select the optimum cost-bandwidth combination is becoming more attractive as applications increasingly require higher transmission bit rates.

Paul H. Fredette

The need to combine readily available network channels into higher bandwidths is not new, however, recent standards activities and worldwide access to digital channels is shaping a new segment of the communications industry. "Inverse multiplexing" refers to the process of aggregating channels to allow applications greater freedom in selecting the optimum communication bandwidth and cost.

The history of the recent Bandwidth On Demand Interoperability Group (BONDING) standard and its relationship to current and emerging network architectures are discussed. Applications of bandwidth-on-demand products to videoconferencing, multimedia, and LAN interconnect are described with respect to current and future equipment capabilities.

Many data transmission applications require transmission at bit rates higher than those available from carriers. Services are most cost effectively provided if they have characteristics common among many user applications. These two often conflicting goals have made designers of service access equipment invent a host of ingenious solutions to match the need for speed with the most commonly available channels provided by public networks. This article describes an increasingly popular solution to this problem given today's expanding switched digital networks.

Referred to as "inverse multiplexers" in the parlance of the marketplace, current implementations are providing national and international connectivity for diverse applications involving high-quality video conferencing, variable-demand LAN interconnections, and low-cost network backup. Development of these bandwidth-on-demand applications are fueled by increasing worldwide availability of high-quality circuit-switched channels at 56 and 64 kb/s, which have characteristics common to those used for standard telephone service.

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The Past

Early attempts at combining network channels paralleled incremental successes in modem technology. The analog voice channels readily available from telephone networks at any given time fixed bandwidth capacity for a given level of modem complexity. International circuits also had impairments, such as phase jitter and noise, which limited maximum transmission capacity and affected the cost per bit per second in a nonlinear fashion. Error detection and correction were also necessary for practical systems, and these functions were normally provided in devices generally referred to as data terminal equipment (DTE). These DTEs were actually special-purpose computers with standardized variable-speed bit-synchronous interfaces such as Electronics Industry Association (EIA) RS449, International Consultative Committee for Telephone and Telegraph (CCITT) V.35, or CCITT X.21. A single terminal interface operating at the combined speed of multiple channels was very desirable if it could operate at the optimum cost per bit per second or maximum rate of available technology. These devices were sometimes referred to as "biplexers" since the most cost effective solutions combined two channels into one. Since a new modem technology evolved to double transmission speed approximately every few years, no standard method of combining channels came into use.

As modem speeds approached theoretical limits of error rate versus signal-to-noise ratio and would have required channel aggregation to attain speeds at 64 kb/s and higher, a new revolution in transmission technology occurred.

The Digital Network Revolution

As noted in many articles [1], the conversion of international telephone networks to digital switches interconnected with optical fibers has changed dramatically in the last decade. Voice signals are now only one of many forms of octet-synchronized network signals that can be transmitted over large distances for as little

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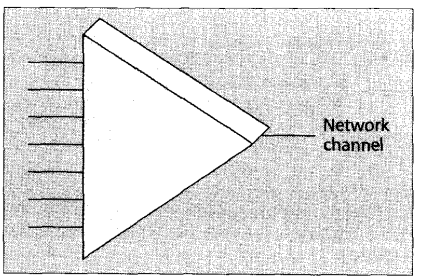
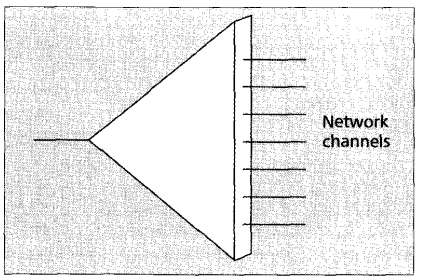


■ **Figure 1.** *Multiplexer symbol.*



■ **Figure 2.** *Inverse multiplexer.*

as pennies per minute.

During the frenzy of this conversion, access equipment was experiencing a similar metamorphosis. ISDN specifications were formalized to provide efficient methods of reusing the massive investment in access wiring between network customers and network switching offices. Existing T1 (1.544 Mb/s) technology in the United States provided the initial multichannel digital access facility. Similar systems in the Far East and Europe were also deployed and continue to grow exponentially. Two-wire technology is now enabling the use of the standard (unloaded) telephone pair to be used for two channels of 64 kb/s, with each channel independently routed through the network.

The Problem

Although combining two or more network channels may appear as straightforward as interleaving bits from each channel in the correct ratio, network channels between the same two locations often take different paths through switching equipment. Each path has a different transmission delay, which the aggregation unit must compute and compensate for. The solution makes use of training signals for selecting the longest delay path as a reference and then adds appropriate delays to data from other paths to allow interleaving of bits in the same order as transmitted. The implementation is also somewhat simplified if the training signals are designed to take advantage of multibit synchronization maintained by the network. Since the public digital networks of today were designed for voice transmission using network-maintained octet synchronization, this property can be exploited in the design of a channel aggregation algorithm. However, the signals should contain enough information to allow synchronization when octet alignment is lost.

Inverse Multiplexing

The term "inverse multiplexing" bears some explanation. Because multiplexing involves the aggregation of several independent channels into a higher-data-rate network channel, it is commonly drawn schematically, as in Fig. 1. Since channel aggregation as defined in the BONDING standard is the process of implementing a high-speed channel by splitting it into several network channels at lower speeds and aggregating the network channels at the remote end, a meaningful illustration of this function is shown in Fig. 2. It is this symbolic reversal that gives rise to the term inverse multiplexing. Equipment performing inverse multiplex functions are also commonly referred to as IMUXes.

Alternatives

Other solutions to the problem of combining channel capacities also exist in the form of packet-based systems, which segment data into numbered packets and recombine them (in order) as they arrive. The CCITT (now the International Technological Union – Telecommunications Section, or ITU-TS) X.25 recommendations of 1984 even provided an optional "multilink" method for segmentation and packet reassembly. Packet-based methods are not explored here, but the evolving availability of ATM networks with various access speeds may resurrect or replace these techniques. However, packet techniques do not readily recombine data onto standard bit-synchronous interfaces such as EIA RS449 or CCITT V.35 and X.21, which are popular on variable-speed terminal equipment used for real-time image and audio transmission, multiprotocol routers, and computer-to-computer communications. The interleaving techniques of standardized IMUXes may also be thought of as the limiting case of packets of one bit.

BONDING — A Breakthrough in Interoperability

As in the past, the market generated proprietary solutions to the inverse multiplexer problem. The wisdom of the past, however, also dictated that a standardized method of combining digital channels to form a single transparent "pipe" was required. This standard would allow multiple forms of access equipment to utilize a commonly available network capability. Market size, it was thought, would increase dramatically if interconnectivity among vendors was achieved. This thinking among telecommunications equipment providers was coupled with a maturing video compression technology, allowing standardized methods of near-television- quality video to be transmitted at speeds on the order of 384 kb/s.

The industry consortium called BONDING was formed in September 1991 and currently has 33 member companies. While the membership continues to grow, by the end of 1993 the group consisted of 31 telecommunications equipment manufacturers, one test equipment company, and one international carrier. The BONDING standard [2] defines a frame structure and procedures for establishing a wideband communications connection by combining multiple switched 56- and 64-kb/s channels through the use of a channel aggregation unit or inverse multiplexer. The group also sponsors interoperability events for demonstration and conformance testing. The first multicompany demonstration was completed in January 1992 and the first conformance event in April 1993. Nine companies participated and verified that interoperability could be achieved on the basis of the agreed-to specification. Subsequent to its acceptance by the BONDING membership, the specification was submitted to American National Standard Institute (ANSI) Telecommunications Industry Association (TIA) TR41.4 for review as a U.S. national standard [3] and has already reached the voting stage. The standard has also been presented

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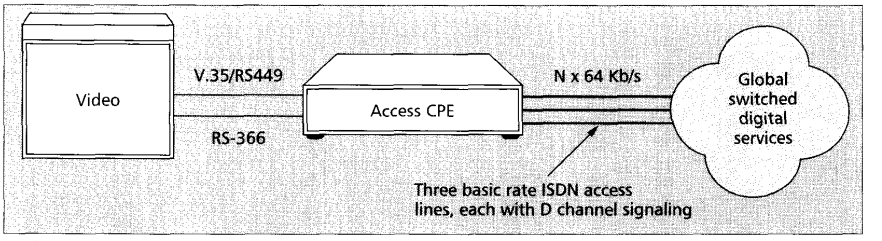
Video conferencing is considered one of the best applications for switched services: it requires a constant stream of data, is often scheduled in advance for blocks of time, and is otherwise idle.



■ **Figure 3.** *Typical IMUX/video conference system connection.*

to the ITU-TS working groups addressing channel aggregation standards. The U.S. draft had reached the TIA letter ballot stage in September 1993.

The Present

When assessing the impact of inverse multiplexing, it is very important to recognize that network channels at 64 kb/s are expected to exist nationally and internationally, and their availability will far exceed that of any other form of digital network service. In addition, this type of channel, coupled with ISDN call control signaling, is quickly becoming a generic form of service independent of the service provider, and could in fact become as ubiquitous as the analog telephone channel used for decades by modems.

ISDN technology also makes call setup far quicker than the time necessary to dial single telephone calls with tone or pulse dialers.

It should be noted that although 64 kb/s is of significance internationally, the method is used extensively on 56-kb/s channels available in North America. Although the inverse multiplexer standard specifically addresses aggregation of 56- and 64-kb/s channels, the framing and procedures have also been used to combine other services such as ISDN hyperchannels (e.g., switched 384 kb/s) and n x 64 kb/s service [4]. Although hyperchannels are not as widely available as 56- and 64-kb/s services, they can be more cost effective than making n calls. Since carriers offering these services only have to charge for one call instead of n, they enjoy reduced billing requirements.

Current Applications

Video Conferencing — Video conferencing is considered one of the best applications for switched services because it requires a constant stream of data, is often scheduled in advance for blocks of time, and is otherwise idle. Also, the flexibility provided by switched connectivity allows unrestricted access to multiple locations. Private lines are often not cost-justified because they would be underutilized and are limited to fixed paths.

This application is typically implemented as shown in Fig. 3. High-quality full-motion video transmission has characterized the most prevalent use of the technology in recent years. While the availability of individual switched 64-kb/s network channels has made the compression of images more feasible than in the past, perceptible quality degradation based on motion tracking capability and processing delays is evident even in expensive systems. Although two call channels (e.g., one for audio and one for video) makes conferencing practical, significant quality increases are observed by the typical user as the speed approaches 384 kb/s — the equivalent of aggregating six channels of 64 kb/s. With inverse multiplexers, each conference call can be assessed for the quality required versus cost of connection.

Image Retrieval and High-Speed Bulk Data Transfer — Document and medical imaging devices now produce large files of digital data that are stored for later retrieval and distribution. The types of documents stored include loan applications, insurance claim forms, invoices, and legal correspondence. Magnetic resonance imaging (MRI) scanners routinely generate a 30- to 50-Mbyte file for each patient scanned. Switched services used in conjunction with IMUXes can reduce the time needed to share such files with distant associates, hence minimizing the time required for appropriate action.

Disaster Recovery and Private Line Backup — Many private networks, such as reservation and air traffic control networks, are critical to the mission of a business and must remain in operation at all costs. For this reason, fully redundant circuits are often deployed at significant cost, even though they are rarely used. IMUX units can provide temporary dial backup at significant savings over dedicated private lines.

Overflow Capacity — This application is similar to disaster recovery, except that the impetus for adding and deleting connectivity is based on peak traffic loads and can take advantage of IMUX technology to reduce overall network cost.

LAN Interconnect — LANs are used to link an assortment of computers with file servers, database servers, printers, and other shared devices. As LAN deployment increases, larger companies find themselves in need of further connecting numerous, geographically dispersed locations. The multiprotocol bridge/router connected to a WAN service, as shown in Fig. 4, has emerged as the ideal solution to this LAN interconnect problem. Until recently, WAN choices have been limited to private line services like 56-kb/s DDS and fractional T1. However, faced with a steadily increasing demand for bandwidth and constant pressure to reduce cost, switched services used in conjunction with inverse multiplexers provide a flexible and cost-effective alternative. Because most routers now use synchronous protocols with the standardized HDLC idle character (an octet with hexadecimal value 7E), inverse multiplexer products are now offered with a feature known as dynamic bandwidth allocation (illustrated in Fig. 5). The IMUX unit measures the router's utilization of the channel and automatically modifies the number of channels in an inverse multiplexer session on the basis of estimated need. The control algorithm for determining when bandwidth changes are required is not standardized at this time, but the utilization criterion is typically a weighted average of the percentage of transmission not containing flag characters, taken over several seconds to several hours. Modifying the actual data rate of the IMUX session is part of the IMUX standard.

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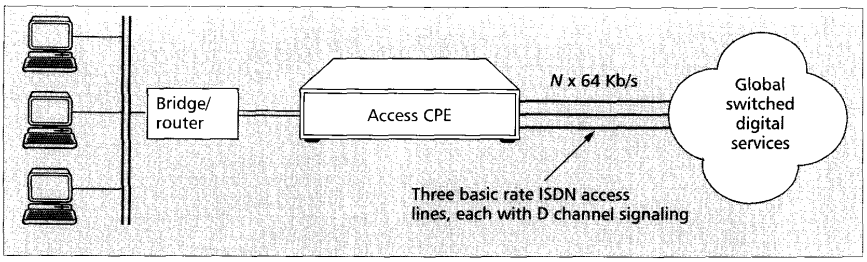
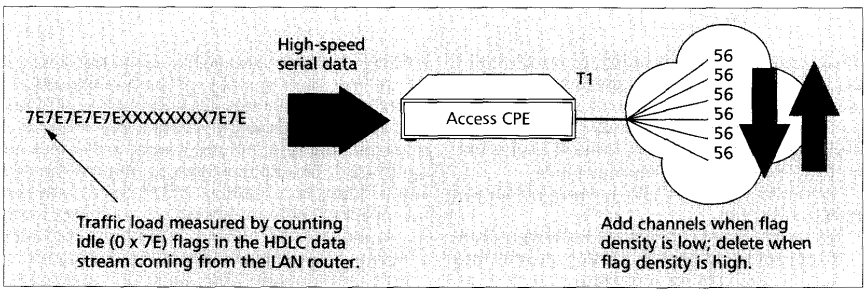


■ **Figure 4.** *Typical LAN-to-WAN connection.*



■ **Figure 5.** *Dynamic bandwidth allocation application.*

Capabilities of Standardized Inverse Multiplexing

While a single technique for establishing connection between two terminals exists in its standard, the BONDING technical committee defined four modes of operation, numbered 0 to 3. Mode 1 is the most efficient in channel utilization and is mandatory for conformance with the standard. Modes 2 and 3 can be negotiated with a conforming terminal using the essential portion of the mandatory mode.

Mode 0 is used to bypass the aggregation process for terminals using specialized methods of channel aggregation such as the ITU-TS H.221 standard [5].

Mode 1 is used to aggregate 100 percent of the capacity of each call channel used. For example, if six calls are made using switched 64-kb/s service, the combined channel will operate at 384 kb/s. In general, the combined data rate is n x 56 or n x 64 kb/s for n calls of the same service data rate. Calls with different service rates are not supported by the standard.

Modes 2 and 3 have the common goals of adding continuous monitoring of the delay per channel and the error rate of the transmission path, but each mode has different overhead characteristics. Mode 2 operates at n x 63/64ths of the service data rate when n calls are aggregated. While Mode 2 is quite efficient with 1.56 percent overhead, Mode 3 uses an extra call to achieve aggregated data rates that are multiples of 56 and 64 kb/s. Data rates that are exact multiples of 56 and 64 kb/s are particularly useful in providing backup paths for systems normally connected to nonswitched services, such as fractional T1 service, which are only available in these multiples. Most time-division multiplexers in private networks are systems in this category.

All modes use the following basic principles:

- Application data is encoded at the transmitter so that it is reconstructed in its original form. Framing bits used to achieve synchronization are transparent to the application.
- The initial call of a group of n calls is termed the "master channel" and is used to complete a negotiation process between the calling and called party before the remainder of the calls are placed.
- The master channel provides the called party an opportunity to indicate the telephone numbers to be used for establishing the remaining channels and to negotiate the mode of operation.

The "master channel" initially contains the Information Channel Frame shown in Fig. 6, consisting

	b1	b2	b3	b4	b5	b6	b7	b8
	Align							
Octet 1	0	1	1	1	1	1	1	1
2	1	Channel ID						1
3	1	Group ID						1
4	1	Operating mode			Res			1
5	1	RMULT						1
6	1	SUBMULT			BCR	Res	MFG	1
7	1	RI	R L Req	R L Ind	REV			1
8	1	Subaddress						1
9	1	Transfer flag						1
10	1	1	1	Digit - 1				1
11	1	1	1	Digit - 2				1
12	1	1	1	Digit - 3				1
13	1	1	1	Digit - 4				1
14	1	1	1	Digit - 5				1
15	1	1	1	Digit - 6				1
16	1	1	1	Digit - 7				1

■ **Figure 6.** *BONDING information channel frame.*

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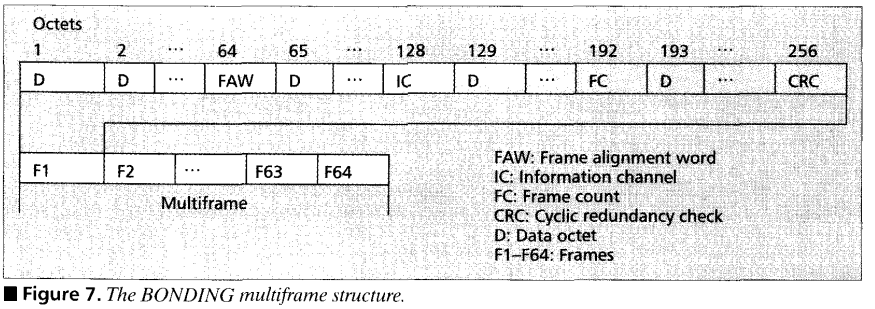

■ **Figure 7.** *The BONDING multiframe structure.*

of alignment, channel identifier, group identifier, mode, rate multiplier and submultiplier, bearer channel rate (BCR), manufacturer code (MFG), remote equalization complete indicator, remote loopback request and indication, revision level, transfer flag, and phone number/cause digits.

Additional aspects of the framing included in each channel are:

- Numbered frames of 256 octets consisting of channel data and, at intervals of 64 octets, an octet that, in sequence, contains a frame alignment octet, one octet of the information channel sequence of Fig. 6, the frame number (called frame count), and an optional cyclic redundancy check.
- 2-s multiframe repetition (64 frames) allowing aggregation of up to 63 channels with up to 1 s of relative delay between the channels.

The optional cyclic redundancy check octet is used for bit-error measurement of each call channel, and a loopback control in the information channel can be used for diagnosing active channels. Figure 7 illustrates the 2-s framing structure.

The Future

Given the current growth rate of switched digital services, the advantages of using inverse multiplexing are many. Competition among public and private network service providers has decreased the cost of making calls with 56- or 64-kb/s capacities, from about 30 cents/min to about 8 cents/min. Competitive pressure has also generated a maze of other promised services, such as ATM and frame relay, which compete with the advantages of combining basic services with inverse multiplexing to meet application-specific requirements. Basic-rate ISDN services capable of bringing 64-kb/s channels to businesses and homes on the same wires as analog telephones have been evolving at a significant rate everywhere but in North America.

However, as the lag in ISDN deployment in North America appears to be getting shorter, newer and less mature technologies are receiving significant attention. Two service offerings, switched 384- and 1536-kb/s hyperchannels (the ISDN H0 and H11 service) and dialable wideband service [4] (also called multirate ISDN), are becoming available, though they are not expected to have the level of worldwide interoperability provided by single-channel digital services. Another drawback to hyperchannel services is that they require primary-rate ISDN access lines, which are significantly more expensive than basic-rate access because they have a minimum capacity of 24 64-kb/s channels. Carriers have made claims that such services can save money by reducing the billing of multiple calls and that equipment designed with only their service will be less expensive. While this may be true when the service becomes ubiquitous, the flexibility needed to call almost anyone with digital telephone service will be accomplished by inverse multiplex equipment capable of both functions. Current IMUX devices can easily adapt to multirate services to save money when they are available, and switch to inverse multiplex mode to call a compatible device. Aggregating newer services to optimize cost can in fact be expected to proliferate the inverse multiplexer concept further.

While the BONDING standard was written for aggregating up to 63 channels operating at 56 or 64 kb/s, the concept is easily extendable to hyperchannels of any rate, including aggregating 1536-kb/s subchannels on DS-3 and synchronous optical network (SONET) facilities to rates comparable to LAN speeds of 16 Mb/s. Such higher-speed inverse multiplexers may require somewhat different equipment designs, since current equipment capable of 2-Mb/s operation is generally based on a single state-of-the-art digital signal processor, which may not be capable of extending operation beyond 5 Mb/s.

Other goals being pursued by the BONDING consortium beyond the promotion of its standard are the sponsoring of interoperability events and the development of methods for demonstrating compliance with the standard. Based on the level of current activity, the future of inverse multiplexing as an effective technique for matching application needs with available services seems destined to continue, as it has proven in the past to be adaptable to a changing network environment.

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Biography

PAUL FREDETTE is vice president and chief technical officer of Promptus Communications, Inc., Portsmouth, Rhode Island, and is also a cofounder and member of the Board of Directors. He received a B.S. in electrical engineering from the University of Massachusetts at Dartmouth and an M.S.E.E. in systems engineering from M.I.T. From 1978 to 1989, he held various posts as VP of engineering in the formative stages, and later chief technical officer, of Avanti Communications Corporation. He has also participated in the development of the ANSI standard for T1, performed computer simulation and systems analysis for the Naval Underwater Systems Center, and was employed at Bell Laboratories.

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