

Developing Leading-Edge Fiber-Optic Network Link Standards

David G. Cunningham

Delon C. Hanson

Mark C. Nowell

C. Steven Joiner

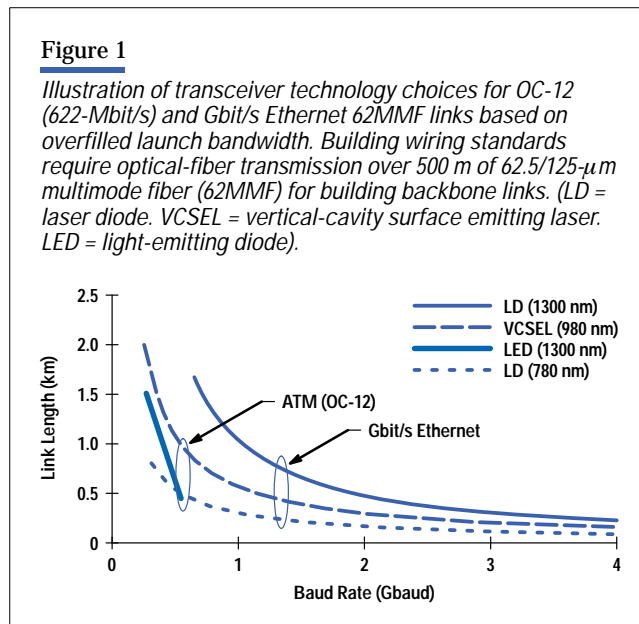
Advances in fiber-optic network technology within Hewlett-Packard are achieved by close cooperation between Hewlett-Packard Laboratories (HPL) and Hewlett-Packard's Communications Semiconductor Solutions Division (CSSD). This paper explores the interaction between HPL and CSSD for the advancement of high-speed LAN standards, particularly in the ATM Forum and IEEE 802.3z (Gbit/s Ethernet). Details of major technical contributions to 622-Mbit/s ATM and Gbit/s Ethernet specifications are presented.

Standardization has created a global fiber-optic LAN market in which Hewlett-Packard competes. However, successful open LAN standards are developed by consensus. Consensus is fundamental to the standardization process, since it ensures that the technological advances embodied in a final standard will be implemented by a number of vendors. In addition, standardization gives customers confidence that LAN products will not originate from a single source with corresponding higher prices. Given the need for consensus, it is important that Hewlett-Packard continuously participate in LAN standards development so that the company remains aware of current industry and future standards requirements. This understanding is a very important input into the strategic planning process for the HP Communications Semiconductor Solutions Division (CSSD) and Hewlett-Packard Laboratories (HPL).

Consensus-based standards make it impossible for any company to dominate the global optical-fiber LAN market. However, a long-term collaboration between HPL and CSSD has enabled Hewlett-Packard to be a market leader in high-speed optical-fiber LANs. Responsibility for developing future business and standards strategy is jointly owned by CSSD's strategic Pathfinders and HPL. CSSD and HPL engage the standardization process as early as possible. Involvement in embryonic standards provides valuable insight into the

capabilities and needs of Hewlett-Packard's competitors, partners, and customers. Based on this insight we adapt our standards and research strategy so that there is maximum likelihood of it being accepted by consensus-driven standards bodies. Actively influencing emergent standards ensures that a good return is achieved from Hewlett-Packard's investment in research and development. Obviously, this is a long-term commitment involving the continuous seeding of the Hewlett-Packard Laboratories research agenda many years in advance of emerging standards or customer needs.

Recently, two major high-data-rate fiber-optic LAN standards have emerged: 622-Mbit/s (OC-12) Asynchronous Transfer Mode (ATM) and Gbit/s Ethernet. Building wiring standards require optical fiber transmission over 500 m of 62.5/125- μm (core/cladding diameter) multimode fiber (62MMF) for backbone links. This building wiring standards requirement determines the choice of transceiver technology, as illustrated in **Figure 1**. The ATM Forum, which requires a 622-Mbit/s line rate, considered long-wavelength LEDs and short-wavelength laser diodes. VCSELs (vertical-cavity surface emitting lasers) operating near wavelengths of 980 nm were also discussed in the context of Gbit/s ATM links. The Gbit/s Ethernet standards committee considered short-wavelength laser diodes and long-wavelength laser diodes. CSSD and HPL made major technical contributions to both standards, which led to the inclusion of 1300-nm LEDs in the OC-12 ATM Forum specification and 1300-nm laser diodes in the Gbit/s Ethernet specification.



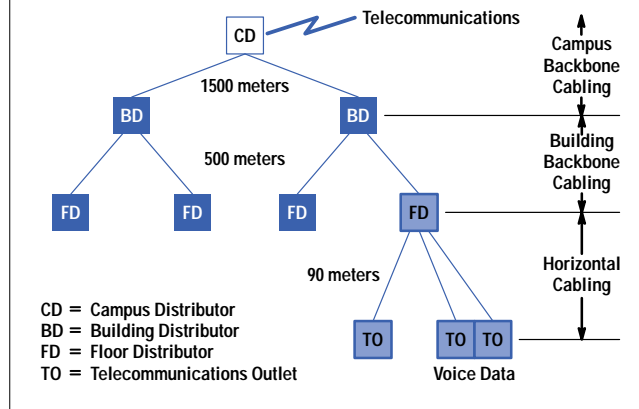
This paper will provide insight into the long-term collaboration between CSSD and Hewlett-Packard Laboratories in the area of fiber-optic LAN standards. The collaboration will be explored through the chronology of Hewlett-Packard's involvement in the development of recent LAN standards, particularly in the ATM Forum and IEEE 802.3z (Gigabit/s Ethernet).

Wiring Link Length and Transceiver Technology

Building wiring is a large capital investment usually amortized over approximately 15 years. To protect this investment, International Standards Organization (ISO) building wiring system standard ISO/IEC 11801 specifies cabling architectures, link lengths, and type. Historically, fiber-optic backbones for LANs are developed to support the link length requirements defined in ISO/IEC 11801. These requirements evolved out of the recognized need in the mid-1980s to achieve a more unified approach to developing and installing LANs. As illustrated in **Figure 2**, a key aspect of this building wiring standard is the definition of link lengths: 100 m horizontal from hubs to the desktop (90 m of cable plus up to 10 m for patch cords), 500 m for building backbone, and 2 km for campus backbone. These link length requirements dictate

Figure 2

ISO/IEC 11801 customer premises cabling model.



the choices of fiber-optic cable and transceiver technology as a function of data rate. In particular, because of its suitability for use with low-cost light-emitting diode (LED) transceivers, the installed base of optical fiber is predominantly 62MMF in both the U.S.A. and Europe. Transceiver vendors and fiber-optic LAN standards must develop transceiver technology that operates in harmony with the building wiring standards to protect the capital investment of both LAN users and LAN equipment suppliers.

The HP Communications Semiconductor Solutions Division is a leading supplier of optical-fiber optoelectronic components used to communicate over both premise backbones using primarily multimode fiber and public networks using single-mode fiber. Because of link performance and cost trade-offs, multimode fiber transceivers are developed using 650-nm, 850-nm, and 1300-nm technology. Visible 650-nm LEDs match the transmission window of large-core (980- μm diameter) plastic optical fiber, which has high attenuation but yields the lowest-cost transceivers and optical connectors as a result of relaxed mechanical tolerances. Infrared 850-nm and 1300-nm technology matches the transmission characteristics of glass multimode fiber having smaller core diameters, that is 62MMF and 50MMF (50/125- μm core/cladding diameter). These fibers have lower attenuation and higher bandwidth at wavelengths near 1300 nm compared to 850-nm operation but yield more expensive systems compared to plastic optical fiber. Single-mode fiber transceiver technology operating at 1300-nm and 1550-nm wavelengths supports the 10-to-50-km distance requirements of telecommunications single-mode fiber links and is still more expensive. Nevertheless, 1300-nm single-mode fiber links have extended transmission capabilities and are being deployed on the campus to extend beyond the distance and data rate limits of multimode fiber.

Fiber Optic LAN Standards Development

The initial fiber-optic backbone link standards developed in the mid-1980s support a 2-km campus backbone length using 62MMF. This requirement influenced the subsequent ISO/IEC 11801 campus backbone link length. The 10-Mbit/s, 2-km IEEE 802.3 Ethernet standard uses 850-nm LEDs while the 100-Mbit/s, 2-km ANSI X3T12 Fiber Distributed Data Interface (FDDI) standard requires 1300-nm LEDs because of the impact of fiber spectral dispersion at this higher data rate. Subsequently, based on the FDDI backbone link standard, a 2-km 62MMF link length specification using 1300-nm LEDs was developed for transmitting Asynchronous Transfer Mode (ATM) cells over Synchronous Optical Network (SONET) links at 155.5 Mbits/s, also referred to as optical carrier level 3 (OC-3). This OC-3 rate standard, initiated in the ATM Forum, was formalized in the T1E1.2 T1.646 broadband ISDN customer interface standard.

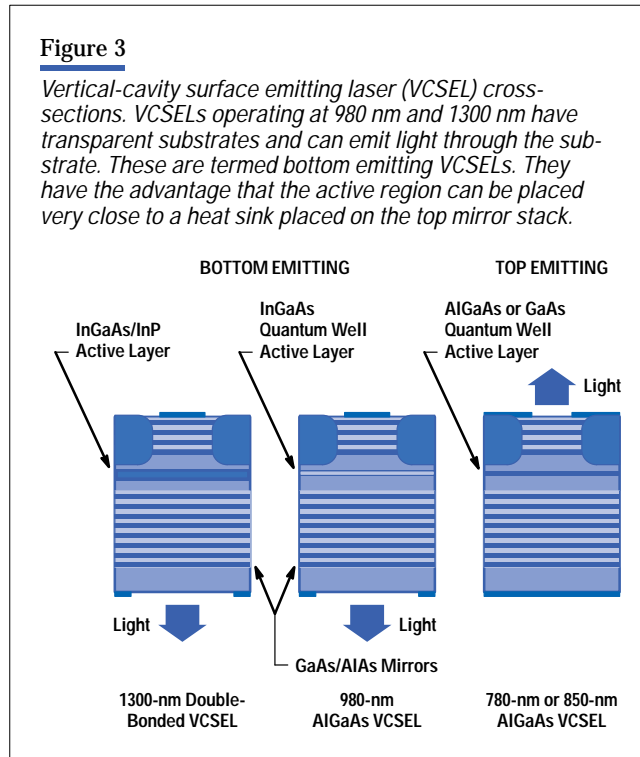
Long-Wavelength LED Specification

It was generally assumed that low-cost 1300-nm LEDs would be too slow for operation at 622 Mbits/s (OC-12). However, exploratory work at HPL Bristol and other manufacturers of 1300-nm LEDs indicated that the necessary 1-ns optical response time was achievable with low-cost designs. This resulted in a development program at CSSD yielding the necessary data to support an OC-12 specification for a 500-m 62MMF link length in both the ATM Forum and T1E1.2 T1.646 specifications. This is the highest data rate at which 1300-nm LEDs can reasonably be specified in multimode fiber link applications.

It was obvious to HPL researchers that a new low-cost, LED-like laser technology was required for multimode fiber Gbit/s LANs and computer interconnects. This realization was key to the initiation of vertical-cavity surface emitting laser (VCSEL) development within Hewlett-Packard Laboratories during the early 1990s.^{1,2} Since 1300-nm LEDs reach their limit at 622 Mbits/s, Hewlett-Packard developed a link length and data rate extension to Gbit/s ATM based on VCSELs operating at wavelengths near 980 nm.³ HPL demonstrated that 980-nm VCSELs could support building backbone link lengths at Gbit/s data rates with 62MMF. CSSD and HPL felt that this proposal was very suitable for Gbit/s LAN standards since it was in harmony with ISO/IEC 11801. By comparison, VCSELs operating at 850 nm were felt to be an inferior choice since they cannot support building backbone link lengths at Gbit/s data rates with 62MMF (see **Figure 1**) based on the standard overfilled launch (OFL) modal bandwidth for 62MMF.

Vertical-Cavity Surface Emitting Lasers (VCSELs)

The ATM Forum OC-12 multimode fiber specification development provided an interesting first view of VCSELs entering the standards arena. **Figure 3** shows VCSEL cross sections for devices operating at 850 nm, 980 nm, and 1300 nm.



A noteworthy aspect of the OC-12 link development in the ATM Forum was the short-wavelength (780-nm and 850-nm) specification developed in competition with the 1300-nm LED specification by short-wavelength laser diode transceiver vendors. The short-wavelength proposal was optimized for 50MMF rather than the dominant 62MMF. It was based on developments in the Fibre Channel (FC) standard for computer interconnect.

The short-wavelength proposal was written in such a way that it included both existing 780-nm Fabry-Perot edge emitting laser diodes, commonly referred to as compact disk (CD) laser diodes, and 850-nm VCSELs. After much contentious debate, the eventual result was that the ATM Forum adopted the two optically incompatible OC-12 multimode fiber specifications—long-wavelength LEDs and short-wavelength (780-nm and 850-nm) laser diodes—and left the marketplace to resolve the choice. In general, the winner will be the interface standard chosen by the major early adopters since other equipment suppliers will need to be compatible. CSSD sells many more long-wavelength LED-based transceivers than short-wavelength laser-based transceivers for OC-12 ATM.

Hewlett-Packard demonstrated to the ATM Forum that VCSELs operating at 980 nm are extremely reliable, are relatively simple to manufacture, are optically compatible with the specified OC-12 1300-nm receivers, and support building backbone link lengths at Gbit/s data rates with 62MMF. However, in the give and take of the standards arena, the Hewlett-Packard 980-nm VCSEL proposal for Gbit/s ATM links did not progress. One reason for this was opposition from multimode fiber suppliers to specify the higher modal bandwidth available at 980 nm with installed 62MMF. As a result of the OC-12 developments, HP focused its efforts on 850-nm VCSELs for use at Gbit/s data rates (described in the next sections) rather than 980-nm VCSELs and concentrated longer-term research on 1300-nm VCSELs, which have multiple uses with both multimode fiber and single-mode fiber.

OC-12 Technical Challenges

The ATM Forum OC-12 multimode fiber specification development brought into focus two major technical issues that must be addressed before Gbit/s optical link specifications will be acceptable to customers and LAN standards bodies. These are modal noise and robust transmission methods for 500-m backbone links using installed 62MMF. Both issues were widely recognized within the industry and ad hoc industry groups were formed to address them. The work of the ad hoc groups has now largely been transferred to Telecommunications Industry Association (TIA) fiber-optic test procedure committees. LAN standards committees have agreed to reference the new TIA fiber-optic test procedures once they mature. HPL and CSSD are very active in both the TIA committees and the LAN standards bodies.

Ethernet Frame-Based Gbit/s LANs

Because of its ease of use and relatively low cost, Ethernet has become the most pervasive LAN, with over 100 million nodes in service. The initial standard operating at 10 Mbits/s was finalized in 1985. This version of Ethernet connected all nodes via a central coaxial bus, which proved to be somewhat inflexible as users changed locations or were added to the network.

Hewlett-Packard proposed the 10Base-T star topology for Ethernet in 1987 and it became part of the IEEE 802.3 standard in 1990. In November of 1992, to meet user requirements for higher data rates and to support emergent multimedia applications, the higher-speed study group of the IEEE 802.3 committee was formed to develop 100-Mbit/s Ethernet. The efforts of the higher-speed study group culminated in July 1995 when the LAN MAN Standards Committee (LMSC) of the IEEE ratified two new 100-Mbit/s standards that use Ethernet frames: IEEE 802.3u⁴ and IEEE 802.12.⁵ These new 100-Mbit/s standards were designed to provide an upgrade path for the many tens of millions of 10Base-T and token ring users worldwide. Both of the new standards support installed customer building cabling as well as existing LAN management and application software. During the development of IEEE 802.3u and IEEE 802.12, Ethernet frame switching gained momentum as a method for increasing network capacity. Switch-based LANs are now being standardized by the LMSC.

The broad market acceptance of the new 100-Mbit/s shared media access LAN technologies is indicated by market estimates that during 1995, 25% of all network interface cards were 100-Mbit/s capable. International Data Corporation has estimated that two million Ethernet LAN switch ports were shipped during 1995.

The new 100-Mbit/s repeater and switch-based LANs require a higher-speed backbone. To address this need, both IEEE 802.12 and IEEE 802.3 initiated Gbit/s projects. It is generally agreed that the pervasiveness of Ethernet frame-based LANs will ensure that the LMSC Gbit/s standards will be the dominant Gbit/s LAN technology. Eventually, Gbit/s Ethernet frame-based LANs may reach the desktop.

Gbit/s IEEE 802.12 (Demand Priority) LANs

During 1995, IEEE 802.12 initiated development of Gbit/s demand priority LAN specifications initially as a higher-speed backbone for the 100-Mbit/s systems. HPL and CSSD demonstrated that higher-speed IEEE 802.12 could leverage some of the physical layers and control signaling developed for Fibre Channel.⁶ We also demonstrated that multimode fiber and short-wavelength VCSEL transceivers can be used to connect repeaters or switches separated by less than 300 m within a building.⁷ For longer campus backbone links, laser transceivers operating at a wavelength of 1300 nm are used. To ensure that only one Gbit/s physical layer solution set will be developed by the LMSC, HP has shifted a major portion of its physical layer activities from IEEE 802.12 to Gbit/s IEEE 802.3. This is sensible because Gbit/s IEEE 802.12 and IEEE 802.3 can use the same physical media interfaces.

IEEE 802.3 Gbit/s Ethernet

The IEEE 802.3 committee is responsible for development of the Ethernet LAN standards. In 1996, a crescendo of activity began to extend this data rate by another factor of 10 to interconnect 100-Mbit/s hubs and switches. The fast pace of the Gbit/s Ethernet standards development effort drove the need for joint efforts between CSSD and HPL Bristol to formulate and quantify HP's optical technology strategy to meet the requirements of this standard. The development of physical layers at Gbit/s data rates brought to the forefront the two key technical challenges previously debated during the ATM Forum OC-12 specification development: modal noise and robust transmission methods for 500-m backbone links using installed 62MMF.

Since the OC-12 debates, HPL and CSSD have worked actively to understand and quantify these issues both internally and externally in various ad hoc industry groups and standards task forces. Much of the knowledge and experience gained from our internal research and the external forums was used to develop the successful dual technology proposal that HP presented to IEEE 802.3z in July of 1996.^{8,9}

Because of their higher modulation rates and narrower spectral widths (compared to LEDs) Fabry-Perot laser diodes and VCSELs are the candidates for Gbit/s Ethernet standards. All new leading-edge LAN standards evolve from the progress made in previous or related current standards. In the case of Gbit/s Ethernet, the launching vehicle was the Fibre Channel standard operating at 100 Mbytes/s or an 800-Mbit/s serial data rate. Because Fibre Channel uses an 8B10B line code and incorporates a 62.5-Mbaud control channel, its line rate is 1.0625 Gbaud.

The vast majority of installed LAN building and campus backbones in the U.S. and Europe use 62MMF. A recent survey conducted as part of the Gbit/s Ethernet standard development process concluded that 44% of the installed 62MMF links in the U.S. have greater than 500-m link length. However, Fibre Channel is an interconnect standard and it was perceived satisfactory to achieve a worst-case maximum link length of 500 m with 50MMF at 1.0625 Gbaud if this resulted in the lowest-cost interconnect solution. The Fibre Channel 50MMF link specification is not sufficient for LANs, which are dominated by 62MMF. 50MMF has a 500-MHz · km worst-case modal bandwidth specified with overfilled launch (see **Figure 4**) at 850 nm, while only 160 MHz · km worst-case modal bandwidth under the same conditions is achieved with 62MMF. Therefore, Fibre Channel operating on 62MMF achieves less than 340-m link lengths at 1.0625 Gbaud, as shown in **Figure 5**. The inclusion of 780-nm lasers would reduce the Fibre Channel link length to less than 300 m. Gbit/s Ethernet uses the Fibre Channel 8B10B line code, which results in a 1.250 Gbaud line rate. As shown in **Figure 5**, the 18% higher data rate of Gbit/s Ethernet results in 19% shorter link length. This reduces the worst-case link length to ≈ 270 m with

Figure 4

Schematic representation of overfilled launch and restricted mode launch.

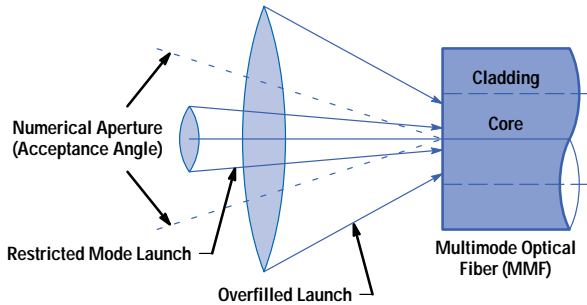
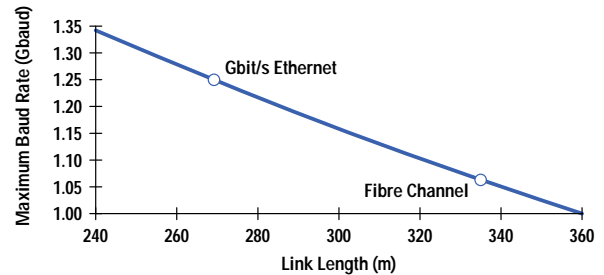


Figure 5

Link lengths with 820-to-860-nm lasers and worst-case 62MMF.



62MMF, far less than both the installed 62MMF LAN link lengths and the lengths specified in ISO/IEC 11801. This disharmony with ISO/IEC 11801 and installed LAN requirements provided the motivation for the dual link technology strategy proposed by HP at the July 1996 meeting of the IEEE 802.3 Gbit/s Ethernet committee. This strategy was launched by joint efforts at HPL Bristol and CSSD. The technical problems raised by the HP strategy and our proposed solutions are the primary focus of the remainder of this paper.

Long-Wavelength Laser and Multimode Fiber Links for Gbit/s Ethernet

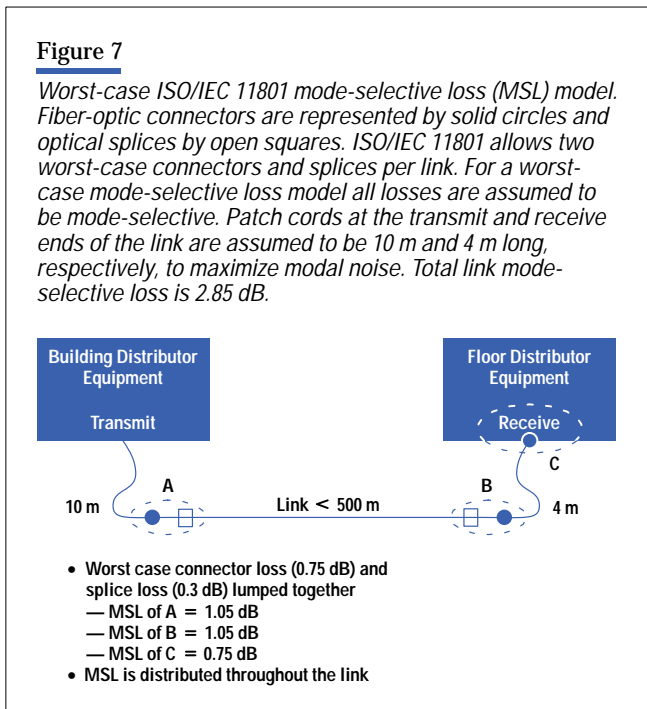
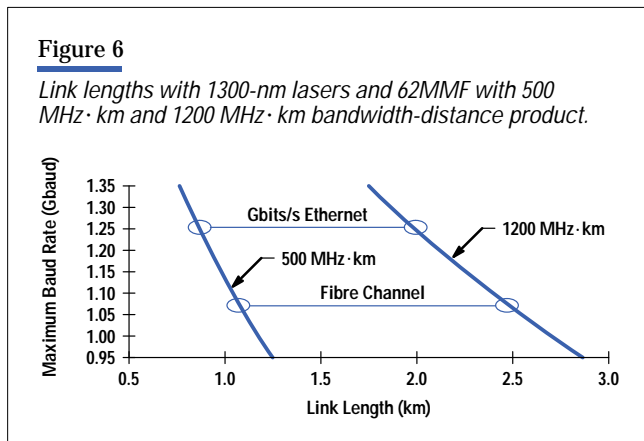
Because of the limited link length capability at 1.250 Gbaud of 850-nm laser diodes with 62MMF, a proposal was needed to service the installed base. The logical choice was to use existing 1300-nm laser diode single-mode fiber transceivers for single-mode fiber links up to 3 km and to extend the link length of multimode fiber. However, the use of long-wavelength laser diode single-mode fiber transmitters in conjunction with multimode fiber has traditionally been resisted by fiber-optic link designers because of the potentially catastrophic problem of modal noise. To support HP's proposal, it was necessary to develop theoretical and experimental evidence that a long-wavelength solution was robust to modal noise.

Modal Noise

Since the mid 1980s, there has been concern about modal noise caused by mode-selective loss when using relatively coherent laser diodes with multimode fiber links (see reference 10 and the references therein). Early research conducted at HPL Bristol indicated that 1300-nm laser diodes operating with 62MMF have the same modal noise performance as the 850-nm laser diodes operating with 50MMF within the ATM Forum OC-12 specification. Additionally, with 1300-nm laser diodes, the 62MMF link length supported (with the existing long-wavelength 500-MHz · km overfilled launch modal bandwidth specification) is ≈ 850 m, as shown in **Figure 6**. This link length exceeds the 500-m building backbone length defined in ISO/IEC 11801 but falls short of the 2-km 62MMF campus backbone length specified for many lower-data-rate LANs. **Figure 6** shows that a modal bandwidth of ≈ 1200 MHz · km is needed to support the 2-km 62MMF link length at 1.250 Gbaud.

Allocation for Mode-Selective Loss (Modal Noise): Theory. Many standards (ATM Forum, Fibre Channel, Serial HIPPI) contain power penalty allocations to allow for mode-selective loss. A modal noise theory¹⁰ has been developed and used to predict the worst mode-selective loss allocation for all these standards.

In addition, an ad hoc industry group (Hewlett-Packard, Honeywell, IBM, VIXEL), sometimes called the *modal noise test methodology group*, developed an initial mode-selective loss power penalty measurement test procedure. A PC-based simulation tool developed by HPL Bristol implements the theory of reference 10 and the tool has been accepted by the



group for calculating worst-case power penalties. Recently, a draft test procedure was transferred to the TIA FO 6.5 committee for standards development.

Distributed Mode-Selective Loss. An important conclusion from the original theory¹⁰ and the work of the modal noise test methodology group was that mode-selective loss is distributed throughout a fiber-optic link.

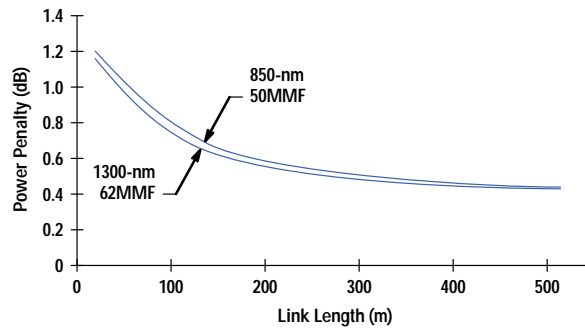
Theory predicts that mode-selective loss close to the transmitter will usually generate the most modal noise. However, even for the worst-case link model of ISO/IEC 11801 (**Figure 7**), only 2.85 dB of loss can be placed near the transmitter for short link lengths. To maximize modal noise, a 10-m patch cord is assumed at the transmit end and a 4-m patch cord at the receive end of the link. The initial 10-m patch cord ensures that both low-frequency and high-frequency modal noise is present.¹⁰ For the calculation, the worst-case loss of the connector and splice at each end of the link are lumped together. The resulting 1.05 dB of loss is assumed to be totally mode-selective loss and the minimum separation between the two 1.05 dB mode-selective loss points is 4 m. An additional 0.75 dB of mode-selective loss is assumed to be present at the connection to the optical receiver. The total amount of mode-selective loss is 2.85 dB.

Figure 8 shows the calculated power penalties as a function of link length for ISO/IEC 11801 links for both short-wavelength and long-wavelength lasers. The calculations assumed three laser modes having relative intensities of 0.1, 1, and 0.1, a linewidth of 5 GHz (laser modulated) for each mode, and a mode partitioning factor (k) of 1. It is clear from the theoretical model that the worst-case power penalties for the short-wavelength 50MMF and the long-wavelength 62MMF are equal. This is primarily because both multimode fiber transmission systems support the same number of modes at these respective wavelengths.

Modal Noise Test Methodology Group Worst-Case Link Model. To ensure that a reasonable worst-case link is analyzed and experimentally tested, the ad hoc modal noise test methodology group assumed that three 1-dB points of mode-selective loss separated by 4 m are placed 12 m from the transmitter output connector. The distance of 12 m ensures that the link has enough bandwidth for both high-frequency and low-frequency modal noise to be present and close to their maximum levels.¹⁰

Figure 8

Calculated power penalties for 850-nm 50MMF and for 1300-nm 62MMF, laser diodes, and the worst-case ISO/IEC 11801 model.



Predicted worst-case power penalties, according to the modal noise test methodology group model, for short-wavelength and long-wavelength lasers as a function of the laser rms spectral width are plotted in **Figure 9** and **Figure 10**. Maximum power penalties of approximately 1 dB are predicted as specified by ATM Forum, Fibre Channel, and Serial HIPPI standards for operation at either wavelength.

Figure 9

Calculated worst-case power penalty for 50MMF, 850-nm laser links as a function of rms source width using the modal noise test methodology group model.

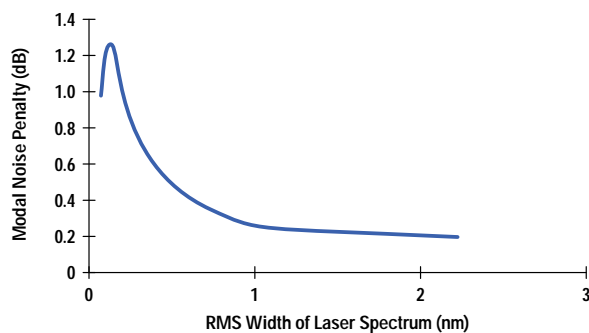
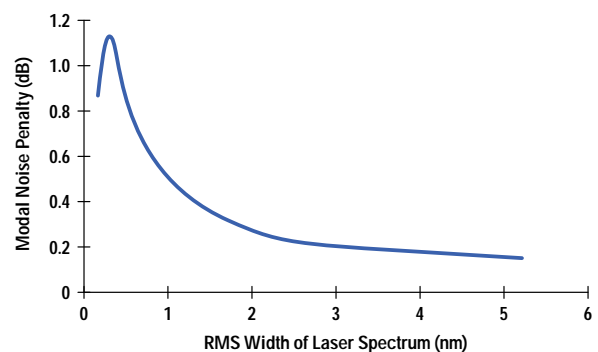


Figure 10

Calculated worst-case power penalty for 62MMF, 1300-nm laser links as a function of rms source width using the modal noise test methodology group model.



Modal Noise: Experimental Results. Modal noise testing has been concentrated on a selection of Hewlett-Packard low-complexity, 1300-nm coaxial lasers, which are expected to produce worst-case modal noise performance. All tests were computer-controlled, as depicted in **Figure 11**. The modal noise test box contains the three points of mode-selective loss and a reference path as required by the draft modal noise test procedure. During the testing the fiber was mechanically agitated and the temperature of the laser under test was continuously ramped. Although near worst-case long-wavelength lasers have been tested, the maximum power penalty observed to date is 0.3 dB. This is consistent with the predicted maximum power penalty of 0.6 dB for the coaxial lasers. A set of modal noise test results is shown in **Figure 12**.

The modal noise data summarized in this section led to consensus within the IEEE 802.3z committee that the HP dual technology strategy was the best option for Gbit/s Ethernet.

Figure 11

Computer-controlled modal noise power penalty measurement setup used for modal noise testing.

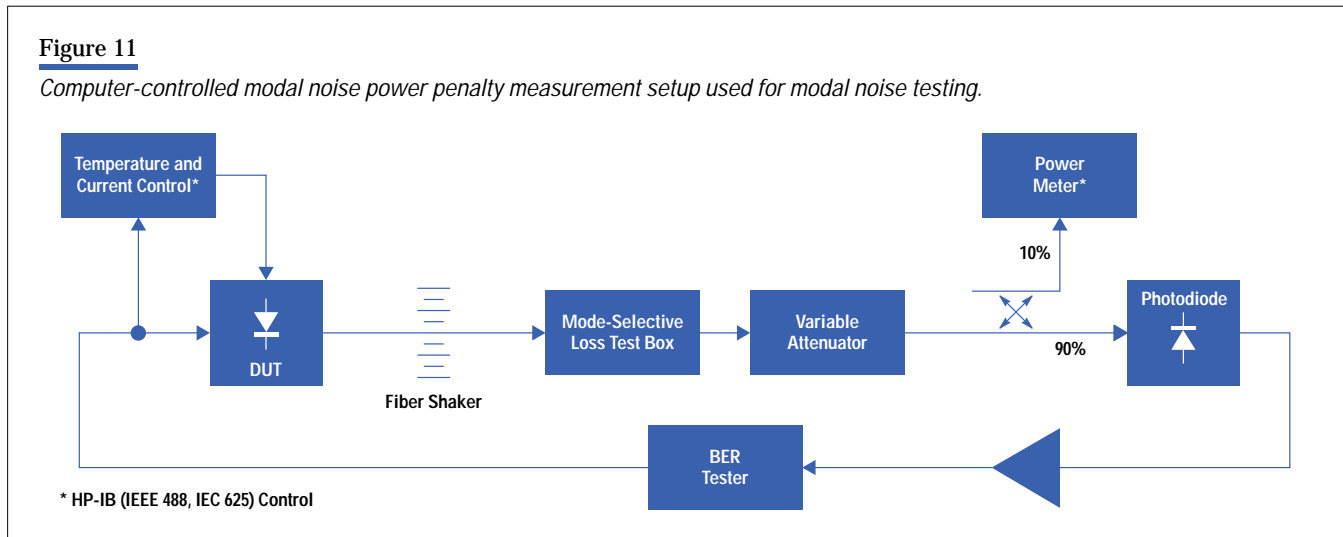
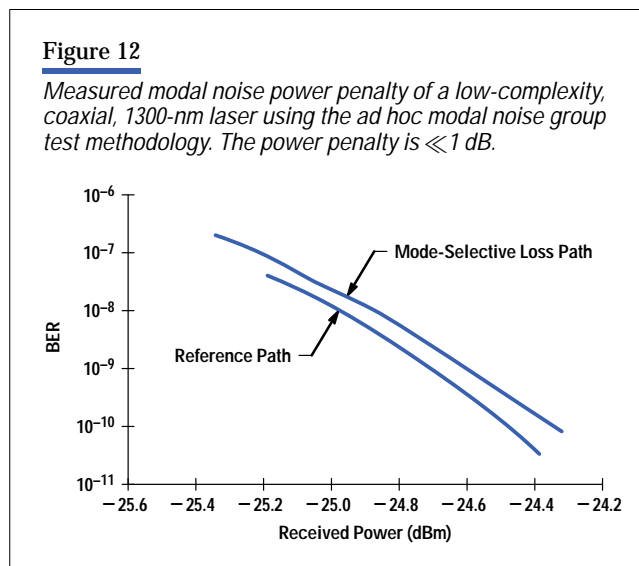


Figure 12

Measured modal noise power penalty of a low-complexity, coaxial, 1300-nm laser using the ad hoc modal noise group test methodology. The power penalty is $\ll 1$ dB.



Extended Link Lengths: Restricted Mode Launch

In contrast to short-wavelength transceivers, long-wavelength transceivers easily meet the 500-m link length needs for building backbones even with worst-case 62MMF bandwidths. However, achieving link lengths of 2 km as required for campus backbones requires new technical developments even at wavelengths of 1300 nm. For this reason, there is interest in using restricted mode launch to increase the bandwidth-distance product of multimode fiber. Such techniques are applicable to both short-wavelength and long-wavelength operation and to both 62MMF and 50MMF systems. The TIA has started a task group, TIA FO 2.2, to investigate restricted mode launch into multimode fiber. If the work of TIA FO 2.2 is successful, the IEEE 802.3 and IEEE 802.12 Gbit/s LANs are expected to incorporate restricted mode launch into their specifications.

Promising results have been presented to TIA FO 2.2 using various restricted mode launches (see *Figure 4*) to increase the bandwidth of multimode fiber. Unfortunately, the restricted mode launch effect with installed fibers is not completely understood and many questions need to be answered (installation effects, mechanical stability, connector effects, etc.) before LAN specifications using restricted mode launch can be developed.

Preliminary data reported to TIA FO 2.2 has indicated that the modal bandwidth can also be reduced below overfilled launch values with some forms of restricted mode launch. Even when pure single-mode launch is used, connector effects have been observed to significantly reduce modal bandwidth. These results indicate that some forms of restricted mode launch may not be a good solution for currently installed fiber.

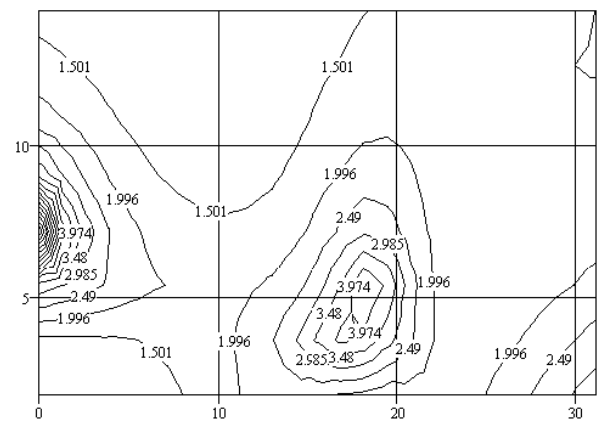
Restricted Mode Launch Theory. Modern graded-index multimode fibers have approximately square-law refractive index profiles. The modal field distribution can therefore be modeled, at least to a first approximation, as the field distribution of the modes of a square-law medium. In addition, it is well established that the WKB method¹¹ can be used to calculate the delay time of the modes. For power-law refractive index profiles, simple analytical expressions for the delay exist.¹¹

Using the analytical expressions for the field distributions and the delay times, it is possible to calculate the rms impulse width of a multimode fiber. In addition, other relevant parameters such as the coupled power can be estimated.

Figure 13 shows a plot of the bandwidth gain (restricted mode launch bandwidth divided by overfilled launch bandwidth) for single-mode excitation of an approximately square-law 62MMF as a function of the offset of the single-mode beam from the center of the fiber core and as a function of the single-mode beam 1/e waist. There is a large gain in bandwidth for center launch when the single-mode excitation has a waist equal to the waist of the fundamental mode of the 62MMF. Surprisingly, there is also a gain peak for offsets near one-half the fiber radius. The 62MMF bandwidth again increases for large offsets. While the intermediate and center launch would generally exhibit high coupling efficiencies, the larger offsets would suffer from substantial power loss.

Figure 13

Bandwidth gain contours for single-mode excitation compared to overfilled launch fiber bandwidth, at a wavelength of 1300 nm, for approximately square-law 62MMF. The x axis is the offset from the center of the fiber core in μm and the y axis is the beam waist in μm of the single-mode exciting beam.



Experimental Results: Single-Mode Fiber Center Launch. We have investigated restricted mode launches of low-complexity, 1300-nm coaxial lasers into 62MMF. The fiber used for the experiments had an overfilled launch bandwidth-distance product of 638 MHz·km. The output of a 1300-nm coaxial laser module with an SC connector was connected directly to various lengths of 62MMF, center launched. Each fiber length was made up by concatenation of 500-m reels of cable. **Figure 14** and **Figure 15** show the measured eye diagrams of zero and 2-km length links. Clearly, the eye is open to distances of 2 km. **Figure 16** plots the measured power penalties for various link lengths up to 2 km. The power penalty at 2 km is less than 0.2 dB at 10^{-10} BER.

Figure 14

Measured eye diagram at 1.25 Gbaud with 1300-nm, back-to-back transceivers

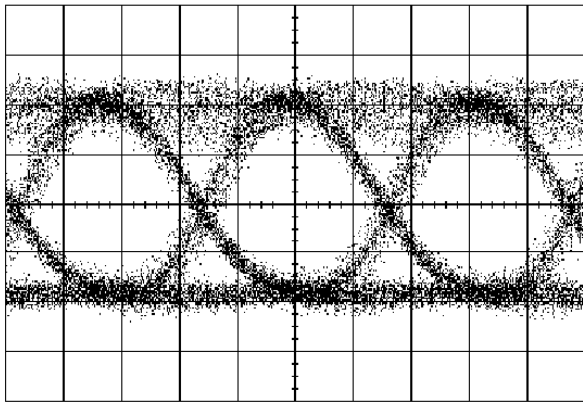


Figure 15

Measured eye diagram at 1.25 Gbaud with 1300 nm transceivers separated by 2 km of 62MMF.

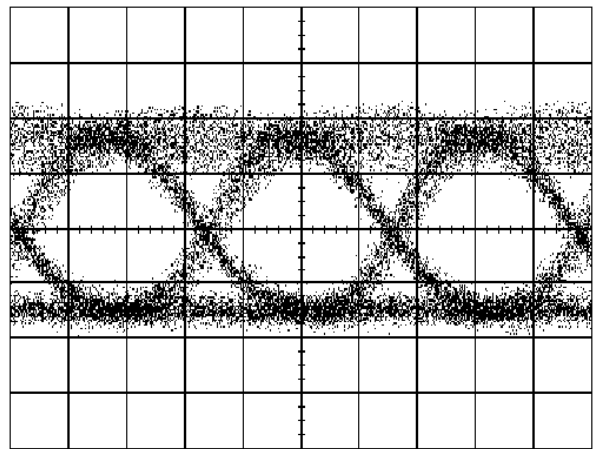
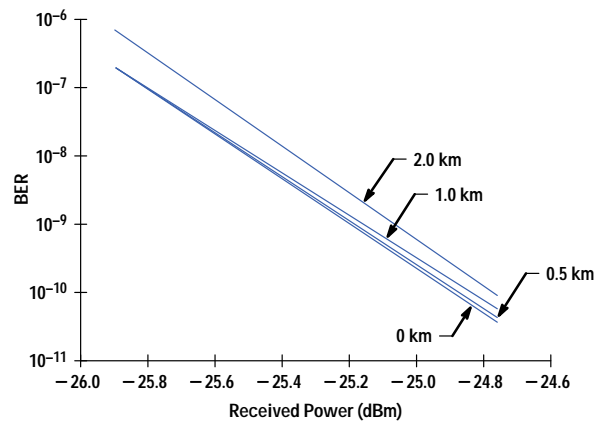


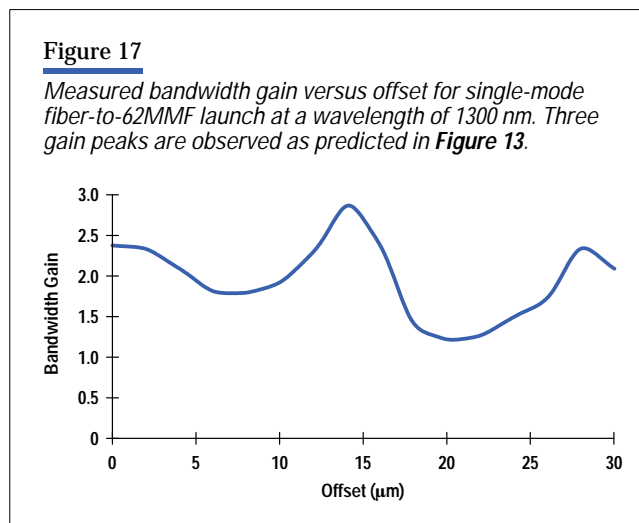
Figure 16

BER curves for 0-km, 0.5-km, 1-km, and 2-km link lengths.



However, with some fibers, particularly fibers with centerline refractive index defects, small connector offsets of the order of 5 micrometers result in very low bandwidth compared to overfilled launch. The use of restricted mode launch results in links much shorter than those obtained with overfilled launch for these fibers.

Experimental: Offset Restricted Mode Launch. A surprising prediction of the theoretical model (see *Figure 13*) is the occurrence of three bandwidth gain peaks. Experimental measurements of the bandwidth gain versus offset for a single-mode fiber-to-62MMF launch are plotted in **Figure 17**. The wavelength of the Fabry-Perot laser diode used was 1300 nm. The measured refractive index profile of the 62MMF had no dips or peaks and was approximately square-law. Three gain peaks were observed near the theoretically predicted offset values.



Although offset single-mode launches are restricted, for 62MMF and offsets in the range of 15 μm to 25 μm , the output intensity distribution is only slightly restricted compared to overfilled launch. This favorable excitation of the multimode fiber results in bandwidths equal to or greater than the overfilled launch bandwidth. We have observed that at least overfilled launch bandwidth can be achieved with offset launch on all fibers tested to date.

We have also investigated the modal noise penalties, connector effects, and mechanical stability of offset launches. No problems have been encountered in these areas. However, it is not clear that offset launches could be easily integrated into HP's manufacturing processes. HPL continues to investigate both center launch and offset launch to determine which type of launch is best for various LAN and interconnect systems.

Gbit/s IEEE 802.3 Link Specification Status

The July 1996 IEEE 803.3z Gbit/s Ethernet plenary meeting agreed to adopt two optical interface specifications. One interface is defined for 850-nm lasers to achieve link lengths of ≈ 250 m with 62MMF and ≈ 500 m with 50MMF. This gives up some extended link length performance to achieve the lowest possible cost. The second interface is defined to meet the installed 62MMF building backbone link lengths with 1300-nm transceivers, which achieve 3 km with single-mode fiber and ≈ 500 m with both 62MMF and 50MMF. Because the bandwidth achieved with center launched transceivers may be less than the overfilled launch bandwidth, IEEE 802.3z has defined its link lengths using a worst-case modal bandwidth. If conditioned launches that guarantee overfilled launch bandwidth are used, the IEEE 802.3z draft standard allows longer link lengths.

Conclusion

CSSD's and HPL's involvement in embryonic standards provides valuable insight that allows us to adapt our standards and research strategy to increase the probability of it being accepted. Our involvement in the ATM Forum OC-12 specification led us to refocus our VCSEL development to operation at wavelengths near 850 nm rather than 980 nm. This was because multimode fiber suppliers were opposed to specifying the higher multimode fiber modal bandwidth available at 980 nm and because all other laser transceiver suppliers were 850-nm focused. Our longer-term research was directed towards long-wavelength VCSELs, which have multiple uses with both multimode fiber and single-mode fiber.

CSSD and HPL have successfully championed long-wavelength LEDs for 622-Mbit/s ATM links. We also have shown, experimentally and theoretically, that long-wavelength lasers have similar modal noise power penalties to short-wavelength lasers when used with multimode fiber. For Gbit/s Ethernet, this enabled us to introduce a dual technology solution: short wavelength vertical-cavity surface emitting lasers for extended horizontal links and long-wavelength lasers for backbone links. The intriguing discovery that restricted mode launch can extend the data rate-distance performance of multimode fiber LAN links without increased modal noise penalties could revolutionize laser/multimode fiber system design. For this reason CSSD and HPL continue to investigate restricted mode launch.

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David G. Cunningham

David Cunningham is a departmental scientist and project manager with HP Laboratories Bristol, England (HPLB). He has been managing and leading HPLB efforts for the physical layer of the Gigabit Ethernet standard. He received his PhD degree in laser physics from The Queens University, Belfast in 1985. Before joining HP in 1987, he worked on integrated optics at British Telecom Research Laboratories. He is married and has a son



Delon C. Hanson

Del Hanson is a principal engineer at HP's Communications Semiconductor Solutions Division. A 30-year HP employee, Del is currently focused on fiber-optic network standards development and strategic product planning. He has published some 20 articles on microwave subsystems as well as fiber-optic components and networks. He is a native of Baldwin, Wisconsin, has been married for 38 years and has three children. Fishing, golfing, and gardening are among his outside interests.



Mark C. Nowell

Mark Nowell is a member of the technical staff of HP Laboratories Bristol, England. He is responsible for optical physical layer work and did the experimental measurements necessary to support the Gigabit Ethernet standards effort. He received his PhD degree from Cambridge University in 1994, specializing in optoelectronics. He is married, plays squash, and enjoys playing with his two children.



C. Steven Joiner

A principal engineer at HP's Communication Semiconductor Solutions Division (CSSD), Steve Joiner is a member of a group of engineers called Pathfinders by CSSD, who are responsible for the development of product definitions. With HP since 1978, he received his PhD degree in Physics from Rice University in 1979. He is married, has three sons, and is active in youth organizations and education.

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