J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

HOME AUTOMATION

Home automation is expected to increase comfort and security around the house and provide economic benefits through energy conservation (1). An ideal home automation system would relieve the inhabitant of a house of any unwanted manual control of every applicance and electrical or gas equipment in the house and would provide for an automated environment that would be aware of specific user needs and habits and program the operation of these appliances accordingly. Given the recent advances and drop in costs in computers, fiber optics, and multimedia communications, the concept of home automation systems has been extended to include data, voice, and visual communications inside a home. The recent expansion of the Internet coupled with efficient home automation systems may provide an additional added value to the concepts of telecommuting, home schooling, interaction between students, teachers, and parents, and remote efficient resource management of home appliances.

It needs to be noted that home automation systems are intended for single-family homes, so they do not usually address the issues of working environment, multiparty cooperation, ergonomics, and floor planning that are usually the problems addressed in the intelligent building design literature.

Home automation systems in various forms have appeared in the market for many years. Thus we have seen many intelligent security systems, energy management units, lighting controllers, entertainment systems, and so on. Interfacing of these products has been limited, however, and has been usually rather costly especially in the US market. Some products have received a wide market acceptance and have become de facto standards in a limited home automation market, such as the power line products marketed by X-10 Inc., or CELECT, the integrated System for Load Management of Electric Heating for Domestic and Commercial Buildings.

Home automation products can in general be categorized as follows:

- Interactive smart products
- Intelligent subsystems
- Central automation systems

Most of us have extensively used interactive smart systems—that is, devices that previously required manual control but now have a wide set of programmable features. The cases of programmable VCRs, automated door openers, and automated sprinkler systems fall into this category. Intelligent subsystems consist of two or more interactive smart systems that are able to exchange information to accomplish more sophisticated tasks. The interaction between a TV and a programmable VCR falls into this category as well as an interface of a telephone answering machine with the lighting or the security system. The ultimate and most comprehensive home automation system would be one that integrates a number of smart systems and/or intelligent subsystems into a system that can be thoroughly and seamlessly controlled by the home owner. Such a system would provide a comprehensive system of home information, telecommunication, entertainment, and control.

Several advantages are realized through the use of such an integrated system. A smart microwave can have its cooking schedule controlled through a central database that stores all the home inhabitants' schedules and habits. A VCR can record only the satellite or cable TV programs that the users like or allow to be viewed and then selectively broadcast them to the TV sets in the house. An integrated security system can be linked with video cameras, the VCR, the telephone network, and the local police station. A smoke detector can be linked to the heating, ventilating, and air conditioning system, and to lighting controls so that in case a fire breaks out, smoke can be cleared and hallways can be appropriately illuminated to help people move out of the house.

Having such a system with so many differing applications brings forth a wealth of problems in terms of the required integration. High-definition video requires several megahertz of bandwidth, while a room thermostat requires a minimum bandwidth occasionally. High-fidelity audio or video traffic requires very strict limits on delays, while a washing machine control signal does not have these requirements.

Products and Standards

As in many other industries, home automation products were first introduced before a complete set of standards was specified. So in tracing the market and product development we see a large number of products that do not follow any standard specifications but are absolutely proprietary. For example, Mastervoice, Inc. of Los Alamitos, CA presented their Environmental Control Unit (*ECU*) at the National Home Health Care Exposition in Atlanta, Georgia. The ECU is a voice recognition device that will allow 16 different devices to be controlled by a particular user. DLS Electronics, Inc. of Miami, FL designed and manufactured a sophisticated residential and commercial lighting system, the LITECOMP 2000. It provides its users with on-site programming capabilities to allow control of different devices through the push of a button. The system can also be used with timers, sensors, and a telephone interface and is an excellent choice for an energy control system. Home Automation, Inc. of Metairie, LA developed the Model 1503 home control and security system with the Model 1102 expansion enclosure. The system can be used for slab heating, outdoor lighting, pool pumps, air conditioning, and much more.

For designers who will be involved in home automation designs, companies like Texas Instruments, Motorola, and Toshiba have been very active in developing the tools and components that will make this process easier. Texas Instruments, along with SMART HOUSE manufacturers, will develop two key chips: the branch slave and the appliance home automation integrated circuits. These chips will be integrated in future designs and will be mainly used for communications purposes between the system controller and its devices.

The idea of using a local area network (*LAN*) to control and connect devices was implemented in Echelon's Lonworks. Lonworks is based on a distributed control LAN using its local operating network (*LON*). Communications media, network communication protocols, and application software are integrated. The LAN implements a predictive p-persistent CSMA protocol and can handle rates up to 1.25 Mbps. In the physical layer, transceivers for a variety of media are offered. The Neuron C application language, an extension of ANSI C, adds several features that allow efficient I/O operations and efficient network management.

International efforts have been under way to develop standards covering the communication between home automation system modules. Most of these efforts use a LAN environment and follow standard layered approaches, such as the ones advocated by OSI.

In the United States the Electronic Industry Association (*EIA*) (2) recognized the need to develop standards covering all aspects of home automation systems communication. A committee was organized in 1983 to carry out the task. In 1988, a home automation system communication standard known as *CEBus* (consumer electronic bus) was made available by the EIA committee for comments. It was upgraded and rereleased in December of 1989 after undergoing several changes. A final document became available in 1992. The CEBus document covers the electrical and procedural characteristics of systems modules communication. Since all the standardization efforts have a large number of common features, in subsequent sections we will use the CEBus architecture as an example to describe the problems, challenges, and designs encountered in home automation systems.

Table 1. Technical Characteristics of Three Bands

<table>
<tr><th>Baseband</th><th>Subband</th><th>FMTV band</th></tr>
<tr>
<td>Transmission media: coax cable (e.g., TVEFCX: 4C-TV)
Maximum number of terminals: 255
Maximum cable length: 200 m (for in-house coax lines)
Network topology: bus (multidrops)
Data rate: 9600 bit/s
Transmission format: baseband serial
Synchronization: asynchronous (with start and stop bits)
Transmission logic: positive
Parity: even parity
Access: CSMA/CD (carrier sense multiple access with collision detection)
Transmission feature: packet, two-way
Packet structure:
<table><tr><td>SA</td><td>DA</td><td>CW</td><td>BC</td><td>. . . .
data</td><td>FCC</td></tr></table>
SA: Source address ('01' to 'FF')
DA: Destination address ('00': broadcast)
CW: Control word
BC: Number of data (max. 256)
FCC: Frame check code (check sum)
Error detection: parity and FCC
Packet priority: 4 level
Collision detection: big verification for each bit period</td>
<td>Transmission media: coax cable (e.g., TVEFCX: 4C-TV)
Cable impedance: 75 Ω
Number of terminals: 8 or more (subject to the number of splitters or distributors)
Maximum cable length: 200 m (for in-house coax line)
Wiring: use splitters and distributors like the ordinary CATV system
Channel control: by baseband control</td>
<td>Transmission media: coax cable (e.g., TVEFCX: 4C-TV)
Cable impedance: 75 Ω
Wiring: same as the sub-band
Signal level: 65 dBμ or more
Transmission channel: VHF 1–3, 4–12 ch., (in Japan) UHF 13–62 ch., mid-band A to J ch., FM (76–90 MHz)</td>
</tr>
</table>

Echelon and CEBus do not require a central controller since they distribute control and communications into the products. CEBus tries to establish a standard protocol for communications, while Echelon has developed the Neuron chip which contains a communications protocol that allows appliances of different manufacturers to work together.

The Japanese home bus system (*HBS*) has been developed as the national standard in Japan for home automation after several years of research and trials. The HBS uses a frequency division multiplexing system using coaxial cable. Three bands are used for transmission of control signals: baseband, for high-speed data terminals; subband; and for transmission of visual information the FM–TV band. Technical characteristics of the three bands are provided in Table 1 (3). It is envisioned that reductions in prices due to LSI design and large markets will lead to information wall outlets installed in every residence at the time of its building. In Japan in 1990, 88% of all Japan's condominiums were wired according to the nation's home automation standard (4). Recent efforts have concentrated on the expansion of the traditional idea of a home automation system into one that incorporates multimedia capabilities by using standard telecommunication services, such as ISDN BRI, and controls that provide low noise and low distortion (5).

The European home systems (*EHS*) specification has been developed under European Commission funding under the ESPRIT program. Its aim was to interconnect electrical and electronic appliances into the home in an open way so that different manufacturers can offer compatible products. An EHS product consists of three parts: a modem chip, a microcontroller, and a power supply. The main power cabling is used to carry the command and control signals at a speed of 2.4 kbps. Digital information is carried by a high-frequency signal superimposed on the voltage of the main. Sensitivity to electrical noise remains a problem, and filters are necessary to eliminate unwanted interference. Other media used include coaxial cable (to carry frequency multiplexed TV/digital audio signals and control packets, 9.6 kbps), two twisted pair cables (telephone and general purpose, 9.6 and 64 kbps), radio, and infrared (1 kbps). The Japanese home bus system has provided the packet format while application specific protocols are supported through gateways. Four classes of information depending on the bandwidth required have been defined:

- Class 1: Low-speed command and control data (datagram service)
- Class 2: Telephony and low-speed user data
- Class 3: Analog audio and low-quality video
- Class 4: VHF/UHF audio and video and digital audio

Standard activities are already underway to find a common ground between the previously presented systems (and a few more national ones like the European installation bus of Germany and the BatiBUS of France). The ISO/IEC WG1 committee has undertaken this task, reaching a consensus on the application layer. The rationale behind the choice of the application layer as the starting point toward integration is the fact that all home automation systems need a common way to set temperature, turn an appliance on and off, and reduce the volume (6).

EIBA. The European Installation Bus Association (*EIBA*) has assumed the role of the integrator in the European market. The *EIB* system for home and building automation is another free-topology, decentralized system with distributed intelligence, based on a CSMA/CA protocol for serial communication. Currently, various EIB bus access units for twisted pair are commercially available. The bus access unit includes a transceiver, locally implements the operating system, and caters for user RAM and EEPROM space.

EIBA's objectives include the development of a unified concept for electrical fitting and home and building management. EIBA is a multivendor body that aims to establish a standard for building system technology on the European market, makes the EIB system know-how available to members and licensees, provides members and licensees with support and documentation, establishes standards among its members, and specifies appropriate criteria for quality and compatibility, with the help of external test institutes. It also maintains the position of the EIB Tool Environment (*ETE*) as an unrivaled platform for open software tool development, at the heart of which is the EIB Tool Software (*ETS*), offering a common tool for the configuration of EIB installations.

EIB components, actuators, and monitoring and control devices communicate via a standardized data path or bus, along which all devices communicate. Little wiring is required. This in turn results in lower fire risk and minimized installation effort. Home automation systems provided by Siemens (see the Web page http://www.siemens.de) follow the EIBA standards and have several desirable features. Siemens's Home Electronic System (*HES*) provides:

- Security due to the continuous control of active processes around the house at the homeowner's fingertips
- Economy in the use of utilities such as water, electricity, and heating energy
- Convenience through simplifying operation and reducing the burden of routine tasks
- Communication by integrating the household management system into external communications facilities

In order to combine entertainment, communication, and computing electronics in consumer multimedia, digital interfaces have been created. Such is the case of IEEE 1394, which was conceived by Apple Computer as a desktop LAN, and then was created as a standard by the IEEE 1394 working group.

IEEE 1394 can be described as a low-cost digital interface with the following characteristics:

- High speed It is able to achieve 100 Mbit/s, 200 Mbit/s, and 400 Mbit/s; extensions are being developed to advance speeds to 1.6 Mbit/s and 3.2 Mbit/s and beyond.
- Isochronous support Bandwidth for time-sensitive applications is guaranteed by a deterministic bandwidth allocation for applications such as real-time video feeds, which otherwise could be disrupted by heavy bus traffic.
- Flexible topology There is no central bus supervision; therefore, it is possible to daisy-chain devices.
- Hot-plug capability There is no need for the user to configure node IDs or unique termination schemes when new nodes are added; this is done dynamically by the bus itself.
- Cable power Peripherals of low cost can be powered directly from the IEEE 1394 cable.
- Open standard The IEEE is a worldwide standard organization.
- Consolidation of ports of PCs SCSI, audio, serial, and parallel ports are included.
- There is no need of conversion of digital data into analog data, and loss of data integrity can be tolerated.
- There are no licensing problems.
- A peer-to-peer interface can be provided.

The EIA has selected IEEE 1394 as a point-to-point interface for digital TV and a multipoint interface for entertainment systems; the European Digital Video Broadcasters (*DVB*) have selected it as their digital television interface. These organizations proposed IEEE 1394 to the Video Experts Standards Association (*VESA*) as the home network media of choice. VESA adopted the 1394 as the backbone for its Home Network Standard.

From Home Automation to Intelligent Buildings. Advances in hardware and software technology have affected not only the home automation market, but the market of intelligent buildings as well. *Intelligent buildings* is a term used to describe buildings that are not passive toward their occupants and the activities that take place in them but can program their own systems and manage the consumption of energy and materials as presented in Varricchione (7). In an intelligent building, sensors receive information on the status of the building and through the communication system of the building transfer it to a central controller where, after the necessary comparisons and processing, actions are taken. An intelligent building consists of the peripheral units, the units that monitor the proper functioning of the equipment and regulate it if needed, and the field elements—that is, the sensors, indicators, and activators present in the building.

Applications

Several applications have been envisioned by designers of home automation systems and standards organizations. Fanshawe (8) presents the following categories of applications:

- Control of homes' heating, lighting, windows, doors, screens, and major appliances via a TV or TV-like screen
- Remote control of house environment via a touch-tone key telephone
- Detectors to identify rooms that have been empty for more than a specified period of time and possibly transfer this information to the security system or regulate the heating of the room
- Help for the elderly and disabled

Stand-alone assistive devices for the elderly have been deployed for many years. The home automation concept can be extended to this market to cover the design and implementation of the systems needed to carry out the control functions and to design the necessary interfaces so that the system interprets appropriately the commands given by the user.

The capability to mix and match software and hardware components to provide the most appropriate user environment is paramount when designing systems home automation systems. Specific needs arise when one considers the elderly and the disabled. Funding by the European Commission through its *TIDE* (Telematic Initiative for the Disabled and the Elderly), MECCS, and MECCS II programs has resulted in gaining significant insight into the necessary steps needed to develop such a system.

In the Home Esprit Project the following applications have been identified:

- Load management
- Domestic appliance system
- Environment control
- Lighting control
- Security
- Safety
- Access control
- Voice communication
- Data communication (including telecontrol)
- Entertainment

Several other applications that can make use of the communications that exist outside the home include:

- Home banking
- Information services
- Working from home
- Health monitoring (health check, health security)
- Telecontrol (appliances security heating, video recording)
- Telemetering (gas, electricity, water)

Looking at the previously presented classifications of applications, one sees that there is a big difficulty in finding and imposing the most appropriate classification and identify nonoverlapping definitions and then identify functional links between different applications. Entertainment applications usually receive the most attention in standardization activities and market products since there already exists a large market that has been accustomed to integration and common formats. Thus the integration of audio devices such as DAT players, record players, cassette players, CD/CD-I players, radio tuners, microphones, headphones, and remote controls has seen a very large market. The same concepts apply to video equipment; that is, the integration of TV display screens, video cassette recorders, TV tuners, video cameras, video disk players, CD-I players, video printers, and satellite dish platforms through a common interface has received considerable attention.

Security applications are the most advanced applications nowadays at homes in terms of providing an integration of controller sensors, actuators, video camera, camera platform, microphones, door phone, push buttons/key access, and timers.

A considerable number of electric utilities have been involved into using advanced techniques of home automation for load management. Given the importance of such an application, we present load management in detail in the following section.

Load Management. Electric utilities might have been in the forefront of home automation systems. However, the increased competition due to deregulation has moved their interest from home automation to load balancing management in order to reduce peak loads.

Load management can be defined as the science of smoothing or flattening the electricity demand versus time curves. Load management or demand-side management is used by electric utilities to reduce peak loads by automatically turning off large loads—usually water heaters, air-conditioning systems, and so on—of customers who have pre-agreed to participate in such a program. The electric utility thus can manage to evenly distribute its load distribution during the day or through various seasons. By such an even distribution the utility does not need to buy electricity from other neighboring utilities or place new plants on-line or use old and inefficient plans. Users get a better rate in their electric bill by experiencing a minor and often unnoticeable disturbance.

Another technique used by some utilities in the United States and all over the world is variable rate pricing—that is, not charging for the kilowatt-hour a constant rate but charging the rate according to other cost functions such as the time of the day, the cost of production of fuel, and the total network load.

A home automation system can be a catalyst in load management by allowing loads to shed in a hierarchical basis from the least necessary to the highly needed and utilized. Thus switching on and off of applicances that have a regular and/or predictable load when demand curves require this is achievable. Appliances that have been on for long periods of time in unoccupied rooms can also be switched off. A detailed list of energy consumption and the associate costs can be provided, thus allowing the consumer to fully understand his/her consumption habits and take corrective actions or possibly reduce voltage to appliances that can work with lower voltage.

Managing efficiently a load management system or a variable rate pricing one requires that the utility has direct communication with the customer premises in an intelligent and efficient way. Customers are willing to accept energy management options as long as they provide visible savings in a way that is simple to manage. Customers should also be given the option of using or not using energy management at will.

Home automation systems can make load control customer-friendly since homeowners can choose when and where to control power in an environment that is potentially more familiar to them since they avoid specialized equipment provided by the electric utility.

Several ways have been proposed for communication between the utility company and the customer premises. The Smart House concept has been studied and implemented by the Smart House Limited Partnership (*SHLP*), a for-profit venture funded by 40 electric utility companies. It includes a patented three-cable wiring system that enables communications between electrically powered devices in the home. A system controller coordinates and distributes all communication signals through the wiring system. A demonstration Electric Smart House has been presented at the National Association of Home Builders annual convention (9). Intelligence is built into the outlets that can also accommodate limited on–off capabilities for conventional appliances.

In the Smart House development, particular effort has been paid on home energy management. A touch screen interface offers the homeowner the capability to monitor and control the temperature in the house across several zones and program the use of high-energy devices in times of low utility rates.

Customer Interfaces. Customer interfaces are an important part of the whole system design and may be the ultimate bait to lure more customers into accepting home automation as a necessary part of their lives. A customer interface like the communicating customer interface developed by EDF and the Gaz de France allows for services such as

- Automated management of supply contracts
- Automatic meter reading
- Self-service energy supply for temporary customers paying with electronic cards
- Payment in advance
- Customer access to more information on consumption and related costs, as well as advice on how to optimize the contract

On the utility side such an interface will provide (10)

- More efficient demand management
- Greater internal productivity

- Possibility of individual load shedding
- Better failure detection in the electric network
- Disconnection of selected customer installations for work on the electric network
- Better public image

Communications and Control Media

Several media, individually or in combination, can be used in a home automation system. Power line carrier, twisted pair, coaxial cable, infrared, radio communications, Digital Subscriber Loop (*DSL*) technologies, cable modems, and fiber optics have been proposed and investigated. Each medium has a certain number of advantages and disadvantages. We will discuss particular implementations in the context of CEBUs. In this section we will present some of the most profound features of the media.

The power line carrier (*PLC*) or mains has been proposed in several applications. It is the natural medium of choice in load management applications. No special cables need to be installed because the power line is the bus itself. From one side the power line medium already has a large number of appliances connected to it, but on the other side it is not a very friendly medium for transmission of communication signals since there is a fluctuation of the power line impedance and a high noise level on the line. There is also interference with communication caused by other houses. Spread spectrum or ASK techniques have been proposed for efficient modulation of the signal in PLC.

Recent advances in twisted pair (*TP*) transmissions especially in telecommunications and computer networking applications make it very attractive for applications that use standard computer interfaces. TP can be the generic system for the home system datagram services; if new communication technologies reach the home, TP can be used for high bandwidth applications as well. TP can be easily assembled and installed, and connectors can be easily attached to it.

Coaxial cables have not been extensively—except from the Japanese market—used in home automation systems. Their high bandwidth and the experience technical people have amassed through the cable systems make them a very attractive medium. Retrofitting them in existing houses is one of their major disadvantages.

Infrareds (*IR*)—that is, electromagnetic radiation with frequencies between 10^{10} and 10^{24} Hz—have been used extensively in remote control applications. Their use in Home Automation Systems will require line-of-sight—that is, detectors in every single room so that there is a full coverage.

Radio waves—that is, electromagnetic signals whose frequency covers the range of 3 kHz to 300 MHz—do not need direct vision between the transmitter and the receiver, but there is a need for a license and problems with interference. Radio frequency technology is being used for real-time data management in local area networks (*LAN*s), in order to give free access to the host system from multiple mobile data input devices. Wireless home networking technology will operate in the large-bandwidth radio frequency ranges and will use proprietary compression techniques. In the future, consumers might receive E-mail messages wirelessly from a compliant handheld device or view enhanced Web content on their connected television sets. The use of a radio frequency of 2.4 GHz will cut down on noise within the home and provide some security.

Home networking opens up new opportunities for cost-effective phones that include Internet capabilities. By sharing resources, manufacturers should be able to reduce the cost of an Internet phone by utilizing the processor and modem of a connected personal computer (*PC*). Currently, a number of major manufacturers are developing their own wireless home networking products, including IBM with its Home Director and Intel with a yet unannounced product line. Two major industry groups, the Home Phoneline Networking Alliance (*HPNA*) and the HomeRF, are attempting to develop standards for two different technology sets.

The HomeRF Working Group (*HRFWG*) was formed to provide the foundation for a broad range of interoperable consumer devices by establishing an open industry specification for wireless digital communication between PCs and consumer electronic devices anywhere in and around the home. The HRFWG, which includes the leading companies from the PC, consumer electronics, peripherals, communications, software, and semiconductor industries, is developing a specification for wireless communications in the home called the Shared Wireless Access Protocol (*SWAP*), with a final version expected to be released in December of 1998.

The Bluetooth program, backed by Ericsson, IBM, Intel, Nokia, and Toshiba, is already demonstrating prototype devices that use a two-chip baseband and RF module and hit data rates of 730 kbit/s at 2.4 GHz. The Bluetooth program also uses a proprietary MAC that diverges from the IEEE 802.11 standard. The SWAP defines a new common interface specification that supports wireless voice and data services in the home.

The specification developed by the HRFWG is to operate in the 2.4 GHz band and use relaxed IEEE 802.11 wireless LAN and digital European cordless telephone (*DECT*) protocols. It also describes wireless transmission devices and protocols for interconnecting computers, peripherals, and electronic appliances in a home environment. Some examples of what users will be able to do with products that adhere to the SWAP specification include:

- Set up a wireless home network to share voice and data among peripherals, PCs, and new devices such as portable, remote display pads
- Review incoming voice, fax, and E-mail messages from a small cordless telephone handset
- Intelligently forward incoming telephone calls to multiple cordless handsets, fax machines, and voice mailboxes
- Access the Internet from anywhere in and around the home from portable display devices
- Activate other home electronic systems by simply speaking a command into a cordless handset
- Share an ISP connection between PCs and other new devices
- Share files, modems, and printers in multi-PC homes
- Accommodate multiplayer games and/or toys based on PC or Internet resources

Digital subscriber line (*DSL*) is a modem technology that increases the digital speed of ordinary telephone lines by a substantial factor over common V.34 (33,600 bit/s) modems. DSL modems may provide symmetrical or asymmetrical operation. Asymmetrical operation provides faster downstream speeds and is suited for Internet usage and video on demand, where the heaviest transmission requirement is from the provider to the customer. It uses packet-switching technology that operates independently of the voice telephone system, allowing the telephone companies to provide the service and not lock up circuits for long calls. Because of this, DSL is not as well suited to videoconferencing as is ISDN. ISDN is circuit-switched, which keeps the line open and connected throughout the session. Both DSL and ISDN use normal copper telephone wires to transmit data; speed is the essential difference between the two.

Although DSL technologies have barely gotten off the ground, there are already different DSL techniques: *Asymmetrical DSL* (*ADSL*) is available using discrete multitone (*DMT*) or carrierless amplitude phase (*CAP*) modulation. *Rate-adaptive DSL* (*RADSL*) adjusts speeds according to signal quality. *ISDN DSL* (*IDSL*) uses in-place ISDN facilities. DSL technologies are very much tied to the distance between the DSL modem at the telephone company switch and the DSL modem at the customer's site.

DSL is taking over the home network market. Chip sets will combine home networking with V 90 and ADSL modem connectivity into one system that uses existing in-home telephone wiring to connect multiple PCs and peripherals at a speed of 1 Mbit/s.

A cable modem is another option that should be considered in home network installations. Cable modem service is more widely available and significantly less expensive than DSL. Cable modems allow much faster Internet access than dialup connections. Because coaxial cable provides much greater bandwidth than telephone lines, a cable modem allows downstream data-transfer speeds up to 3 Mbyte/s, as opposed to 56 kbyte for a standard modem. This high speed, combined with the fact that millions of homes are already wired for cable TV, has made the cable modem the top broadband contender. Cable modems can increase Internet access more than 100-fold over traditional modems, loading even complex webpages with streaming video in less than a second. The advent of cable modems also promises many new digital services to the home, including video on demand, Internet telephony and videoconferencing, and interactive shopping and games.

At first glance, *xDSL* (i.e., DSL in one of the above-mentioned varieties) appears to be the frontrunner in the race between cable modems and DSL. After all, it can use the phone wire that is already in place in almost every home and business. Cable modems require a television cable system, which is also in a lot of homes and businesses but does not have nearly the same penetration as basic telephone service. One important advantage that cable modem providers do have is a captive audience. All cable modem subscribers go through the same machine room in their local area to get Internet access.

In contrast to cable modem service, xDSL's flexibility and multivendor support is making it look like a better choice for IT departments that want to hook up telecommuters and home offices, as well as for extranet applications. Any Internet service provider will be able to resell xDSL connections, and those connections are open to some competition due to the Telecommunications Act of 1996. The competitive multivendor environment—coupled with the G.lite standard, which was expected to arrive by 1999—should lead to a brisk commodity market for xDSL equipment and make it a particularly attractive and low-cost pipe. But while new services are sure to be spawned by all that bandwidth, xDSL providers will not be able to depend on the guaranteed captive audience of their cable modem counterparts.

Fiber optics at home have been evaluated in the literature. A thorough discussion of their advantages, disadvantages, and potential applications is provided in the following sections.

Architecture of Cebus

The CEBus network architecture is modeled after the OSI layered network architecture. The OSI model consists of seven layers, where each layer handles one aspect of the network communication. The OSI network node layers are located between the communication medium and a user process and are as follows: physical, data link, network, transport, session, presentation, and application (we find similar models in the Japanese and the European proposals).

The CEBus utilizes four of the seven OSI layers, as shown in Fig. 1. The transport, session, and presentation layers have been omitted from the CEBus network architecture. A portion of the functionality of the transport layer is incorporated into the CEBus network and application layers. The session and presentation layers have been omitted since their functions are not necessary in the CEBus network. Eliminating these layers reduces both packet lengths and node complexity.

The interface between different layers in the CEBus node is defined as a set of service primitives. Every layer in the network node provides services to the layer above it, while higher layer subscribe to the services of the lower layers.

An additional layer known as the layer system management (*LSM*) is part of the CEBus network node. The LSM layer's responsibility is to maintain the functionality of the CEBus node. Its functions are of local importance (such as initializing and monitoring the protocol of every layer) or of system-wide performance such as monitoring the network performance. The LSM layer is capable of monitoring the status of the communication channel through information passed to it from other layers.

Data sent from one application process to another device enters the source node via the application layer. The data propagates down to the lower layers. Each layer appends its own specific information to the data received from the layer above it. Finally the original data, along with all the additional appended information, is embedded into a CEBus frame and transmitted on the communication medium. Once received, the data make their way up through the destination node's layers. Each layer strips away the information sent by its peer layer in the source node passing the packet to the layer above it.

On top of the network sits the user's interface to the system. Users request a particular action from the network simply by entering a command through a terminal. The request is then passed down from each

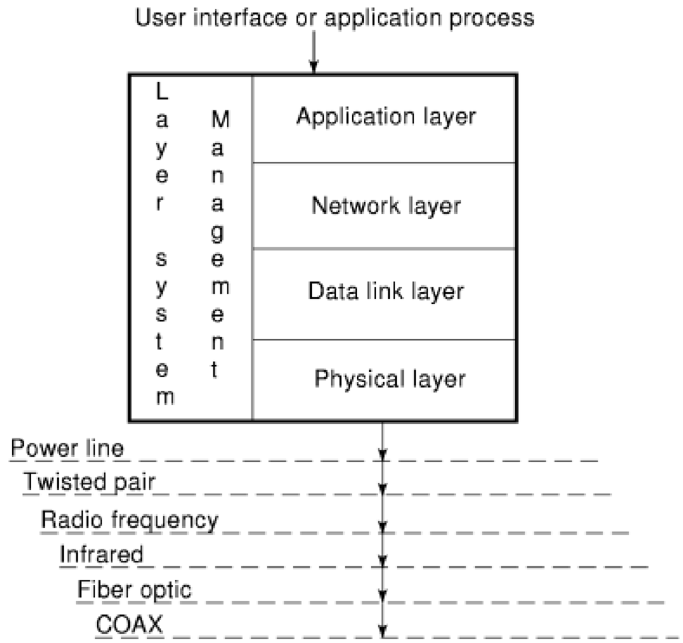

Fig. 1. The layer architecture and the communications media for home automation systems. More media can be added and layers can be upgraded independently.

layer to the next until final transmission on the bus occurs. Each layer will form and/or append some type of information to each packet depending on the nature of the task. The information is in the form of bytes, which comprise a protocol data unit (*PDU*). The lowest layer is the physical layer, which is responsible for the actual transmission of the final message to the destined node. The receiving node will get the message and pass it upward, extracting at each layer the control information that was appended while it was sent. Figure 2 illustrates the process from node A to node B.

The user is often provided with a terminal on which requests can be placed. Packets are sent over the CEBus to and from all different modules. The system is capable of interfacing as many terminals as needed to the CEBus. A minimum of one terminal must exist on the system at all times; this terminal is called the *supervisor*. The supervisor is a dedicated terminal that monitors and maintains information that the system needs in order to provide safety and synchronization between all modules. Information such as the module's properties, address, and status are crucial to the user. New modules can be added in the future to the existing system without any hardware or software modifications by simply informing the supervisor, through the provided user interface language about the new module characteristics, and they can then be integrated as part of the working system without further delay.

The supervisor must always be aware of all existing contexts and defined methods, so that any addition of devices to an installed system would be done properly. When the user requests a particular action from a device, the supervisor has to determine first if the device exists and then check to see if the device belongs to the same context. For instance, the user should not request to raise the volume on a heater, or turn on a fan if a fan does not exist in the system. Thus, the supervisor only allows the possible requests to go through and therefore decreases the traffic on CEBus.

Application Layer. The CEBus application layer is the highest in the CEBus node (11). It provides the user interface to the CEBus network and supports a common application language (*CAL*) through which

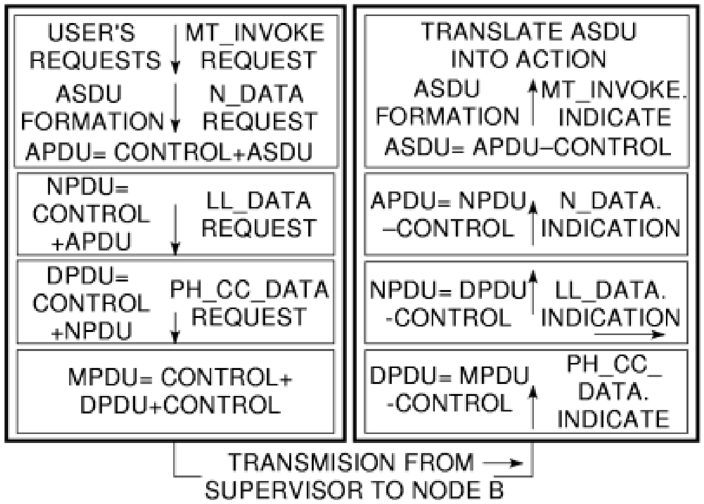

Fig. 2. The flow of information between receiver and transmitter (node A & node B) is seen in this figure through the layered architecture.

manufacturers may communicate with other devices in the network. The application layer is functionally divided into four elements: the user element, the CAL element, the message element, and the association control element.

The user element is the interface of the application process to the CEBus, and the application process is the element which controls the device of a CEBus node. It performs actions requested by remote devices, such as "TURN ON"/"TURN OFF," and generates requests to other devices on the network. The application process interfaces the application layer via the user element. The user element invokes the services of the CAL to formulate CAL commands and relay requests from the application process to remote devices on the network. The CAL element provides the mapping of requests generated by the user element into CAL commands, and it translates incoming CAL commands into tasks to be relayed to the application process. Figure 3 presents the application layer design.

The CAL element performs two distinct functions: control and resource application. The control function of the CAL element handles the transformation of "control requests" into CAL commands. "Control requests" refers to actions to be performed by a remote application process on the device it is controlling. The resource allocation function of the CAL element handles the request, use, and release of CEBus resources; these resources include digital and analog data channels, individual addresses, and system house codes. The CAL element is also responsible for dividing long messages into shorter segments that will fit into one CEBus frame. The CAL element of the application layer subscribes to the services of the message transfer element to relay the CAL commands to their destinations. The message transfer element uses the services of the network layer to accomplish its function.

The association control element allows the association of two application processes. This service and its implications are not fully specified yet. The information exchanged between peer application layers is known as application protocol data unit (*APDU*) and consists of the CAL command and a header appended by the message transfer element as shown in Fig. 4.

The user is capable of introducing the new objects to the system through the modification of a file that contains information on the object node such as its contexts, all the objects that belong to it, and its physical address on the CEBus. The user is capable of formatting a request either by selecting a programmed function using one of the F keys or by browsing through different database files to construct an action.

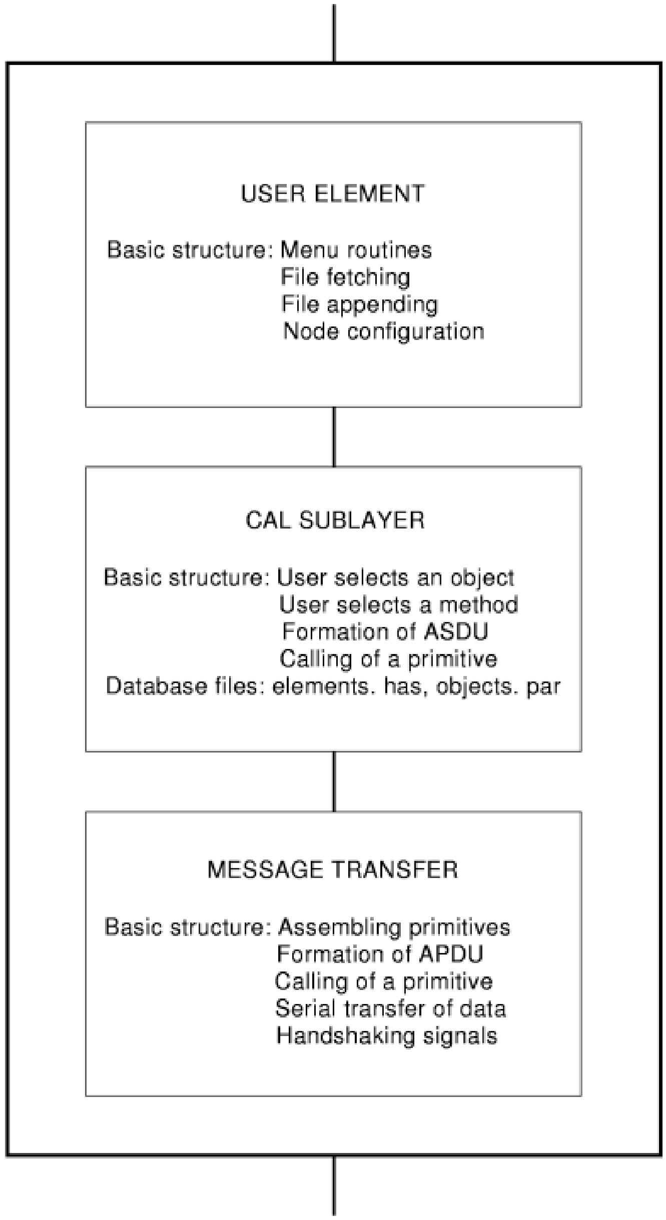

Fig. 3. Application layer design presented with the basic structures of its components.

CAL (Common Application Language). *CAL* (common application language) is one of the application layer functional units. It provides services to the user such as allocation of resources and control. Resource allocation is concerned with allocating and releasing CEBus resources—for example, analog or digital data channels. Control is the response to incoming commands and the forwarding of others such as dimming up and down, opening and closing, and more complicated actions such as alarming and responding to telephone commands. Requests for services are received and translated into application layer service data units (*ASDUs*)

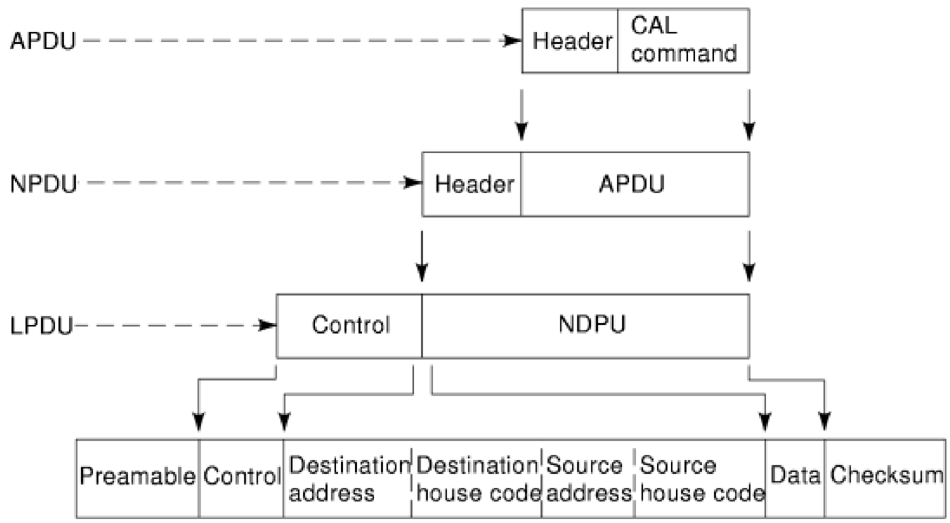

Fig. 4. Step-by-step design of an MPDU. Every layer adds some information, which then is extracted at the receiving node.

through the CAL syntax. The layer system management also forwards incoming messages to the application layer CAL unit for interpretation.

CAL is expressed using complete Backus–Nauer format (*BNF*) descriptions. Messages formed by CAL are structured using the BNF's symbols. A message is a string of bytes consisting of a context, an object, a method, and an optional list of arguments.

Objects, such as a switch, button, or volume control knobs, have access to a set of internal numbers known as instance variables. For example, the ON/OFF switch, or object, on an audio amplifier can be referred to as the main switch, while another switch might select between two different types of players. The instance variables in this case could be a counter for the volume and could be a flag for the selection of a particular player. Objects respond to incoming messages by referring to a set of internal methods.

A method can be one of six categories: boolean, arithmetic, data transfer, logical, control transfer, and other. In Table 2 we see a list of all the methods presently available with a lot of room for expansion. In the case of the amplifier, the methods might be to ADD or SUBSTRACT to or from the volume control counter.

Messages consist of a method identifier followed by zero or more parameters. Messages carry commands which the object tries to match from its list of methods. If found, the methods are chosen for execution. The parameters that follow provide necessary information to proceed with the execution. For example, setting the alarm clock in the bedroom would require the time within the argument. Packets sent by CAL over the CEBus network are called ASDUs. An ASDU is a collection of messages that are bundled together to form a packet. The destination can be a node or group of nodes that identify the packet by the address that it carries. Objects respond to a particular command that is determined by the device context under which it exists. Each object on the CEBus is associated with a particular context. In the case of the amplifier, its context would be "AUDIO PROCESS" with the same objects that were described earlier. Table 3 lists the present context categories over the whole range of home automation devices. The IEEE 1394 standard proposed that CAL be a part not only of CEBus but of more general in-home networks, making it an increasingly popular language platform. After the 1997 publication of EIA/CEMA of CAL as a different EIA standard, known later as EIA-721, EIA's CAL became the common application language for in-home networks.

Table 2. Present CAL Methods

80	FALSE	99	EXIT
81	TRUE	9A	REPEAT
84	TEST	9B	NEXT
85	COMPARE	9C	PREVIOUS
86	ADD	A9	POSITION
87	ADD_immediate	AA	X_TRANSLATE
88	SUBSTRACT	AB	Y_TRANSLATE
89	SUBSTRACT_immediate	AC	Z_TRANSLATE
8A	LOAD	AD	X_ROTATE
8B	LOAD_immediate_num	AE	Y_ROTATE
8C	LOAD_immediate_strng	AF	Z_ROTATE
8D	STORE	B0	DATE
8E	SWAP	B1	TIME
8F	NO OPERATION	B7	ALIAS
90	AND	B8	BUILD
91	OR	B9	DEFINE
92	XOR	BA	DO-WHILE
93	NOT	BB	DUMP
94	BRANCH	BC	FOR
95	BRANCH_conditional	BD	IF_THEN_ELSE
96	JUMP	BE	SWITCH
97	CALL	BF	WHILE_DO
98	RETURN		

Table 3. Defined Contexts

00	Abstract utility
30	Audio process
31	Audio source
32	Audio record
38	Video monitor
39	Video source
3A	Video record
40	Tuning system
48	Time service element
60	Appliance control system
64	Communication system
65	Answering machine
66	Intercom
68	Environment management
69	Environment sensors
6A	Air-conditioning system
6B	Heating system
70	Information system
74	Security system
78	Lighting system

CAL divides products into structures or identifiers called *contexts*, in order to obtain information about the product in a uniform manner. The Cebus Industry Council (*CIC*) has proposed in EIA-600 the following general contexts: universal, data channel, time, and user interface. The first one is obligatory in all products. It does not model their functional systems, but contains information about the node control object and has an object that downloads code, information over the network, and CAL commands. In the contexts, the operation of a product can be defined by the function of each of its subunits; for example, an audio context can be found in the audio amplifier in a radio as well as in the tuner, allowing a standard context to control them.

There exist more than 60 different defined contexts, covering different categories for the different kind of appliances. This context list can be found in the CIC home page http://www.cebus.org.

Binding allows contexts to work together. Binding between objects is executed among network output objects and network input objects; the output objects are always the ones that send the information. Binding of contexts is predefined (i.e., specific contexts can be tied to specific objects); thus, the context classes operate on each other through prespecified interoperation schemes.

This binding is not obligatory among contexts, but it helps in controlling functions. As an example of context binding, suppose that a sensor (which belongs to a certain context) measures a specific variable; then the objects that belong to this sensor are tied to a corresponding network input context (belonging to another context), which is the one used in a user product in order to read the action read.

In CEBus, there exist two address acquisition methods: self-acquisition and directed acquisition. In self-acquisition the addresses are stored in the application software of the node. In directed acquisition the node stores the addresses on the CAL context.

Security (the need to prevent unauthorized nodes from reading or writing information) is an issue of concern for every networking product. Many manufacturers have decided to create a security context on their products and have the key information on them. This means that one object of one context sends a message to another context object, and thus both have to be built by the same company so that the security encoding algorithm can be exchanged between them.

Various security techniques are in use, including *message authentication algorithms*, which are of two main types. A *two-way authentication algorithm* requires the nodes involved in the checking to know the encoding algorithm, and each node must have an authentication key in order to accept the command issued. A *one-way authentication algorithm* verifies only the transmitter and the information that goes on the APDU; it requires only one authentication key, but the encoding algorithm must be known by the nodes. Both types of algorithm require a random number that is encoded with the authentication keys.

Encryption is also used in order to obtain greater security in the message and in the data sent on the APDU. The algorithm or technique used has to be known by receiver and transmitter. Encryption is implemented with the help of the authentication algorithm ID in the second byte.

Additions to the application layer of the original CEBus standards have been made in order to create the *Home Plug & Play* specification, transforming standalone products into interactive network products. This is expected to make systems easier to install and combine in a reliable in-home network. Among the objectives to be covered by Home Plug & Play standards is transport protocol independence, so more than one networking protocol can be used in the same home.

Home Plug & Play has three object types: *status, listener*, and *request* objects, which adapt the system in which the status information is given to the other systems. By the use of these objects, products from different producers can be used without detailed knowledge of their working.

An important feature of Home Plug & Play is that it enables consumers to install more complex systems incrementally without complicating their use or requiring burdensome upgrades.

Network Layer. The network layer provides the application layer with connectionless acknowledged and unacknowledged services. For unsegmented APDUs, only unacknowledged transmission services are available from the network layer. The data unit transfer for unsegmented APDUs may be point-to-point, multicast (flood routing), or broadcast. For segmented APDUs, the data transfer must be point-to-point; however, acknowledged transmission sevices are allowed. The network layer appends a header to the APDU received from the application layer to form a network protocol data unit (*NPDU*). Two NPDUs are defined: normal and extended. Normal NPDUs are used for unsegmented APDUs, whereas extended NPDUs are primarily used for segmented messages.

The network layer is the higher layer (the application layer being nonexistent) in the CEBus routers which provide connectivity between the different physical media of the CEBus network. The CEBus routers support two types of packet routing: directory routing and flood routing. Directory routing refers to point-to-point data transfer, where a packet destined for a node on a different physical medium is retransmitted only on the medium to which the destination node is connected. In flood routing the packet is retransmitted on all media connected to the CEBus router that receives the packet.

Data Link Layer. The data link layer function is to provide the network layer with a communication channel that appears free of transmission errors. It is responsible for implementing frame assembly and disassembly, error detection, and medium access control.

The data link layer provides the network layer with point-to-point acknowledged and unacknowledged or broadcast unacknowledged connectionless data transfer. Acknowledged and unacknowledged connectionless services may operate on a local medium or use routers to reach other media. If a frame requires an acknowledgment, it is transmitted to a nonlocal node. The source node has no means of ensuring proper reception of the frame by the destination node.

The data link layer consists of two sublayers: the medium access control (*MAC*) sublayer and the logical link (*LLC*) sublayer. Peer LLC sublayers exchange logical link protocol units (*LPDUs*). An LPDU consists of an NPDU and a header referred to as the control field.

MAC sublayers embed LPDUs into the medium access sublayer protocol data units (*MPDUs*). Two frame formats are defined in the CEBus document: normal MA frame and acknowledge MAC frame. The normal MPDU is the unit of data exchanged between CEBus nodes and is referred to as the CEBus frame. The normal MPDU consists of the following fields: preamble, control, destination address, destination house code, source address, source house code, data, and frame checksum. The acknowledge MAC frame consists of the following fields: preamble, control, information, and frame check sequence.

The data link layer interfaces to the physical layer through its medium access control sublayer and to the layer system management and network layers via its logical link control sublayer. A data link layer hardware implementation consists of three major components: a central processing unit, a local random access memory, and a layer interface unit.

CSMA/CDRC CEBus Medium Access Control Protocol. The CEBus control channel is designed to allow network nodes to exchange messages of variable bounded length. Channel access is regulated by the CEBus medium access protocol, which is a modification of the carrier sense multiple access with contention detection (*CSMA/CD*) protocol widely studied in computer networks. The CEBus medium access protocol is known as CSMA/CDCR, where CR refers to its contention resolution capability. Unlike CSMA/CD, CSMA/CDCR utilizes a contention resolution scheme which allows one of several contending nodes to proceed with its transmission while all the others defer transmissions to a later time. Each CEBus frame starts with the preamble field which is solely used for contention resolution purposes and is not part of the information embodied in the frame. The contention resolution is performed during the preamble field transmission and therefore does not affect the integrity of the transmitted data. The method that allows nodes to detect channel contention and permits one of the contending nodes to proceed with its transmission has been analyzed by Manikopoulos et al. (20). After the reception of the "EOP" symbol, each network node that wishes to transmit must wait for a period of time before attempting channel access. This period of time is referred to thereafter as the node wait time and consists of two parts.

(1) A delay of six unit symbol times (*USTs*) which is observed by all nodes with pending transmissions This delay is necessary to allow the destination node to initiate a transmission of a positive or negative acknowledgement packet, in the case of acknowledged transmission.
(2) A delay which corresponds to the node priority Node priorities are translated into self-imposed delays by which high-priority nodes attempt channel access before lower-priority nodes. Three message priorities are defined: high, standard, and deferred. No additional delay is imposed on high-priority nodes, whereas the added delays for standard and deferred priority nodes are four and eight USTs, respectively.

To further assure orderly access to the channel, a node can be in two states within its priority: queued or unqueued. A node that places itself in the unqueued state attempts channel access as soon as its corresponding priority delay has expired and the channel has remained idle, whereas in the queued state it imposes on itself an additional four USTs delay after the expiration of its corresponding priority delay. This causes an overlap between queued nodes of one priority and the unqueued nodes of the lower priority. A node changes from a queued state to an unqueued state if one of the following occurs:

(1) The node experiences an unsuccessful channel access attempt during its priority queueing time slot.

(2) The node has no packet to send and the medium remains idle during its queued random slot interval.
(3) The channel remains idle up to the point where the self-imposed node priority delay has elapsed; each node within its priority class observes another random delay interval, ranging from one to four USTs. The random delay is used to reduce the probability of collisions between nodes of the same priority and state. The random delay is obtained by summing the two least significant bits of the preamble word with the two least significant bits of the destination address.

Several delay analyses have been performed and shown the relationship between the performances of high, standard, and deferred packets. Several modifications have also been proposed. Other protocols propose very similar access techniques as the one discussed above.

Physical Layer. The physical layer accomplishes the physical connection of the CEBus node to the communication channel. It is the only layer that is specific to each physical medium. The physical layer accepts CEBus symbols sent sequentially from the MAC sublayer, and it translates these symbols into proper electrical signaling. It also receives signals from the physical channel, translates them into CEBus symbols, and passes the received symbols to the MAC sublayer. The physical layer also reports failures and recoveries of the physical channel to the LSM layer.

The physical layer is made up of two sublayers: the medium-dependent physical sublayer (*MDP*) and the symbol encoding sublayer (*SE*). The MDP is the electrical interface to the communication medium. It is responsible for detecting and reporting the medium state and medium state transitions to the SE sublayer. It also places the medium into a state requested by the SE sublayer. The physical layer interfaces to the MAC sublayer via its SE sublayer. The SE sublayer functions are as follows:

It monitors the communication channel and reports channel failures and recoveries to the layer system management.

- It provides the data link layer with a time base that allows its MAC sublayer to execute the CEBus medium access protocol.
- It accepts transmission requests from the MAC sublayer and reports back the success or failure of the transmission.
- It accepts state change indications from the MDP sublayer, translates the period between state changes to CEBus symbols, and relays the received symbols to the MAC sublayer.

The MDP sublayer is responsible for placing the proper electrical signaling on the communication medium and reporting medium "states" and medium state transitions to the SE sublayer. The design of the MDP sublayer is divided into two parts: (1) the SE sublayer interface and noise rejection circuit and (2) the control channel transceiver.

The symbol encoding sublayer may be in one of the following states: initialization, idle, transmit, receive, and diagnostics. At power up or after recovering from a local node or global network failure, the layer system management directs the PLSE to go to an initialization state. In this state, the PLSE circuit controller initializes the various timers and peripheral components, clears any outstanding requests, and informs the layer system management layer of the success of its request. The SE sublayer hardware consists of four components: controller, transmitter, receiver, and layer interface.

The CEBus Communication Medium. The CEBus network embodies two types of communication channels: a control channel and one of several data channels. The control channel is the primary medium through which the CEBus devices exchange control information related to non-data-intensive applications such as energy management, remote instrumentation, entertainment equipment coordination, security systems, and appliances control.

Data channels are reserved for data-intensive application such as voice, music, and TV/video signal distribution. Data channels are allocated via requests exchanged on the control channel. When a device wishes to use a data channel, it must first capture the resource by sending a request on the control channel. Only the current owner of this resource may release it to the requesting device.

Data communicated between two or more devices are first collected into a CEBus frame and then placed on the communication medium. Two types of CEBus frames are defined: normal frame and acknowledge frame. The normal frame consists of several fields and is the carrier of control information. The acknowledge frame is used in acknowledged transmissions and relays a positive or a negative acknowledgment sent after the reception of a normal frame. The EIA specification dictate that the CEBus control channel be in one of two physical states: a superior state or an inferior state. A superior state emanating from any node overrides inferior states generated by any number of nodes. This specification is the cornerstone of the CEBus medium access contention resolution scheme.

The CEBus utilizes a non-return-to-zero pulse width encoding scheme (*NRZ-PWE*) using four symbols: "1," "0," "EOF" (end of frame), and "EOP" (end of packet). A CEBus frame consists of several fields separated by the "EOF" symbol. The encoding of each symbol is strictly related to the duration of the medium state and not in the medium state per se. The duration of each symbol is defined in terms of a unit symbol time where "1" is 1 time units long, "0" is 2 time units, "EOF" and "EOP" are 3 and 4 time units, respectively. The CEBus data rate is defined in terms of how many "1" symbols are transmitted per second.

The CEBus specifications define six different physical media which consist of the power line (*PL*), twisted pair (TP), infrared (IR), radio frequency (*RF*), coax (*CX*), and fiber optic (*FO*) (12). Different physical media may be used in a single CEBus network where communication between nodes mounted on different physical media is accomplished through CEBus routers.

Each of the six communication media specified has advantages and drawbacks. The choice of one communication medium over another should be based on the original goal behind the CEBus standards: to provide increased convenience, comfort, energy management, and safety around the house at an affordable cost. It is also desirable to simplify interconnection of CEBus products and allow installation to be performed by home owners.

Different industry groups are working on developing the physical layer of the six communication media specified by CEBus. Even though complex and elaborate home automation systems will most probably utilize more than one media, a single communication medium satisfying the basic operations of the CEBus should be specified for simple and not complicated systems used in the average home.

Power Line Medium. The PL physical medium consists of existing ac lines in the house. The original communication method specified by the committee is called *ASK* (amplitude shift keying) signaling scheme were bursts of 120 kHz signals present on the power line indicate a superior state and the lack of the 120 kHz signal indicates an inferior state. The PLBus (power line bus) uses a unit symbol time of 1 ms; a "1" is 1 ms long, a "0" is 2 ms long, an "EOF" is 3 ms long and a "EOP" is 4 ms long. A null symbol (125 ms long) is inserted every 158 ms of continuous activity.

Prior to the release of the PLBus specifications, an office and home automation system using the power line medium as a communication medium known as X-10 was developed by X-10 Inc. and had become a *de facto* standard. The X-10 modules also use a 120 kHz signal and are synchronized with the zero crossing of the 60 Hz 120 V line voltage. The X-10 protocol denote a logic "1" with a 1 ms burst of a 120 kHz signal and a logic "0" with its lack. One bit is transmitted every zero cross (or 8333 ms). The X-10 packet consists of 22 bits with a 4-bit start code (1110) followed by 9 bits of data each sent in its true and complemented form.

Since adopters of the PLBus may have devices already installed, CEBus devices have to ensure that no CEBus packet is interpreted as a valid X-10 command. The null symbol is introduced as a PL symbol to prevent false triggering of equipment that might use the X-10 protocol. CEBus devices are sophisticated enough to discard any X-10 devices as line noise.

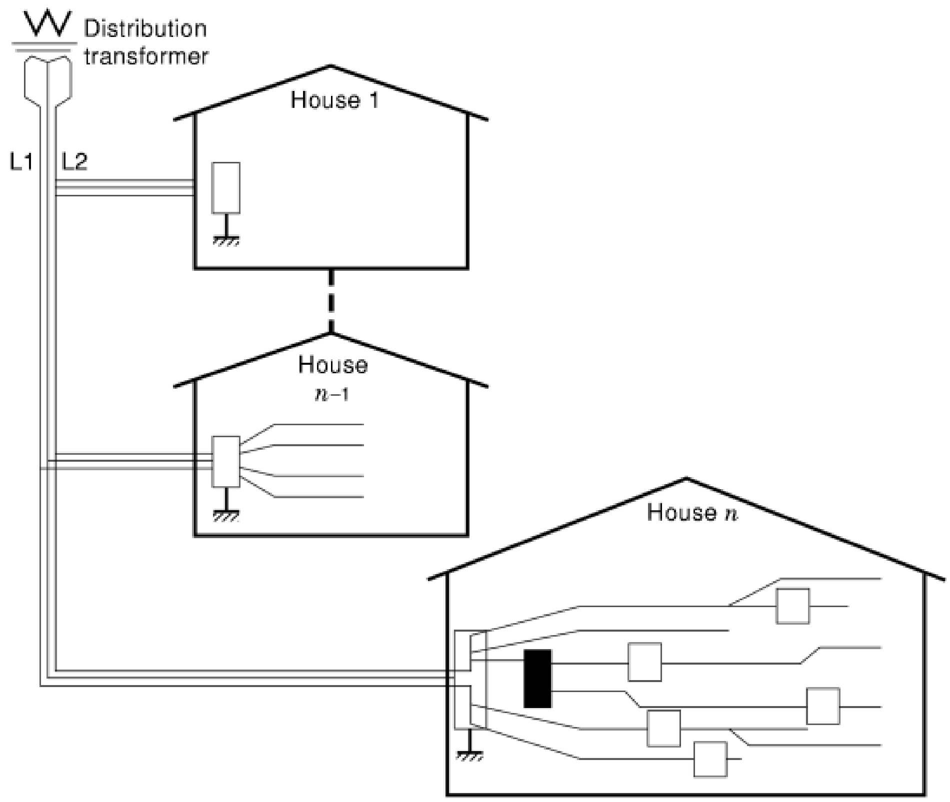

Fig. 5. A power line connection for a home automation system is shown. Houses are connected to a common distribution transformer.

The inefficiency of the original PL line specifications caused enough complaints and prompted the inclusion of the 1991 release of the standard of spread spectrum signaling. This signaling is more robust and noise tolerant, since a burst of noise is less likely to destroy the information transmitted at different frequencies.

Among the six communication media PLBus is the best medium for retrofit installations where the PLBus nodes connect to the power line through existing ac outlets without any additional rewiring. The savings and installation convenience provided by using the existing power lines is offset, though, by several drawbacks. The power line medium is a harsh and noisy environment. An analysis of the residential power lines was performed by O'Neal (13). The noise generated on the secondary of the main distribution transformer was analyzed. The most detrimental noise on the power line was found to be due to light dimmers and universal motors. The second drawback of the PL physical medium is the coupling of the physical layer circuit to the high voltage (120 Vrms) ac line. This coupling presents electrical hazards such as high-energy transients coupled on the power line from external sources. Extra precaution should be taken to prevent the installer of the node from coming in contact with the high line voltage during operation or installation of the power line device. Another disadvantage of the PL network is a consequence of the PL network topology. A PL network consists of all the houses wired to the same distribution transformer as shown in Fig. 5. Signals generated by nodes in house 1 propagate to the nodes in house 2 through n, causing unnecessary collisions.

All houses should be assigned different IDs which constitute a part of the packet destination address in order to assure that nodes in house 1 only accept packets from other nodes in the same house. Privacy and voluntary or involuntary interference from nodes outside a house become an important issue. It should be

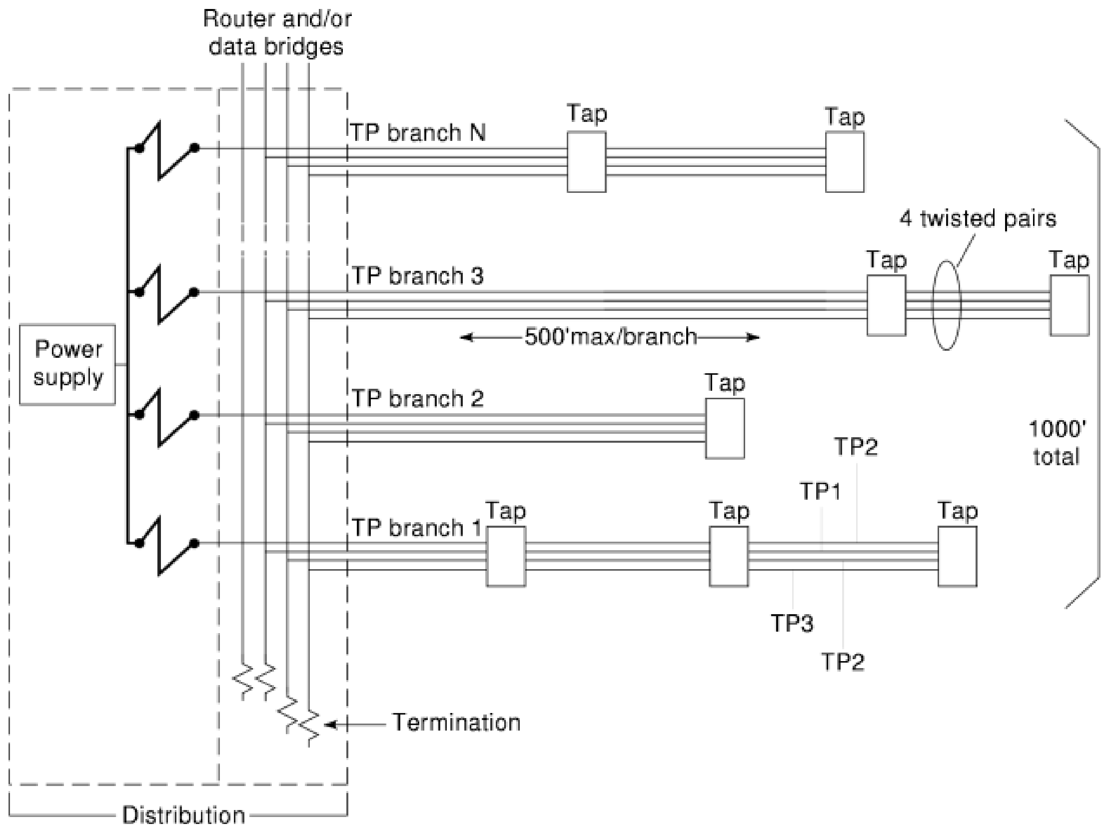

Fig. 6. A twisted pair implementation is shown using router and/or data bridges.

noted that the PLBus requires more than plugging PLBus devices into ac outlets. This is due to the fact that most houses are wired in a two-phase of three-phase power system. Some appliances are connected between phase 1 and the neutral, while other between phase 2 and the neutral; 220 Vrms devices are connected between phase 1 and phase 2. Communication between PLBus equipment on phase 1 with other on phase 2 cannot be accomplished without signal coupling between the different phases.

Twisted Pair Medium. The specifications for the twisted pair medium were released in 1991. The twisted pair bus (*TPBus*) is designed around a four twisted pair jacketed cable currently in use in home telephone wiring. The TPBus is structured in a “star” topology as shown in Fig. 6. The TP branches originate from a shared power supply and have a maximum length of 500 ft. The transfer of data between TP branches is accomplished via routers or data bridges.

The TBPus supports both the CEBus control channel and a number of data channels through frequency division multiplexing. Each TP wire is divided into a set of predefined channels occupying a frequency space between 0 and 512 kHz. Each data channel is 32 kHz wide, and the control channel occupies the first two data channels on TP0. Data channels may be combined if a larger bandwidth is required.

Three signal levels are used to define the CEBus inferior and superior states. Signals are generated using a differential bipolar signaling scheme.

A superior state is represented by a negative or positive differential voltage with respect to the average dc voltage presented at TP0, whereas the inferior state is represented by the absence of any voltage swing.

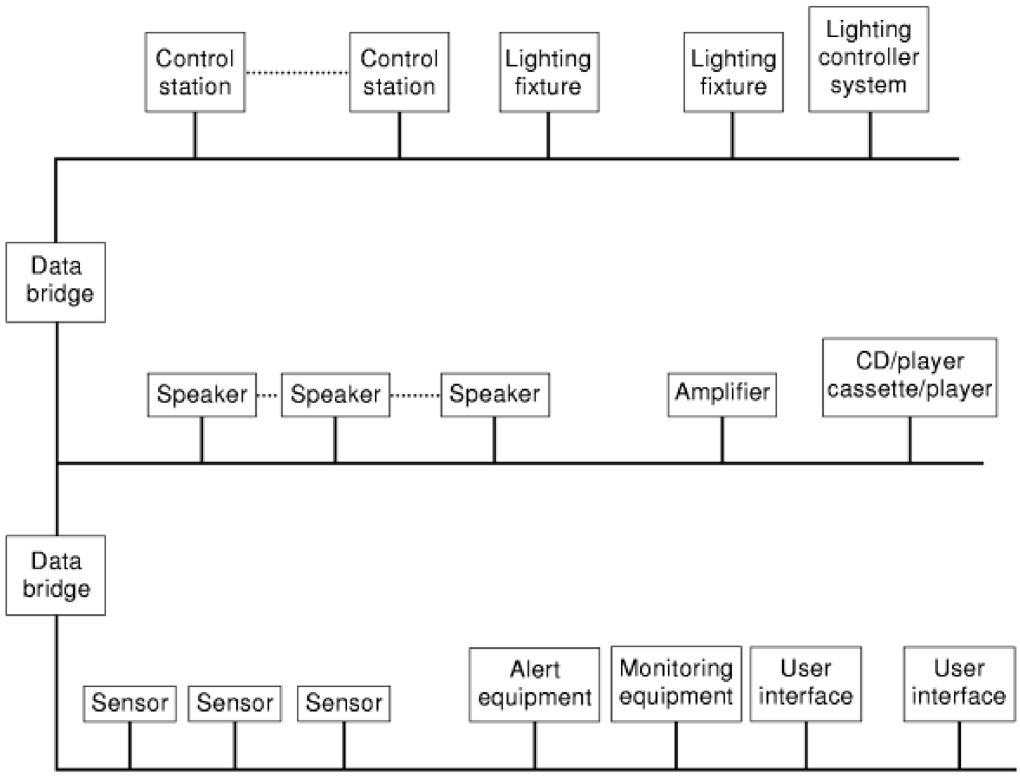

Fig. 7. Data bridges separate groups of similar devices to reduce collisions and improve performance.

The unit symbol time length is set to 100 μs, providing a data rate of 10 Mbps. The TP overcomes many of the drawbacks of the PL medium. It is more immune to noise and provides complete isolation from the high-voltage power lines. Interference from neighboring houses is nonexistent in the TPBus.

To decrease the probability of collisions and further improve the performance of the CEBus network, the network topology can be modified to group-related TP devices in separate groups as shown in Fig. 7. In this example the house lighting control devices share one bus while the home security system communicates on another bus and the house audio and video system uses a third bus. Such a configuration is not possible with a PLBus.

The twisted pair cable is thin and can be routed through the attic of the house or even across the edge of the wall and ceiling without affecting the aesthetics of the house. The routing of the cable can be done by the home owner and does not need a professional installer.

Coax Medium. The coax (CX) communication medium has been widely used in the home bus system (HBS) in Japan (14). The use of coax cables in the American standard is still in the research phase. Coax cables provide excellent immunity to external sources and the support of high-frequency and wide-bandwidth channels. It also provides through frequency multiplexing several data channels that can be allocated upon request to different CEBus equipment simultaneously.

Infrared Medium. The IR medium, also referred to as single-room bus (*SRBus*), has been investigated by several industry groups. The specifications for the IR medium were released in 1991 (15). The IR signaling scheme consists of modulating an IR carrier in the range of 850 nm to 10000 nm with a 100 kHz subcarrier.

The superior state is represented by the presence of the carrier and the inferior state by the absence of the carrier. A data rate is 10 kbps is accomplished.

The IR medium is intended to support some remote control operations and is not intended to be utilized as the primary CEBus communication channel. In IR transmissions the receiver has to be in the line of sight of the transmitter. Communication between a receiver and a transmitter in two different rooms requires optical routing through one of the five other communication media using infrared routers.

Radio-Frequency Medium. Like the IR, the RF medium gives consumers the ability to remotely control their home devices. The RF medium overcomes the problem of signal transmission across walls and house divisions experienced by IR. The design, however, has to conform with strict FCC regulations. Interference from RF equipment in neighboring houses is also to be addressed. No RF signaling has yet to be specified or approved by the EIA committee. Various RF signaling schemes are being considered, with a spread spectrum method as the chief contender (16).

Fiber Optic Medium. A standard for a fiber optic CEBus (*FOBus*) was set originally in Wolff et al. (17) and revised in draft (18). The well-known advantages of fiber, such as increased bandwidth, immunity to electromagnetic noise, security from wiretaps, and ease of installation, compete with its disadvantages, such as higher cost, difficulty in splicing, and requirement of an alternate power supply.

One of the major drives behind the use of fiber optics is the ability to carry multimedia traffic in an efficient way. Since telecommunication companies are planning to bring fiber to the home, a fiber optic network in the house will make internet working with places outside the house cost effective and convenient. Connection with multimedia libraries or with other places offering multimedia services will be easily accomplished to the benefits of the house occupants, especially students of any age who will be able to access, and possibly download and manage, these vast pools of information.

Several minimum requirements of a FOBus are set forth. In terms of service the FOBus should provide the following services:

- Voice, audio, interactive, bulk data, facsimile, video.
- One-way, two-way, and broadcast connectivity.
- Transport of continuous and bursty traffic.
- Interfaces to external networks and consumer products.
- Multiple data channels and a single, digital control channel.

The network should meet the following physical requirements:

- Low installation costs and ease of installation
- High reliability
- Easy attachment of new devices
- Service must not be interrupted while a new node is being connected
- The network is to be accessed via taps in each room

The FOBus standard should also have a layered architecture in which layers above the physical layer are identical to the corresponding CEBus layers in other media.

Given the limited deployment of fibers in home applications, it is suggested that a step-by-step approach be followed in the specification. A proposal presented in Cross (19) utilizes a hybrid architecture between proposed bus (DQDB) and ring (FDDI) architectures for computer networks that allows for meeting of all the requirements.

Some of the applications of a fiber-optic network in the home which will drive the design of the fiber-optic CEBus are: (1) connection to emerging all-fiber networks, which will provide high-quality, high-bandwidth

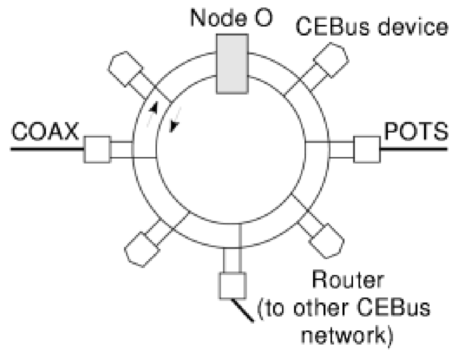

Fig. 8. A ring topology for the fiber optic bus with connections to the Plain Old Telephone Services (*POTS*) network.

audio/visual/data services for entertainment and information; (2) fiber network connection to all-fiber telephone networks to allow extended telephone services such as ISDN, videotelephone, and telecommuting; (3) transport of high-quality audio/video between high-bandwidth consumer devices such as TVs and VCRs; and (4) transport of CEBus and non-CEBus control and data signals for a high degree of home automation and integration.

The topology for the FOBus network is shown in Fig. 8. It is a dual passive ring bus. Each device is attached to both rings via a passive T-junction, except for node 0, which terminates both rings. Node 0 therefore acts similarly to the head-end devices of the DQDB. The FOBus is connected to other networks such as the telephone, cable television, and other CEBus media by way of data bridges, gateways, and routers. Node 0 may also support multiple FOBus networks, which may be carried by alternate physical channels or by the same physical channel but at different wavelengths of light using wavelength division multiplexing (*WDM*). Because the device connections are passive taps, the network need not be taken out of service when installing a new device or while a device is taken off-line for repair.

The advantages of this topology include ease of adding nodes to the network, minimal changes to the CSMA-CD protocol, ability to use WDM to increase network capacity, and the fact that frames will not have to be buffered and retransmitted by any node. The last point will become more important as the services carried by fiber grow beyond the capacity of the electronic/optical interface.

Future Directions

Home automation systems have been presented as a promising technology for bringing the computer and communications revolution that has swept the office and industrial environments in the last decade to the home environment. However, there has not been a use of home automation systems and an increase in the market share as predicted from market analysts. This lack of acceptance can be attributed to marketing problems, costs of installation and retrofitting, slow growth of new housing, and a lack of standards that synchronize with the developments in the other technological areas.

The wide availability of powerful computers at homes and the availability of high-speed telecommunications lines (in the form of cable TV, satellite channels, and in the near future fiber) make a redirection of the home automation industry necessary. More emphasis should be on applications that require access to external sources of information—such as video-on-demand and Internet—or on access from outside the home to home services—such as the load management application discussed above from utilities or individuals and remote surveillance.

User-friendly customer interfaces combined with reasonable pricing will certainly move the industry ahead. The availability of the Internet and the World Wide Web should be exploited in different ways. First the interfaces and the click and drag operations could be adopted and then the high use of bandwidth could be accomplished. The above considerations should be viewed in light of cost and retrofitting issues in existing dwellings and the availability of appliances that are compatible to standards and that can be purchased from multiple vendors.

With regard to the future of fiber optics at home, several observations can be made. External or non-premises service providing networks, and second-generation television receivers such as high-definition television (*HDTV*) are two main areas in which developing technologies will impact the design of the FO CEBus. One external network which the FOBus will have to accommodate is the public telephone network. The current public switched network uses copper wire in its local loop to provide service to a neighborhood, but in the future the use of fiber in the loop (*FITL*) will be gradually phased in. Neighborhood curbside boxes will be replaced with optical network units (*ONUs*) which will provide plain old telephone service (*POTS*) as well as extended network services. Initially, the service to the home will be provided on copper medium, but eventually this will be replaced with fiber as well. The FITL system will support integrated services digital networks (*ISDNs*) and broadband ISDNs (*BISDN*) which will carry voice, data, video, and even interactive applications. The BISDN will employ the synchronous optical network (*SONET*) physical layer standard with asynchronous transfer mode (*ATM*) data transfer. The FOBus specification will have to take this evolution into account.

Another external network which will impact the FOBus design is the cable television network, which is also gradually being replaced by fiber. The FOBus specification will have to accommodate the high-bandwidth services delivered by the cable network (generally in the form of broadcast channels); it may also have to support interactive services which are envisioned for the future.

The other developing technology which will impact the design of the fiber-optic CEBus is the emerging advanced television (*ATV*) standard which will most likely include HDTV. In the United States, the EIA is examining digital standards for HDTV transmission. Most require bandwidth of 20 Mb/s, which the proponents of the standards claim can be transmitted on a standard 6 MHz channel using modulation techniques such as quadrature amplitude multiplexing. In addition, the ATV receiver will likely have separate input ports for RF, baseband digital, and baseband analog signals. The choice of which of these ports to use for the CEBus/ATV interface has not been made. Each has its own advantages. Using the RF port would allow a very simple design for the in-home fiber distribution network, and the interface would only have to perform optical-to-electrical conversion. The digital port would remove bandwidth constrictions from the broadcast signal and also allow for interactive programming and access to programming from various sources. The ATV could become the service access point for all audio/visual services in the home.

An important issue in home automation is the integration of Internet technology in the house. Some companies have proposed a technology to embed network connectivity. The idea is to provide more control and monitoring capability by the use of a Web browser as a user interface. In this new technology, Java and http (standard Internet technology) are accessed through a gateway that manages the communication between the Web browser and the device.

Among the advantages of this new technology are the following:

- Manufacturers can provide their products with strong networking capabilities, and increase the power of Internet and intranet.
- The use of a graphical user interface (*GUI*) allows a simple display of the status, presence, and absence of devices from the network.
- Java, Visual Basic, and Active X development environments reduce the development time of device networking projects.
- Interface development is easy.
- Batch processes to gather data are easy and fast.

Standard technologies to network devices via the Internet provide for the development of internetworking solutions without the added time and costs of building proprietary connections and interfaces for electronic devices.

BIBLIOGRAPHY

1. K. P. Wacks, Utility load management using home automation, *IEEE Trans. Consum. Electron.*, **37**: 168–174, 1991.
2. *The EIA / CEG Home Automation Standard*, Electronics Industries Association, EIA/CEG, Washington, DC, Dec. 1989.
3. X. Murata, T. Namekawa, R. Hamabe, A proposal for standardization of home bus system for home automation, *IEEE Trans. Consum. Electron.*, **CE-29**: 524–530, 1983.
4. M. Inoue *et al.*, A home automation system, *IEEE Trans. Consum. Electron.*, **CE-31**: 516–527, 1985.
5. H. Kojima, Y. Iijima, Visual communication system in an apartment house using fiber optics, in *Proc. IEEE Int. Conf. Consum. Electron.*, Chicago, IL, 1993, pp. 362–364.
6. P. S. Vishwanath, The evolving standard for home automation systems, in *Int. Appl. Tech. Conf.* 45th 1994, Univ. Wisconsin, Madison, May 9–11, 1994, pp. 2:9.2, 1–7.
7. E. Varricchione, Buildings and telematics, *IEE Int. Telecommun. Energy Conf. Proc. INTELEC*, **886** (1): 1989, pp. 1–7.
8. D. G. J. Fanshawe, Traffic analysis yields efficient home network architecture, *IEEE Trans. Consum. Electron.* **CE-33**: 376–383, Aug. 1987.
9. L. Lamarre, Building the intelligent home, *ESPRI-J.*, **16** (4): 4–15, June 1991.
10. J.-Y. Bolvi, Y. Anguill, Home automation for the future, *Transm. Distrib. World*, **48**: 56–61, March 1996.
11. D. A. Butler, The impact of home bus standards on consumer product design: addressing the challenge of a better user interface, *IEEE Trans. Consum. Electron.*, **37**: 163–167, 1991.
12. C. Douligeris, J. Khawand, C. Khawand, Communications and control for a home automation system, in *Proc. IEEE Southeast Conf. '91*, vol. 1, 1991, pp. 171–175.
13. J. B. O'Neal, The residential power circuit as communication medium, *IEEE Trans. on Consum. Electron.*, **32**: 567–577, Aug. 1986.
14. R. Hamabe, M. Murata, T. Namekawa, Home bus system (HBS) interface LSI and its standard protocol example, *IEEE Trans. on Consum. Electron.*, **36**: 807–812, 1990.
15. J. Hoffman, The consumer electronic bus infrared system, *IEEE Trans. on Consum. Electron.*, **37**: 122–128, 1991.
16. S. Winick, The RF medium in the home—the move to spread spectrum, *IEEE Trans. Consum. Electron.*, **37**: 108–115, May 1991.
17. R. Wolff *et al.*, Why a standard for fiber optics in premises networks?, *IEEE Trans. Consum. Electron.*, **37**: xv–xxv, May 1991.
18. *Draft CEBus FO Network Requirements Document*, Electronic Industries Association, May 15, 1992, Washington, D.C.
19. D. Cross, C. Douligeris, A fiber optic home automation system, in *Proc. IEEE Int. Conf. Consum. Electron.*, Chicago, IL, 1993, pp. 352–354.
20. S. Pakkam, C. N. Manikopoulos, Performance evaluation of the consumer electronic bus, *IEEE Trans. Consum. Electron.*, **36**: 949–953, Nov. 1990.

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