Residential Communications

Daniel A. Pitt

Establishing a communications infrastructure to get information to, from, or around a residence is not a straightforward task today. However, in the future the equipment and wiring within a residence for Internet communications will be treated the same as the wiring and equipment for services such as telephone, electricity, and cable television are treated today.

Residential communications involves getting information to, from, and around where people live. What makes this different (from, say, enterprise communications), unique, or interesting? Well, for one thing, people do different things at home than they do at work (although they are working more at home today). Also, there are many more homes than there are places of work. Perhaps most important, residents themselves pay for most of the communications out of their discretionary budgets. What is clear is that residential communications is growing in magnitude, type, and extent. It is being driven by demand (as for Internet access) and competition (from deregulation) rather than by technological advances, which are being sought as a means of satisfying demand.

As we discuss residential communications, we must keep in mind two distinctions. The first is between communications to the residence and communications within the residence. The second is between different types of residences. All too often we fall into the trap of equating the residence with the owner-occupied single-family home, but the worldwide market includes huge numbers of potential customers in single-family rental and multiple-dwelling units. These can vary from duplexes to high-rises, and they differ from single-family homes in their construction materials, infrastructure, and ownership. Indeed, the fact that these dwelling units are not owned by their residents is significant.

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Communications to the Residence

Communications to a residence today comes in many forms and what is notable is that they are all service-specific. Telephone lines provide telephone service. Cellular networks provide telephone service. Cable TV networks provide video entertainment. Satellite networks provide video entertainment. Paging networks provide paging services. Where they exist, energy-management networks provide energy-monitoring and control services. Moreover, each type is owned and operated by a service provider whose business is to sell a particular service. To date, only the telephone and cellular companies view communications as their business, and the others view services as their business. While the telephone and cellular providers welcome the growth of revenue from fax and data applications on their networks, they are not adequately equipped to handle the growth. These *residential access networks* base their economics on the cost of bringing the network to each residence and the anticipated revenue from each residence, especially as regulation diminishes.

The effect of deregulation and competition is an attempt by network operators to offer multiple services on their networks and to increase the capacity of their networks. These efforts stimulate the advance of network technology. Let us now examine some of these technologies. In each case we will connect the technology to the services it most naturally supports and speculate on its future. Specific technical aspects of these technologies are discussed in other articles in this issue.

Wireline Telephony Networks

Over 80% of homes in the U.S.A., and a not dissimilar percentage elsewhere, connect to the central offices of their telephony providers with twisted-pair copper wires (see **Figure 1a**). In some cases a few dozen customers share a high-quality twisted pair partway from the central office to the home, but in all cases each home has 4 kHz of analog bandwidth dedicated to itself. A bidirectional telephone conversation occupies all of this band, or it can be modulated to carry bidirectional, half-duplex data. Advances in signal processing have enabled the data rate to rise recently from the common 14.4 kbits/s to 28.8 kbits/s, 33.6 kbits/s, and even 56 kbits/s.

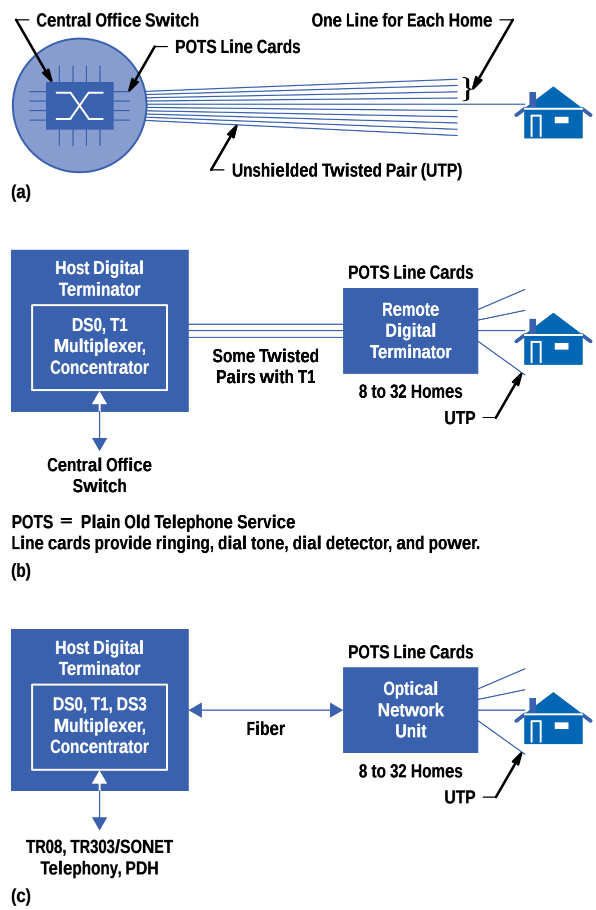
Perhaps 12 to15% of U.S. homes are served by digital loop carrier systems (**Figures 1b and 1c**). In these systems, the telephone signals are carried in digital form on an optical fiber from the central office to a point somewhere in the neighborhood, with all the signals for a group of homes multiplexed onto the same fiber. In a typical case, the fiber carries around 700 simultaneous calls (each at 64 kbits/s) giving an aggregate bit rate of 43 Mbits/s. Calling patterns suggest that this capacity can serve around 3500 homes. The remote node where the fiber terminates converts the digital signals to analog (for voice, dialing, ringing, and other signaling) and sends them on individual twisted pairs to each home. The user sees no difference between the all-copper system and the digital loop carrier system, but the operator's maintenance costs are lower with digital loop carriers. Telephone operators that wish to offer higher-bandwidth services have three main alternatives: integrated services digital networks (ISDN), asymmetric digital subscriber line (ADSL), and fiber to the curb (FTTC).

ISDN. This service provides a circuit-switched service made up of two full-duplex 64-kbit/s data (or voice) channels and a 16-kbit/s signaling (or data) channel. Many ISDN modems allow the user to combine the data channels to gain 128 kbits/s full-duplex, which is markedly better than dial-up modems. Because ISDN is a switched service, the user dials the destination (which must also be equipped with ISDN), uses the connection, and hangs up. During the connection, a path through a telephone switch is dedicated to the connection, whether or not data is flowing. A switch connection is a costly resource for both the subscriber and the operator, and it has proven notoriously difficult to get an ISDN line up and running, so ISDN is not a good technology for bursty, packet data. Its speed is much too slow for digital video, which requires anywhere from 1.5 to 6 Mbits/s for acceptable quality.

ADSL. The asymmetric digital subscriber line provides a packet-stream overlay on analog twisted pairs at megabit rates, exploiting unused bandwidth on the twisted pair of up to 1 MHz. Voice is sent unchanged in its analog form in the 0-to-4-kHz band. Megabit rates are possible in only one direction, hence the asymmetry, which is typically ten times greater in the downstream direction, which is in the direction of the home. Rates today range from 1.5 to 8 Mbits/s in the

Figure 1

Telephone network evolution. (a) All-metal beginnings in which twisted-pair copper wires go to each home. (b) Digital loop carriers. (c) Fiber-optic digital loop.



downstream direction and depend on the length of the line. Some 95% of U.S. customers are within 18,000 ft of their central offices, and 1.5 Mbits/s should be able to reach all these subscribers. Those at 12,000 ft or less could receive up to 8 Mbits/s. The latest designs incorporate rate adaption so that the ADSL modem adjusts its speed to the line quality (for which distance is one factor) in a static or dynamic manner. At the central office, the voice and data are separated, with the voice signal going through a circuit switch as usual and the data going into a separate packet network. A similar separator operates in the home, feeding the voice into the telephone wires and the data available to an Ethernet port.

Two competing technologies appear in ADSL products. One, endorsed by American and European standards organizations, employs discrete multitone (DMT) modulation, in which 1024 kHz of bandwidth is divided into 256 4-kHz segments, each modulated at a bit rate dictated by its noise characteristic at the moment. Thus, it is robust to narrowband interference. The other ADSL product, which has been on the market longer and is vying for standards approval, employs carrierless amplitude and phase (CAP) modulation. We believe it unlikely that either one will prove vastly superior to the other in real deployments.

The main advantage of ADSL is that it can be deployed without any modification to the infrastructure in the field (only endpoint modifications are necessary). It can be deployed one subscriber at a time when the subscriber agrees to pay for it and without the security risks of a shared medium. The barriers to ADSL's acceptance are (1) the cost of the equipment, which has been slow to drop below U.S.$1000 per line, (2) the data line concentration task at the central office, (3) the continued maintenance of the copper plant, and (4) its inability to carry broadcast video. As a medium-term technology for Internet traffic, ADSL might be promoted where there is competing cable-modem service.

FTTC. Fiber to the curb provides very high data rates over an expensive plant that carries fiber very close to the home. Voice traffic for one to three dozen homes is conveyed in digital form using digital loop carrier technology to the end of the optical fiber. Data is conveyed on the same or a different fiber to the same point but is kept logically separate. At the end of the fiber, the voice is converted to analog form (with ringing and signaling converted as well) and frequency multiplexed with the data on a dedicated twisted pair or coax line to each home. Downstream data rates can reach 51 Mbits/s with upstream rates ranging from 2 to 20 Mbits/s. Like ADSL, these figures represent dedicated bit rates for each home, not shared rates. FTTC has not been deployed widely because of its high cost and its inability to carry analog broadcast video. However, its data capabilities are unsurpassed and it represents how most telephone operators would like to send voice in the future. A compromise on cost, data rate, and distance between ADSL and FTTC is called *very high bitrate digital subscriber line,* VDSL. VDSL takes fiber to within 3000 ft (instead of FTTC's <1000 ft), reduces the data rate to 25 Mbits/s, and lowers the system cost substantially. From the end of the fiber to the home the techniques of ADSL are applied.

Cable TV Networks

The networks used for those 30, 50, or 70 channels of broadcast analog video are being upgraded to carry digital video and two-way data services. This requires replacing the all-coax tree-and-branch network with a fiber link that leads to a much smaller coax tree to just a few hundred homes instead of thousands. This is called hybrid fiber/coax (HFC).

More than any other factor, the development of wideband linear AM lasers, allowing the optical fiber to be modulated exactly as if it were coaxial cable has made HFC possible. HFC expands the system bandwidth from 300 MHz (a typical value) to 750 MHz. The 6-MHz channelization is retained,* and the new channels each carry around 30 Mbits/s of digital traffic, be it video, Internet, or voice. All traffic reaches every home since the system was designed for broadcasting. At home, a subscriber tunes to a given channel to receive one analog TV program (by a cable converter box), or one of up to 10 digital TV programs carried in one channel (by a digital set-top box), or some Internet data packets (by a cable modem).

The cable modem and digital set-top box also transmit upstream to convey upstream data or program-selection commands. Upstream transmissions fall into the 5-to-42-MHz band, which is notoriously noisy and narrow. Downstream transmission typically employs 16-, 64-, or 256-level quadrature amplitude modulation (QAM) to squeeze as many bits into the 6-MHz channel as possible. The most common upstream modulation scheme is quadrature phase shift keying (QPSK). Some vendors advocate spread-spectrum techniques to combat high noise levels and some even claim satisfactory operation over all-cable plants. At this point proprietary media access control (MAC) protocols govern the shared upstream channel, but several organizations are working on standardizing the MAC.

The 30 Mbits/s of downstream digital traffic is shared among several hundred homes. Upstream capacity is in the range of 10 Mbits/s with individual homes limited in most designs to around 2 Mbits/s; this, too, is shared among these same homes. Telephony, which requires symmetric bandwidth, must share the same upstream capacity but uses its own dedicated downstream channel. Eventually, Asynchronous Transfer Mode (ATM) is likely to multiplex all traffic types in each channel so that integrated receivers in the home can access nearly all of the home's traffic from a single 6-MHz channel and system capacity is optimized.

The strength of the HFC solution is that it carries on one network all types of traffic types including broadcast analog video, broadcast and interactive digital video, high-speed data, and telephony. Its weak points are its upstream capacity, the cost of upgrading the existing all-coax plants, and the lack of experience in highly reliable two-way communications.

* The 6-MHz channelization divides the spectrum into channels 6 MHz wide with each channel used either for one analog television program or for digital traffic of any sort.

It is a natural upgrade choice for those cable operators that can afford it. However, it is not likely to become popular among telephone operators.

Wireless Networks

Cellular Telephony Networks. Cellular systems can be and are used for data, but their capacity is limited and their cost is high. Speeds are typically limited to 19.2 kbits/s and the charges for cellular digital packet data make it unsuitable for file transfer, web page downloading, or anything other than small message exchange. The main advantage of cellular networks is their accessibility from nearly any location, including while moving.

Terrestrial Microwave and Millimeter-Wave Networks. These networks are emerging as attractive alternatives to reaching the home without digging up roads or yards or stringing cable. They use a grid of base stations, often similar in siting to cellular stations, and fixed receivers on homes (so no mobility is provided). Multichannel multipoint distribution service (MMDS), also known as wireless cable, is a one-way scheme occupying 200 MHz of bandwidth in the 2-GHz band. So far only broadcast analog video has been sent on the 33 6-MHz channels assigned to these wireless networks. However, many of these channels are gradually being converted to digital using 16- or 64-quadrature AM. There is no upstream channel so interactive services are limited to dial-up return. A multichannel multipoint distribution base station can serve tens of thousands of subscribers (at distances of tens of miles) so the data capacity per subscriber is low.

Local multipoint distribution service (LMDS) offers much greater capability. In 1997 the U.S. Federal Communications Commission (FCC) allocated over 1000 MHz in the 28-to-30-GHz band for local multipoint distribution. Other countries have allocations in that band and in the 40-GHz bands. Deployments are expected to start in 1998 with most of the bandwidth being used for downstream and broadcast transmission, partly because of the way the bandwidth was allocated.

Depending on the amount of broadcast traffic and because of the use of sectorized antennas, the downstream capacity ranges from 1 to 2 Gbits/s and the upstream capacity from 300 to 600 Mbits/s (aggregate). A typical cell radius is 1 km serving anywhere from 1,000 to 20,000 subscribers, so the capacity is considerable. The rooftop antenna need be no larger than one square foot and is not expensive, though it needs to be correctly aimed. The main problem with local multipoint distribution service is that a line of sight between the base station and the home is required, so the technology works poorly or not at all in heavily forested areas. Also, the entire transmission must be digital for adequate signal reception, so analog video is not supported.

Satellites. For quite a while satellite networks have been employed for broadcasting television programs. They also offer capabilities for other services. Geosynchronous satellites, which are used for TV today, can be and are being used for data by modulating a TV channel digitally as is done in cable networks. The difficulty is finding the right application for this. The satellite has no return channel so interactivity is not possible without using telephony return, which is awkward and undesirable. Moreover, today's satellites, designed for broadcasting, have footprints that reach tens of hundreds of millions of people, so the capacity per subscriber is minuscule. These features, along with the long transmission time, make the geosynchronous satellite a very suboptimal choice for interactive services.

As applications for data broadcasting grow, however, the satellite could become the ideal transmission medium. Low earth orbit satellites (LEOS) offer an altogether different service. Designed for telephony, these systems of dozens or hundreds of satellites offer ubiquitous access without the erection of base stations or the worry of being out of range of them. They also allow access by users in motion. However, if these satellites retain the data rates of terrestrial cellular services, they will be suitable only for telephony and control services and of little use for Internet services. Video, it seems, is out of the question, as is broadcasting of any sort.

There is also some activity in other wireless technologies, using various little places in the spectrum and speeds in the ISDN range. These are likely to remain niche services. The pursuit of an effective and affordable wireless data service with capacities of tens of Mbits/s continues mainly as a research activity.

Where Are these Network Technologies Heading?

What we expect is a period of experimentation with these new technologies in which we will try to determine:

- How easy they are to install
- How well they support various services
- Which services are profitable
- Which technologies lead to the greatest profitability in the shortest time.

The deregulation of the telecommunications business in most countries will result in competing operators, usually with different technologies, in many regions and to many homes. Our expectation is that some services will migrate to certain technologies that offer incomparable economic advantage, such as satellites for nonlocal broadcast video, while most remaining services will be carried jointly on a few multiservice networks. The subscribers will have little say regarding which technologies reach their homes, but will increasingly have more than one multiservice network at the home. Homes in wealthy urban areas will have the greatest choice the soonest, since, for example, a telephone company is more likely to accelerate ADSL or FTTC deployment to homes that are getting cable modem service from a cable operator. In general, subscribers will get more bandwidth to the home, lower cost, and greater choice of service type.

Communications within the Residence

Application Areas

The deployment of communications technology within the home will depend on, more than anything else, the applications that the user wishes the communications to enable. We see the most important of these being: work at home, entertainment, and personal life and communications. Work at home includes home business, daytime telecommuting, and night and weekend access to corporate networks. Entertainment includes passive video and audio programming as well as interactive games and information. Personal life and communications includes home finance, home photography and videography, home e-mail, and of course fax and telephony. Other areas of lesser importance are home automation, home health care, and electronic commerce. We have not mentioned the Internet explicitly because nearly every application area cited above will use the Internet. Particularly significant as motivators for home communications are the following factors:

- Increasing use of the home computer to interact with entertainment and automation equipment (especially using web technology),
- The growth of home imaging (embodying digital cameras, printers, and storage media)
- The multiplicity of home computers in many homes
- The need to share digitally delivered programming to cable modems and set-top boxes by multiple devices within the home.

Obstacles to Home Communications

Communications within the home will not become pervasive (nor will the applications that require it) until a number of obstacles are overcome.

Wiring. Although wiring is not a major obstacle in offices, it is a major one in homes. If the wires are not already in the walls or do not go where they are needed, the user needs to install wires or forgo communications between rooms. This obstacle, in terms of cost and delay, motivates the development of wireless and powerline communications.

User Skills. Knowledge about how to hook up, configure, and use a home communications system cannot be so great that it reduces the market to the technically adept few. Even the technically adept have a dedicated support staff at the office for maintaining their complex communications networks.

Consumer Pricing. Affordability for home communications systems will probably be reached only with mass markets, which suggests standard approaches. Standards, as well, promote interoperability among different vendors, another consumer necessity.

Embedding Communications Functions. This obstacle, perhaps better stated as the invisibility of communications functions, reflects a consequence of the previous two obstacles. For low cost and ease of use, it will be helpful to embed the communications into appliances that perform some application function, rather than develop a bevy of communications widgets that users will have to tangle with.

Privacy. Users will demand privacy not only for financial records but for all communications that leave or enter the home. The broadcast media of HFC, LMDS, and satellite violate this, so explicit techniques to ensure privacy must be added.

External Access. While external access is not necessary for all home communications, which increasingly will originate and terminate in the home, it will be mandatory for many devices in the home to deliver their full value to the user. How the combination of internal and external communications is provided most simply and economically is a matter of no small import.

In-Home Communications Technologies

In-home communications technologies fall into three categories: wireline, power line, and wireless. Wires are suitable when devices to be connected are in the same room, when existing wiring suits the communications, or when new construction allows the installation of special wiring. Otherwise, power line or wireless communications is highly desirable. Other than telephone twisted pair or cable TV coax, there is no installed base of any magnitude for in-home communications.

Ethernet and AppleTalk. These two network technologies are used today to connect home computers to their peripherals. With cable modems and ADSL modems terminating in Ethernet ports, Ethernet will be used increasingly to connect multiple home computers. Its 10-Mbit/s data rate, inexpensive adapter cards, and operation over unshielded twisted pair (with a hub) make it attractive for computer interconnection. Ethernet versions with 100-Mbit/s and 1000-Mbit/s data rates will trickle into the home as their cost comes down because of increased enterprise penetration and as the need for more bandwidth justifies their higher cost.

Universal Serial Bus (USB). This is a new peripheral bus that supports up to 12 Mbits/s with a simple connector and daisy chaining or hub/star wiring. It has features for isochronous and asynchronous traffic and we expect it to appear on PC motherboards in 1997.

IEEE 1394. This standard, which is also called *firewire*, has been embraced by the consumer electronics manufacturers for connecting digital video cameras, VCRs, and televisions. It is being adopted by home computer and set-top box manufacturers as well. IEEE 1394 is a high-performance serial bus that operates at 100, 200, or 400 Mbits/s over its own special cable. The cable is currently limited to 4.5 meters but developers are working to extend it to whole-house distances. It is hooked up in daisy-chain fashion, which allows flexible configuration and requires no hubs.

Consumer Electronics Bus (CEBus). This bus is an emerging home networking standard defined for operation over power line carrier, radio frequency, infrared, coax, and twisted pair. It defines a 10-kbit/s control channel and frequency spectra for data on coax and twisted pair but no data protocol, allowing various MAC protocols to be used. CEBus is being deployed for home automation and control of low-bandwidth applications and not for high-speed data (or video, or voice). The CEBus specification also includes a common application language (CAL), which is being adopted in the IEEE 1394 world as well. A simple, object-oriented programming language, CAL will find use for control and communications among security systems, light switches, and consumer goods.

Power Line Carrier. This transmission medium allows communications over the home's electrical mains. It offers the advantage of using wires that are already in the walls and requires no separate plug. Data rates of tens of kbits/s are available now, and claims for Mbits/s are viewed skeptically. Powerline transmission is highly susceptible to noise and attenuation through transformers. The latter is an advantage for transmissions intended to stay within one home. However, the signals reach all homes that share the same transformer, resulting in loss of privacy and the need to coordinate transmissions.

Infrared Communications. Infrared offers regulation-free, radiation-free communications within a room. Interference with neighbors is never a worry, although high levels of ambient light can be a problem. Infrared links exhibit a high inverse relationship between speed and distance, with Gbits/s speeds possible over a few centimeters, a few Mbits/s possible over a meter, and kbits/s in diffuse room-wide use. Many in the industry are interested in seeing the speed-distance product increase, and no organization has been more effective at gaining industry-wide adoption, pervasion, and interoperation of infrared than the Infrared Data Association (IrDA).

Plastic Optical Fiber. Optical fiber offers regulation-free, radiation-free, high-bit-rate communications at the expense of having to be strung around the home and using unfamiliar connectors. The diameter of plastic fiber is fifteen times that of glass fiber (980 μm versus 62.5 μm), so affixing connectors is easy, and 650-nm LED drivers and detectors are inexpensive. Its modal bandwidth of 10 MHz · km* allows whole-house distances at 100-Mbit/s data rates. The cost of the medium and its connectors is comparable to that of data-grade twisted pair.

Radio Frequency (RF). RF communications covers a broad array of technologies, even within the context of the home. The attractions of RF are that it requires no wiring or connectors and that it allows mobility. The challenges are keeping the transmissions out of the neighbors' houses, finding an appropriate operating point in the speed-distance-cost triangle, dealing with the highly-regulated RF environment, defining suitable medium access controls, and keeping the power low enough for its use in small, lightweight, battery-powered appliances.

There is far too much material on RF for us to be anything but brief so here are only the barest of highlights. The most prominent RF technologies are for telephony (cellular and cordless) and these are only now moving from analog to digital and rising in frequency to the 900-, 1800-, and 1900-MHz bands. Their use for data transmission is limited. The highly regulated 1.9-to-2.4-GHz band is used for industrial, scientific, and medical purposes, for emerging 1-to-2-Mbit/s wireless local area networks in enterprises, and for unlicensed personal communications services. Modulation ranges from analog to QPSK digital to direct-sequence and frequency-hopping spread spectrum.

Most viable for the home is the 2.4-GHz band yielding around 1 Mbits/s. The real opportunity for the home lies at 5 GHz, where the European HIPERLAN and U.S. unlicensed national information infrastructure (UNII) allocations have opened up 150- and 300-MHz slots, respectively. Data rates of 10 to 20 Mbits/s per channel, with multiple channels, meet the needs of digital video, Internet communications, and home file and image transfer. The UNII band, especially, offers sufficient bandwidth to allow reasonable modulation efficiency with minimal interference.

All the frequencies mentioned thus far propagate through most home walls without difficulty, allowing whole-house coverage (and perhaps some of your neighbor's). The next frequency band, at 60 GHz, offers enormous bandwidth (5 GHz) but has difficulty propagating through walls. Products are still some years away and component costs are uncertain, especially with GaAs being necessary. Also, it is not clear if 60 GHz is best suited for point-to-point or omnidirectional use. At both 60 and 5 GHz, open questions remain regarding modulation, and especially whether multicarrier modulation can effectively be harnessed to combat narrowband noise or if distributed feedback equalizers are necessary.

Where Are these Technologies Heading?

The in-home communications technologies are heading in whatever direction they can that leads to just enough capability at the lowest possible cost for the applications that will actually be there. None of these factors is known yet so a great deal of investigation is still required. Everyone seems to think that consumers want more bandwidth than they have but no one can say exactly what for. We do not yet know what devices will need to communicate with other devices,

* The product of the number of megahertz times the number of kilometers is (at most) ten. Thus, you could transmit at 10 MHz over a distance of 1 km or at 1 MHz over a distance of 10 km, or anything in between as long as the product does not exceed 10.

what applications and demographics will tolerate the installation of new wiring, or how much money there is to be made in the communications versus the appliances that communicate. We feel that the pushes toward higher speed, mostly digital communications, and decreased reliance on wires are the right ones.

Interconnection Technologies

One other important aspect of residential communications is the means of allowing different devices to actually find and communicate with one another, regardless of where they are located. Thus the picture of residential communications is incomplete without the switches, routers, gateways, and networking software that devices and users need to identify, find, and reach one another.

These technologies exist for public and enterprise networks but their translation to residential use is tenuous for several reasons. One is that they are presently far too expensive for consumers. Another is that they are too complex to set up and use, especially considering that the home has no dedicated information-technology staff. A third is that they do not deliver end-user applications or services but are only a means to that end, so vendors would have to overcome great consumer resistance to purchasing them. Nonetheless, consumers need ways to interconnect their automation network (CEBus?) with their computer (Ethernet?), their digital VCR (IEEE 1394?) to their printer (USB?), and lots of their in-home gear with the outside world.

People (and not just engineers) using these devices will need to know what other devices there are and how to address and name them. The interconnection of the in-home technologies with the access-network technologies is a particularly intriguing problem because the two domains have such different technologies, economics, demographics, and performance characteristics. A body of study has emerged on the *residential gateways* that allow devices within the home to access and exploit the external networks without understanding their technical specifics.

Conclusion

Residential communications offers enormous potential for communications technology development, pervasion, and revenue. The key problems to be solved are matching communications capabilities to the needs of the applications, appliances, and users, driving down costs to consumer levels, and making these systems usable for the nontechnical mass market. Technical innovation is needed in wireline, optical, powerline, satellite, terrestrial microwave, and millimeter-wave technologies and in their transceivers, media, connections, interconnections, configurations, and more. The other papers in this issue describe a wealth of basic-technology work touching most of these areas.

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