What do you think of when someone mentions local area data networks? The chances are you picture communications ICs, protocols, network-interface connectors—the high-profile elements that engineers immediately equate with linking PCs into systems. But you'd be entirely wrong to ignore or dismiss the interconnection hardware that glues the infrastructure together. There's a revolution going on here: engineering connections to support speeds that you'd find hard to believe. Just how do you get 1-Gbps data rates across copper media? Surely, only fibre would support this kind of environment. Why do you need copper? And how does anyone develop, install, test, or verify these installations, which are now at the forefront of network managers' attention?

LANs once used a 10-Mbps bus topology with industrial-strength "thick Ethernet" coaxial cable, but 80 to 85% of today's LANs employ 10- or 10/100-Mbps Ethernet technology (Figure 1). This near-total market domination is due to a combination of availability, cost, flexibility, performance, and, last but not least, deployment ease. Although its main commercial competitor, token ring, traditionally uses a ring topology to connect network nodes, the ubiquitous Ethernet 10BaseT supports a hub-to-desktop, star distribution model that's far easier to configure and maintain. Critically, 10BaseT dispensed with Ethernet's dependence on coaxial cabling, substituting a low-cost cable that comprises two active 16-MHz bandwidth Category 3 unshielded twisted pairs (UTPs), terminated with RJ-45 modular connectors.

If 10BaseT didn't directly give birth to the structured cabling industry, it might just as well have done. Structured cabling systems provide architects with a uniform method for incorporating all the telecomm systems that organisations need within a building's fabric. In a structured cabling strategy, resources such as phone lines and LAN links radiate from local telecomm, or "wiring," closets to individual workspaces. Two four-pair cables or one four-pair cable plus a fibre cable connect each work space to the wiring closet. (Although you could run most LAN protocols and
phone lines within just one cable, it's better to separate these functions.) The flexibility that structured cabling endows made it an instant winner and in turn helped to promote 10BaseT to its dominant position.

**Bandwidth demand grows exponentially**

When Robert Metcalfe and his Xerox Park colleagues in 1976 unveiled their plans for Ethernet, 10 Mbps was a huge amount of bandwidth. More than two decades later, some 90% of desktop connections still communicate at this speed, and 100-Mbps connections are reserved for server-to-hub links. But PCs on every desktop and the rise of distributed databases demand exponential increases in connection speed throughout the system. The International Standardisation Organisation (ISO) in 1995 ratified Category 5 interconnection hardware specifications, which extend link bandwidth to 100 MHz and mainly support 100-Mbps 100BaseTX Fast Ethernet systems. Despite much argument at the time, Category 5 hardware will also run 155-Mbps asynchronous-transfer-mode (ATM-155) traffic. (You can download the specifications document from the ATM Forum.)

Today's bandwidth expectations mean that Category 5 is strategically dead. The Category 5 Enhanced (5e) standards, which should have been ratified in August and may be finalised at November's committee meeting, specify new measurements that provide more margin for 100BaseTX and ATM-155 traffic. Critically, Category 5e standards make reliable Gigabit Ethernet connections possible. But many structured cabling suppliers argue that Category 5e is only an interim solution on the road to Category 6, which will support at least 200 MHz; in the interests of sufficient operating margin, the IEEE is requesting a 250-MHz Category 6 specification. Despite the fact that the Category 6 standards are only at draft stage, manufacturers are offering a host of products and claiming that these products comply with the draft proposals.

**Who needs Gigabit Ethernet?**

In niche applications, such as special effects and postproduction houses, any flavour of Gigabit Ethernet offers the opportunity to work more efficiently. Instead of downloading a sequence from a server and running it locally in real time, multiple artists can view 27-Mbps video streams concurrently at their workstations. Other early adopters in the United Kingdom include meteorological offices and hospitals; both environments move gigabytes of data to model weather patterns or exchange medical images around campuses. But for most users, the best reason for installing the latest copper technology lies with providing the greatest degree of "future-proofing."

Carol Harris, UTP product manager at Molex Premise Networks, observes, "Unlike, say, workstations, network-cabling infrastructures expect a life span of at least 10 years. Pervasive computing and the rise of thin-client, or server-based, architectures mean that network loading will continue to grow dramatically, compounded by rich data types and ever more complex application software." Putting today's situation in perspective, Harris continues, "Category 5 cabling is adequate for most installations today, whereas Category 5e supports any of today's protocols and provides more margin."

She believes that Category 6 will extend that capability for future protocols and provides the best path for customers who are concerned about future-proofing their investments. However, Category 6 is far from final: "We're not expecting concrete specifications until 2001. In that sense, there's a risk that customers may buy Category 6 networks today and expect them to comply with a future definition," she says. To avoid that risk, Molex refrained from launching Category 6 products until the company was confident that the specs were stable enough. But, she cautions, like every other manufacturer, Molex claims draft Category 6 compliance only if you use the company's products.
As for cost, gigabit-level copper is expected to be less than half the cost to install than traditional multimode fibre. Compared with Category 5 products, you can currently expect a 15% premium for Category 5e and as much as 50% for Category 6. But notice that new-generation fibre-to-the-desktop systems, such as 3M’s Volition, are aggressively priced with connections that can cost as little as $80 per link, depending on the network design. Spurred on by copper media, a vendor price war looms in the Gigabit Ethernet switch market, with expectations for 800,000 Gigabit ports shipping at an average cost of $600/port by the end of this year.

Transmission-signal characteristics highlight the challenges that face advanced copper-LAN hardware designers. 10BaseT systems transmit binary-level Manchester-encoded pulses that provide a bit transition at the centre of each data cell for easy clock recovery (Figure 2a). This approach results in a bit rate that’s equal to the 10-MHz system-clock frequency with a useful frequency spectrum that’s double the bit rate. A founding principle in 100-Mbps Fast Ethernet’s design is that it runs over the same cable system as 10BaseT with one transmitting and one receiving path. Important design issues include limiting the clock rate to ease cabling requirements and limiting EMC emissions without resorting to shielded cabling.

A three-level modulation scheme allows Fast Ethernet to avoid a tenfold transmission-frequency increase. A repeating one-zero-minus-one-zero sequence provides the basis for determining the output signal—if the next data bit is zero, the output remains the same; if it’s one, the output changes to the next state. So, a long run of ones generates the highest signal frequency with a cycle length that’s 25% of the clock rate. To avoid long runs of zeros, the signal is first encoded into a 4B/5B format in which each 4-bit data nibble becomes a 5-bit code with additional bit transitions. Accordingly, the clock frequency is 125 MHz for 100-Mbps performance, and the worst-case signal has a 32.5-MHz maximum fundamental component.

In comparison, ATM-155’s NRZ signal yields a maximum fundamental component that approaches 78 MHz. But, because energy goes to the encoding rate that preserves signal definition, ATM-155 and 100BaseTX protocols require Category 5-level, 100-MHz links to operate reliably. Inevitably, energy exists above the encoding rate too, but you can actively filter this energy or use the cabling system’s lowpass characteristics passively to attenuate it without losing any useful information content.

In March 1997, the IEEE Standards Board approved the 1000BaseT project under the number P802.ab, whose committee’s objective is to design a Gigabit Ethernet system that runs over Category 5-level cabling. The new system must be seamlessly compatible with Ethernet environments, easing considerations such as dual-sensing network-interface card designs. The new system has the same basic transmission frame as the previous system, allowing compatibility with the huge application-driver-software base; optional "jumbo-frame" support reduces the negotiation overhead to more efficiently carry large data packets. Complementary developments include the possibility of breaking free of Ethernet’s historic model, whereby each machine on the network competes equally for the available bandwidth. By replacing hubs with intelligent Layer 3 switches and using protocols that prioritise data flows, such as IEEE 802.1p/1q, Ethernet can begin to rival ATM for quality-of-service (QoS).

From the cabling viewpoint, because UTP prevails in the United Kingdom and the United States, 1000BaseT must work seamlessly within this environment. The shielded-versus-unshielded cable debate has raged since 10BaseT’s introduction. Shielded cable may be preferable for high-frequency work and is the media of choice in many European countries, most noticeably in Germany, where most installations use cables such as screened twisted pair (ScTP) or foil-covered twisted-pair (FTP).
From an induced-noise perspective, a typical airport radar running at 600 kW creates a field strength of 4.2V/m at 1 km, enough to disrupt networks that are already close to their operating margins. UTP's supporters note that overall screening increases attenuation by as much as 15% per unit length, and ground-loop problems can negate any potential performance gain.

The solution that the IEEE's 802.ab committee found for 1000BaseT uses all four twisted pairs simultaneously in a half- or full-duplex configuration. The Fast Ethernet-compatible symbol rate of 125 MHz with 2 bits per symbol yields 250 Mbps per twisted pair. The encoding scheme is five-level pulse-amplitude modulation (PAM-5), a signal that yields 625 symbol combinations—sufficient for 8 data bits, an error-correction bit, and 113 additional symbols for control functions. The resulting power spectrum closely resembles that of 100-Mbps Fast Ethernet (Figure 2b). Compared with Fast Ethernet, the 6-dB SNR penalty that results is exactly compensated with Viterbi forward-error correction. In full-duplex mode, 1000BaseT's signal becomes a 5x5-matrix "constellation" that is familiar to communications engineers (Figure 3).

Despite the IEEE 802.ab committee's best attempts, 1000BaseT transceivers present silicon designers with huge problems and are only beginning to emerge. The transmit path is straightforward, but to maintain an efficient bit-error rate of less than 1 in 10^10, each of the four receivers requires an adaptive equaliser, an echo canceller, three near-end crosstalk (NEXT) cancellers, and five adaptive filters. At last July's Networks show at the UK's National Exhibition Centre, Foundry Networks was the first company to show a working 1000BaseT switch, the FastIron-II series. Price is currently approximately $650/port. The underlying transceiver silicon is Broadcom's BCM5400, a 3.5 million-transistor design that performs 250G operations/sec. The device is available for sampling for around $75; compare this level of complexity with the original estimates for transceivers with 200,000 transistors. Other companies planning 1000BaseT silicon include AMD, Intel, and Lucent Microelectronics.

100 MHz over copper is difficult

Designers must optimise every element in the connection-hardware chain before combining them to achieve 100-MHz-plus performance and to evaluate the overall system's interactions. Cable-test recommendations specify three link models (see sidebar "Navigating the standards maze"). Each element in the chain contributes cumulatively to overall system performance. Manufacturers combine materials and construction techniques with passive frequency compensation to meet overall link specifications. Table 1 compares the relative performance that standards demand.

Jason James, technical director at RW Data, says that the company manufactures all of its connectors using a pc board with a jack-and-insulation-contact-block arrangement. "The pc-board tracks connect the blocks to the jacks with any additional balancing. Balancing may include capacitance, inductance, or both, to reduce levels of NEXT, far-end crosstalk, and return loss. Inside the cable jacket, the four twisted pairs have different twist rates that help minimise NEXT. But the twist rates for each pair must remain constant along the cable's length to avoid impedance changes that increase return loss and crosstalk. Because twist rates are so important, you must control the cable's termination onto the blocks or within the patch-cord plug. For best performance, you cannot add or deduct twist at these termination points."

Cable management is important for Category 5 systems and becomes critical for high-bandwidth systems, such as RW Data's 400-MHz Category 6 GigaBand system. "The more the cable is disturbed in the form of tight bends, too many overtightened cable ties, too much pressure applied to the cable, and the like, the worse the performance of the cable gets," says James. "This performance reduction is cumulative. A poor installation wrecks high-speed links." According to James, these limitations are why the company uses registered installers to guarantee the long-term performance
of its systems. So, don't overlook the raceways that carry horizontal cabling from the wiring closet to
the outlet, and make sure that each termination preserves the cable's intended twist rate.

Lab tests assure performance

Manufacturers evaluate interconnection elements and links under laboratory conditions using
reference-standard network analysers from vendors such as Hewlett-Packard and Rohde & Schwarz.
Test setups for each cabling system follow Basic/Permanent Link and Channel configurations (see
sidebar "Navigating the standards maze," Figure A). The baseline TSB-67 tests require wire-map,
length, attenuation, and NEXT tests. New Category 5/5e requirements add propagation delay, delay
skew, equal-level far-end crosstalk, return loss, and power-sum measurements to the original TSB-67
suite. These new measurements result from 1000BaseT's full-duplex transmission mode (Figure 4).

"Delay" and "delay skew" refer respectively to the time it takes for a signal to propagate through the
link and to the relative alignment between signals received at the far end. Important factors of these
conditions include the cable's velocity of propagation, which is typically around 70% of the speed of
light, and, more important, how well each path matches. Category 5e/6 specifications require less-
than-548-nsec propagation delay and less-than-45-nsec worst-case skew, which is easy to meet;
crosstalk and return loss are today's most difficult areas to certify. NEXT measures crosstalk from a
transmitting pair to an adjacent passive pair in the same cable at the near (transmission) end. Equal-
level far-end crosstalk (ELFEXT) is similar to NEXT but measures the effect at the far end of the
cable. Power-sum (PS) NEXT measures the crosstalk that three transmitting pairs induce on the
fourth pair at the transmission end; power-sum ELFEXT makes this measurement at the far end.
Additional computations produce attenuation-to-crosstalk ratios (ACR and PS-ACR) that represent
signal-to-noise measurements that indicate safe operating margin.

Return loss measures the ratio of reflected-to-transmitted signal strength and is the single most
difficult test to repeat with consistent results; at Category 6 levels, the difference between a pass
and a fail can be the amount of bend in a test cord. Return loss is also causing headaches for
connector manufacturers, because the RJ-45 system isn't up to the job. The final stumbling block
with Category 5e ratification concerns the RJ-45 hardware; Category 6 is committed to RJ-45 for
backward compatibility, but the ISO's proposed Category 7 system will have a new and as-yet-
unspecified connector to accompany its revised cabling. Today, the return loss problem explains
why manufacturers of Category 6 hardware, which is supposed to be interoperable, claim Category 6
performance only if you use the manufacturers' matched parts throughout a channel link.

How do you check your network?

If you have a network installation that you want to verify because it is not providing the expected
results or because you have a Category 5 installation that you want to run 1000BaseT, don't lose
heart. Because the later Category 5 products considerably exceed their original design specification,
you may be able to upgrade components such as patch panels, connectors, and drop cables without
touching the installed wiring. You don't need a $30,000 network analyser to test your installation or
the specialist knowledge to use it and correctly interpret the results. Cable installers certify their
work with LAN cable testers, which are basically network analysers in a portable, user-friendly
format. (For an overview of what's inside a LAN tester, see sidebar "DSP techniques power LAN
tester."

Five major manufacturers offer LAN-cable testers for approximately $5000 (Table 2). Each tester
comprises a main unit and an intelligent remote unit that you attach to either end of the link under
test. Intelligent remote units adapt to the main unit's commands, so one person can use the test set
without reconfiguring the remote for each new test. Preprogrammed test sequences with
specification-limit lines perform the test suites that category 3 through 6 links require. Graphical user interfaces ease setup and data interpretation, and testers store results that you can download to a PC; some support graphical printouts that brighten textual reports. If you want to develop your own test routines or implement custom limits, ensure that the tester supports this capability.

Because higher level tests aren't final, ensure that your tester accommodates revised hardware and software modules. The tester-to-link interface is crucial for Category 6 performance. To minimise mismatches that magnify crosstalk and return-loss values, matched ports often link with a hardware manufacturer's product. This subject is a bone of contention among rival vendors and won't be settled until parties (all of whom sit on the industry's standards committees) agree on final specifications for link hardware and its test methods.

Industry insiders are clear that Category 5e is a stable, usable system. No one currently wants to discuss Category 6's shortcomings, fearing the wrath of corporate men in suits. The truth is that Category 6 is immature and needs further development before it's fit to roll out with confidence. Installation is as big an issue as the hardware itself; watch for the increasing European influence of cable installers' organisation, Building Industry Consulting Services International (BICSI). BICSI aims to raise installation standards and recently opened its first European office in Colchester, UK. Against this background, industry insiders regard talk of Category 7 as pie in the sky.

Adrian Young, product manager for Fluke's LAN cable testers, reports: "Last week, for the first time, I went to an installation that met and exceeded the latest Category 6 proposal. No coincidence that the installer had to go back to the manufacturer of the cabling system for retraining and education on what it takes to achieve Category 6! If only all installers were trained on how sensitive Category 6 is; being trained to install Category 5 gives you no automatic right to install Category 6. Why not ask your installer what additional training he's undertaken to install Category 6?"

DSP techniques power LAN tester

Like the network analysers from which standard measurement techniques derive, most LAN-cable testers use a variable-frequency oscillator to sweep the cable, with narrow filters differentiating received signals. The original TSB-67 specifies near-end-crosstalk tests that sweep frequency from 1- to 31.25-MHz bands in 150-kHz steps and then upward to 100 MHz in 250-kHz steps. But length measurements employ a time-domain-reflectometry technique, transmitting a pulse and then listening for echoes that indicate impedance variations. Most testers switch between these frequency-domain and time-domain modes to suit the current test style.

When Fluke designed the DSP-100, its first-generation TSB-67 tester, the designers decided to do it all in the time domain, transmitting pulse streams and analysing broadband signals using DSP algorithms to transform the results back into the frequency domain. One advantage of this technique is that the time domain also captures phase information, providing the possibility for more analysis from the same measurement sequence and to save overall test time, which increases rapidly while a cable installer is making a series of measurements to certify an installation.

Fluke has refined its time-domain approach in today's DSP-4000 tester. Although the company is close-mouthed about its latest tester's inner workings, the original DSP-100 is a combination precision pulse generator and waveform digitiser (Figure A). A sequencer triggers pulse-train generation, producing 16-, 64-, and 240-nsec pulses; a pulse-shaping circuit compresses the shortest pulse to 5 nsec. Like a DSO, the DSP-100's waveform digitiser uses sequential sampling techniques. The sampling rate results in an intersample spacing of 256 nsec. The sequencer adjusts the track/hold clock in 16-nsec increments, sampling 256-nsec periods every 16 nsec so that the overall measurement resolution becomes one sample every 2 nsec. Computation then transforms signal measurements into the units of interest. The only remaining analogue measurement is loop resistance, which uses the normal dc-source, reference-resistor, voltage-sensing technique that's familiar with any DMM. Results appear on a bit-mapped display, and are automatically compared with limit lines for the test standard selected. Beyond pass/fail, a popular measurement is headroom, which compares results with limit lines to indicate operational margin. In the home office, an installer can download field-test results to produce reports or certificates. Like every other manufacturer in Table 2, Fluke bundles PC-compatible software to support this process; as with anything to do with standards and measurement, the end product is a piece of paper.
Navigating the standards maze

A quick glance at Table 2 shows the plethora of standards that manufacturers target. The main standards bodies are the European Committee for Electrotechnical Standardization (CENELEC), the Telecommunications Industry Association/Electronics Industries Association (TIA/EIA), the ATM (asynchronous-transfer-mode) Forum, IEEE, and the International Standards Organization/International Electrotechnical Commission (ISO/IEC).

The TIA/EIA specify cable-test methods such as TSB-67 and TSB-95, as well as a standard for commercial building wiring in TIA-568A and its amendments. ISO/IEC 11801 and CENELEC’s EN 50173 are effectively equivalent, again specifying cabling infrastructures for customer premises. Other national standards authorities, such as those in Australia and New Zealand (Aus/NZ 3080) and Japan (JIS X 5150) administer broadly equivalent specifications. Incidentally, it's pedantic but true to observe that the TSB-series test suites aren't "standards" as such; they're "technical-service bulletins" that the industry adopts as de facto standards.

Just to confuse the issue, the TIA/EIA uses "category" definitions to describe cables, connectors and links. The ISO/IEC and CENELEC use equivalently numbered categories for cables and connectors but grade links according to "class" (Table A).

The main link definitions are the basic/permanent link and the channel. Basic and permanent links are a subset of the channel. The permanent link comprises the permanently installed horizontal wiring from the wiring-closet cross-connection to the work-area outlet; the basic link adds patch cords for test purposes (Figure A). A channel link contains every element you need to carry data from the wiring-closet hub to the desktop PC (Figure B).

A cable installer's test instruments must comply with the appropriate "Level" specifications to test these links. The test recommendations specify formulae from which you can derive the performance requirements across the frequency band (Table 2). TSB-67 introduced the Level-II test specifications for Category 5 cabling that Level-IIe extends for Category 5e environments. The TIA's 568A Addendum 2 cabling specifications require additional parameters to accommodate 1000BaseT; a yet-tighter, 100-MHz cabling definition appears in Addendum 3, which requires power-sum measurements that reflect 1000BaseT's full-duplex operation.

Level III specifications will address Category 6 link testing at frequencies as high as 250 MHz. These specifications are in development and aren't expected to be final until at least 2001. Mandatory tests that Level III adds to the Level IIe suite include resistance, capacitance, and impedance, although some testers already include these tests, which are especially useful in helping cable installers to characterise cable lots. Because the ISO has assured a future for a 600-MHz system in Category 7, some manufacturers are investing R&D effort in what many regard as pure vapourware; the difficulty in achieving unequivocal compliance is currently driving US installers to resist installing today's draft Category 6 systems.

Author info

You can reach Contributing Editor David Marsh at forncett@compuserve.com.