Home Automation

Taren Duke

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Email: info@wtbooks.com

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Chapter 1

Home Automation

Home automation (also called **domotics**) is the residential extension of "building automation". It is automation of the home, housework or household activity. Home automation may include centralized control of lighting, HVAC (heating, ventilation and air conditioning), appliances, and other systems, to provide improved convenience, comfort, energy efficiency and security. Home automation for the elderly and disabled can provide increased quality of life for persons who might otherwise require caregivers or institutional care.

A home automation system integrates electrical devices in a house with each other. The techniques employed in home automation include those in building automation as well as the control of domestic activities, such as home entertainment systems, houseplant and yard watering, pet feeding, changing the ambiance "scenes" for different events (such as dinners or parties), and the use of domestic robots. Devices may be connected through a computer network to allow control by a personal computer, and may allow remote access from the internet.

Typically, a new home is outfitted for home automation during construction, due to the accessibility of the walls, outlets, and storage rooms, and the ability to make design changes specifically to accommodate certain technologies. Wireless systems are commonly installed when outfitting a pre-existing house, as they reduce wiring changes. These communicate through the existing power wiring, radio, or infrared signals with a central controller. Network sockets may be installed in every room like AC power receptacles.

Although automated *homes of the future* have been staple exhibits for World's Fairs and popular backgrounds in science fiction, complexity, competition between vendors, multiple incompatible standards and the resulting expense have limited the penetration of home automation to homes of the wealthy or ambitious hobbyists.

A typical domestic patch panel.

Overview and benefits

In modern construction in industrialized nations, homes have been wired for electrical power, telephones, TV outlets (cable or antenna), and a doorbell.

Many household tasks were automated by the development of special appliances. For instance, automatic washing machines were developed to reduce the manual labor of cleaning clothes, and water heaters reduced the labor necessary for bathing.

Other traditional household tasks, like food preservation and preparation have been automated in large extent by moving them into factory settings, with the development of pre-made, pre-packaged foods, and in some countries, such as the United States, increased reliance on commercial food preparation services, such as fast food restaurants. Volume and the factory setting allows forms of automation that would be impractical or too costly in a home setting. Standardized foods enable possible further automation of handling the food within the home.

The use of gaseous or liquid fuels, and later the use of electricity enabled increased automation in heating, reducing the labor necessary to fuel heaters and stoves. Development of thermostats allowed more automated control of heating, and later cooling.

A remote control for moving vessels and vehicles was first patented by Nikola Tesla in 1898.

World's Fairs in Chicago (1934), New York (1939) and (1964–65) depicted electrified and automated homes. In 1966 Jim Sutherland, an engineer working for Westinghouse Electric, developed a home automation system called "ECHO IV"; this was a private project and never commercialized.

With the invention of the microcontroller, the cost of electronic control fell rapidly. Remote and intelligent control technologies were adopted by the building services industry and appliance manufacturers worldwide, as they offer the end user easily accessible and/or greater control of their products.

As the number of controllable appliances in the home rises, the ability of these devices to interconnect and communicate with each other digitally becomes a useful and desirable feature. The consolidation of control or monitoring signals from appliances, fittings or basic services is an aim of home automation.

In simple installations this may be as straightforward as turning on the lights when a person enters the room. In advanced installations, rooms can sense not only the presence of a person inside but know who that person is and perhaps set appropriate lighting, temperature, music levels or television channels, taking into account the day of the week, the time of day, and other factors.

Other automated tasks may include setting the air conditioning to an energy saving setting when the house is unoccupied, and restoring the normal setting when an occupant is about to return. More sophisticated systems can maintain an inventory of products, recording their usage through bar codes, or an RFID tag, and prepare a shopping list or even automatically order replacements.

Home automation can also provide a remote interface to home appliances or the automation system itself, via telephone line, wireless transmission or the internet, to provide control and monitoring via a smart phone or web browser.

An example of a remote monitoring in home automation could be when a smoke detector detects a fire or smoke condition, then all lights in the house will blink to alert any occupants of the house to the possible fire. If the house is equipped with a home theatre, a home automation system can shut down all audio and video components to avoid distractions, or make an audible announcement. The system could also call the home owner on their mobile phone to alert them, or call the fire department or alarm monitoring company.

System

The elements of a domotics system are:

- hardware controllers or software controllers
- sensors
- actuators

A centralized controller can be used, or multiple intelligent devices can be distributed around the home.

Interconnection

By wire:

1. optical fiber
2. cable (coaxial and twisted pair) , including:

   xDSL

3. powerline, including:

   X10
   Universal powerline bus (UPB)
   PLCBUS

Wireless:

1. radio frequency, including:

   Wi-Fi
   GPRS and UMTS
   Bluetooth
   DECT
   ZigBee
   Z-Wave
   X-Comfort
   ONE-NET

EnOcean

2. infrared, including:

Consumer IR

Both Wireless and Wire

1. INSTEON

Classifications of domestic network technologies

- Device interconnection:
  - Bluetooth
  - IEEE 1394 interface (FireWire)
  - IrDA
  - Universal Serial Bus (USB)
  - ZigBee
- Control and automation nets:
  - SCS BUS with OpenWebNet
  - C-Bus (protocol)
  - CEBus
  - EnOcean
  - EHS
  - INSTEON
  - KNX (European Installation Bus)
  - LonWorks
  - ONE-NET
  - Universal Powerline Bus
  - X10
  - ZigBee
  - Z-Wave
- Data nets:
  - Ethernet
  - Homeplug
  - HomePNA
  - WiFi

There have been many attempts to standardise the forms of hardware, electronic and communication interfaces needed to construct a home automation system. Some standards use additional communication and control wiring, some embed signals in the existing power circuit of the house, some use radio frequency (RF) signals, and some use a combination of several methods. Control wiring is hardest to retrofit into an existing house. Some appliances include USB that is used to control it and connect it to a domotics network. Bridges translate information from one standard to another, *e.g.*, from X10 to European Installation Bus.

Centralising control

Besides the upcoming standardisation of home automation hardware, there is also the issue of the control software. In older systems (and some contemporary ones), the control of each home automation system needed to be done separately, and there was thus no central control system. This sometimes led to a great amount of remote controls, one being needed to control each individual part of the system. However, with the new generation of home automation systems, central control can be foreseen. Software such as Fast Track Team Home Personality Software Greeter 1.0 (aka "Cleopatra"),, e-Home Automation, ... allows the control to happen from a single computer or television screen, and/or even from a smart phone (e.g. iPhone).

Tasks

HVAC

Heating, Ventilation and Air Conditioning (HVAC) solutions include temperature and humidity control. This is generally one of the most important aspects to a homeowner. An Internet-controlled thermostat, for example, can both save money and help the environment, by allowing the homeowner to control the building's heating and air conditioning systems remotely.

Lighting

Lighting control systems can be used to control household electric lights.

- Extinguish all the lights of the house
- Replace manual switching with Automation of on and off signals for any or all lights
- Regulation of electric illumination levels according to the level of ambient light available
- Change the ambient colour of lighting via control of LEDs or electronic dimmers

Natural lighting control involves controlling window shades, LCD shades, draperies and awnings.

Audio and video

This category includes audio and video switching and distribution. Multiple audio or video sources can be selected and distributed to one or more rooms.

Security

Control and integration of security systems.

With Home Automation, the consumer can select and watch cameras live from an Internet source to their home or business. Security cameras can be controlled, allowing the user to observe activity around a house or business right from a Monitor or touch panel. Security systems can include motion sensors that will detect any kind of unauthorized movement and notify the user through the security system or via cell phone.

This category also includes control and distribution of security cameras.

- Detection of possible intrusion
  - sensors of detection of movement
  - sensors of magnetic contact of door/window
  - sensors of glass breaking
  - sensors of pressure changes
- Simulation of presence.
- Detection of fire, gas leaks, water leaks
- Medical alert. Teleassistance.
- Precise and safe closing of blinds.

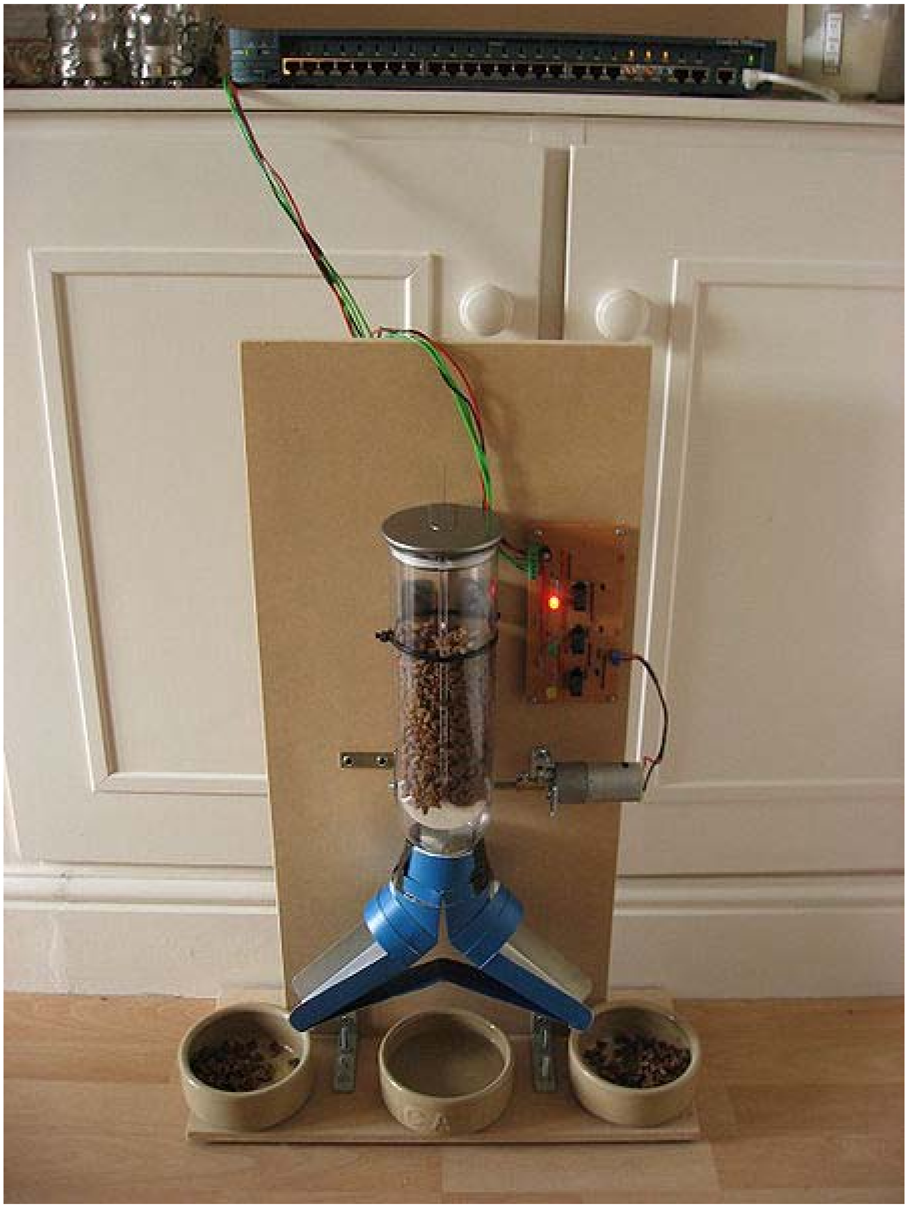
Intercoms

An intercom system allows communication via a microphone and loud speaker between multiple rooms. Integration of the intercom to the telephone, or of the video door entry system to the television set, allowing the residents to view the door camera automatically.

Robotics

- Control of home robots, using if necessary domotic electric beacon.
- Home robot communication (i.e. using WiFi) with the domotic network and other home robots.

Other systems



A homemade Internet-enabled cat feeder.

Using special hardware, almost any device can be monitored and controlled automatically or remotely, including:

- Coffeemaker
- Garage door
- Pet feeding and watering
- Plant watering
- Pool pump(s) and heater, Hot tub and Spa
- Sump Pump

Costs

An automated home can be a very simple grouping of controls, or it can be heavily automated where any appliance that is plugged into electrical power is remotely controlled. Costs mainly include equipment, components, furniture, and custom installation.

Ongoing costs include electricity to run the control systems, maintenance costs for the control and networking systems, including troubleshooting, and eventual cost of upgrading as standards change. Increased complexity may also increase maintenance costs for networked devices.

Learning to use a complex system effectively may take significant time and training.

Control system security may be difficult and costly to maintain, especially if the control system extends beyond the home, for instance by wireless or by connection to the internet or other networks.

Smart Grid

Home automation technologies are viewed as integral additions to the Smart grid. The ability to control lighting, appliances, HVAC as well as Smart Grid applications (load shedding, demand response, real-time power usage and price reporting) will become vital as Smart Grid initiatives are rolled out. Green Automation is the term coined to describe energy management strategies in home automation when data from smart grids is combined with home automation systems to use resources either at there cheapest prices or most available. For example taking advantage of high solar panel out put in the middle of the day to run washing machines automatically.

Organizations

- CEDIA
- Continental Automated Buildings Association
- Digital Living Network Alliance
- CENELEC
- MIT AgeLab
- SIMO TCI
- Living Tomorrow

Chapter 2

Programmable Logic Controller

Siemens Simatic S7-400 system at rack, left-to-right: power supply unit PS407 4A,CPU 416-3, interface module IM 460-0 and communication processor CP 443-1.

A **programmable logic controller** (**PLC**) or **programmable controller** is a digital computer used for automation of electromechanical processes, such as control of machinery on factory assembly lines, amusement rides, or lighting fixtures. PLCs are used in many industries and machines. Unlike general-purpose computers, the PLC is designed for multiple inputs and output arrangements, extended temperature ranges, immunity to electrical noise, and resistance to vibration and impact. Programs to control machine operation are typically stored in battery-backed or non-volatile memory. A PLC is an example of a *hard* real time system since output results must be produced in response to input conditions within a bounded time, otherwise unintended operation will result.

History

The PLC was invented in response to the needs of the American automotive manufacturing industry. Programmable logic controllers were initially adopted by the automotive industry where software revision replaced the re-wiring of hard-wired control panels when production models changed.

Before the PLC, control, sequencing, and safety interlock logic for manufacturing automobiles was accomplished using hundreds or thousands of relays, cam timers, and drum sequencers and dedicated closed-loop controllers. The process for updating such facilities for the yearly model change-over was very time consuming and expensive, as electricians needed to individually rewire each and every relay.

In 1968 GM Hydramatic (the automatic transmission division of General Motors) issued a request for proposal for an electronic replacement for hard-wired relay systems. The winning proposal came from Bedford Associates of Bedford, Massachusetts. The first PLC, designated the 084 because it was Bedford Associates' eighty-fourth project, was the result. Bedford Associates started a new company dedicated to developing, manufacturing, selling, and servicing this new product: Modicon, which stood for MOdular DIgital CONtroller. One of the people who worked on that project was Dick Morley, who is considered to be the "father" of the PLC. The Modicon brand was sold in 1977 to Gould Electronics, and later acquired by German Company AEG and then by French Schneider Electric, the current owner.

One of the very first 084 models built is now on display at Modicon's headquarters in North Andover, Massachusetts. It was presented to Modicon by GM, when the unit was retired after nearly twenty years of uninterrupted service. Modicon used the 84 moniker at the end of its product range until the 984 made its appearance.

The automotive industry is still one of the largest users of PLCs.

Development

Early PLCs were designed to replace relay logic systems. These PLCs were programmed in "ladder logic", which strongly resembles a schematic diagram of relay logic. This program notation was chosen to reduce training demands for the existing technicians. Other early PLCs used a form of instruction list programming, based on a stack-based logic solver.

Modern PLCs can be programmed in a variety of ways, from ladder logic to more traditional programming languages such as BASIC and C. Another method is State Logic, a very high-level programming language designed to program PLCs based on state transition diagrams.

Many early PLCs did not have accompanying programming terminals that were capable of graphical representation of the logic, and so the logic was instead represented as a series of logic expressions in some version of Boolean format, similar to Boolean algebra. As programming terminals evolved, it became more common for ladder logic to be used, for the aforementioned reasons. Newer formats such as State Logic and Function Block (which is similar to the way logic is depicted when using digital integrated logic circuits) exist, but they are still not as popular as ladder logic. A primary reason for this is that PLCs solve the logic in a predictable and repeating sequence, and ladder logic allows the programmer (the person writing the logic) to see any issues with the timing of the logic sequence more easily than would be possible in other formats.

Programming

Early PLCs, up to the mid-1980s, were programmed using proprietary programming panels or special-purpose programming terminals, which often had dedicated function keys representing the various logical elements of PLC programs. Programs were stored on cassette tape cartridges. Facilities for printing and documentation were very minimal due to lack of memory capacity. The very oldest PLCs used non-volatile magnetic core memory.

More recently, PLCs are programmed using application software on personal computers. The computer is connected to the PLC through Ethernet, RS-232, RS-485 or RS-422 cabling. The programming software allows entry and editing of the ladder-style logic. Generally the software provides functions for debugging and troubleshooting the PLC software, for example, by highlighting portions of the logic to show current status during operation or via simulation. The software will upload and download the PLC program, for backup and restoration purposes. In some models of programmable controller, the program is transferred from a personal computer to the PLC though a programming board which writes the program into a removable chip such as an EEPROM or EPROM.

Functionality

The functionality of the PLC has evolved over the years to include sequential relay control, motion control, process control, distributed control systems and networking. The data handling, storage, processing power and communication capabilities of some modern PLCs are approximately equivalent to desktop computers. PLC-like programming combined with remote I/O hardware, allow a general-purpose desktop computer to overlap some PLCs in certain applications. Regarding the practicality of these desktop computer based logic controllers, it is important to note that they have not been generally accepted in heavy industry because the desktop computers run on less stable operating systems than do PLCs, and because the desktop computer hardware is typically not designed to the same levels of tolerance to temperature, humidity, vibration, and longevity as the processors used in PLCs. In addition to the hardware limitations of desktop based logic, operating systems such as Windows do not lend themselves to deterministic logic execution, with the result that the logic may not always respond to changes in logic state or input status with the extreme consistency in timing as is expected from PLCs. Still, such desktop logic applications find use in less critical situations, such as laboratory automation and use in small facilities where the application is less demanding and critical, because they are generally much less expensive than PLCs.

In more recent years, small products called PLRs (programmable logic relays), and also by similar names, have become more common and accepted. These are very much like PLCs, and are used in light industry where only a few points of I/O (i.e. a few signals coming in from the real world and a few going out) are involved, and low cost is desired. These small devices are typically made in a common physical size and shape by several manufacturers, and branded by the makers of larger PLCs to fill out their low end product range. Popular names include PICO Controller, NANO PLC, and other names implying very small controllers. Most of these have between 8 and 12 digital inputs, 4 and 8 digital outputs, and up to 2 analog inputs. Size is usually about 4" wide, 3" high, and 3" deep. Most such devices include a tiny postage stamp sized LCD screen for viewing simplified ladder logic (only a very small portion of the program being visible at a given time) and status of I/O points, and typically these screens are accompanied by a 4-way rocker push-button plus four more separate push-buttons, similar to the key buttons on a VCR remote control, and used to navigate and edit the logic. Most have a small plug for connecting via RS-232 or RS-485 to a personal computer so that programmers can use simple Windows applications for programming instead of being forced to use the tiny LCD and push-button set for this purpose. Unlike regular PLCs that are usually modular and greatly expandable, the PLRs are usually not modular or expandable, but their price can be two orders of magnitude less than a PLC and they still offer robust design and deterministic execution of the logic.

PLC Topics

Features

Control panel with PLC (grey elements in the center). The unit consists of separate elements, from left to right; power supply, controller, relay units for in- and output

The main difference from other computers is that PLCs are armored for severe conditions (such as dust, moisture, heat, cold) and have the facility for extensive input/output (I/O) arrangements. These connect the PLC to sensors and actuators. PLCs read limit switches, analog process variables (such as temperature and pressure), and the positions of complex positioning systems. Some use machine vision. On the actuator side, PLCs operate electric motors, pneumatic or hydraulic cylinders, magnetic relays, solenoids, or analog outputs. The input/output arrangements may be built into a simple PLC, or the PLC may have external I/O modules attached to a computer network that plugs into the PLC.

System scale

A small PLC will have a fixed number of connections built in for inputs and outputs. Typically, expansions are available if the base model has insufficient I/O.

Modular PLCs have a chassis (also called a rack) into which are placed modules with different functions. The processor and selection of I/O modules is customised for the particular application. Several racks can be administered by a single processor, and may have thousands of inputs and outputs. A special high speed serial I/O link is used so that racks can be distributed away from the processor, reducing the wiring costs for large plants.

User interface

PLCs may need to interact with people for the purpose of configuration, alarm reporting or everyday control.

A Human-Machine Interface (HMI) is employed for this purpose. HMIs are also referred to as MMIs (Man Machine Interface) and GUIs (Graphical User Interface).

A simple system may use buttons and lights to interact with the user. Text displays are available as well as graphical touch screens. More complex systems use programming and monitoring software installed on a computer, with the PLC connected via a communication interface.

Communications

PLCs have built in communications ports, usually 9-pin RS-232, but optionally EIA-485 or Ethernet. Modbus, BACnet or DF1 is usually included as one of the communications protocols. Other options include various fieldbuses such as DeviceNet or Profibus. Other communications protocols that may be used are listed in the List of automation protocols.

Most modern PLCs can communicate over a network to some other system, such as a computer running a SCADA (Supervisory Control And Data Acquisition) system or web browser.

PLCs used in larger I/O systems may have peer-to-peer (P2P) communication between processors. This allows separate parts of a complex process to have individual control while allowing the subsystems to co-ordinate over the communication link. These communication links are also often used for HMI devices such as keypads or PC-type workstations.

Programming

PLC programs are typically written in a special application on a personal computer, then downloaded by a direct-connection cable or over a network to the PLC. The program is stored in the PLC either in battery-backed-up RAM or some other non-volatile flash memory. Often, a single PLC can be programmed to replace thousands of relays.

Under the IEC 61131-3 standard, PLCs can be programmed using standards-based programming languages. A graphical programming notation called Sequential Function Charts is available on certain programmable controllers. Initially most PLCs utilized Ladder Logic Diagram Programming, a model which emulated electromechanical control panel devices (such as the contact and coils of relays) which PLCs replaced. This model remains common today.

IEC 61131-3 currently defines five programming languages for programmable control systems: FBD (Function block diagram), LD (Ladder diagram), ST (Structured text, similar to the Pascal programming language), IL (Instruction list, similar to assembly language) and SFC (Sequential function chart). These techniques emphasize logical organization of operations.

While the fundamental concepts of PLC programming are common to all manufacturers, differences in I/O addressing, memory organization and instruction sets mean that PLC programs are never perfectly interchangeable between different makers. Even within the same product line of a single manufacturer, different models may not be directly compatible.

PLC compared with other control systems

Allen-Bradley PLC installed in a control panel

PLCs are well-adapted to a range of automation tasks. These are typically industrial processes in manufacturing where the cost of developing and maintaining the automation system is high relative to the total cost of the automation, and where changes to the system would be expected during its operational life. PLCs contain input and output devices compatible with industrial pilot devices and controls; little electrical design is required, and the design problem centers on expressing the desired sequence of operations. PLC applications are typically highly customized systems so the cost of a packaged PLC is low compared to the cost of a specific custom-built controller design. On the other hand, in the case of mass-produced goods, customized control systems are economic due to the lower cost of the components, which can be optimally chosen instead of a "generic" solution, and where the non-recurring engineering charges are spread over thousands or millions of units.

For high volume or very simple fixed automation tasks, different techniques are used. For example, a consumer dishwasher would be controlled by an electromechanical cam timer costing only a few dollars in production quantities.

A microcontroller-based design would be appropriate where hundreds or thousands of units will be produced and so the development cost (design of power supplies, input/output hardware and necessary testing and certification) can be spread over many sales, and where the end-user would not need to alter the control. Automotive applications are an example; millions of units are built each year, and very few end-users alter the programming of these controllers. However, some specialty vehicles such as transit busses economically use PLCs instead of custom-designed controls, because the volumes are low and the development cost would be uneconomic.

Very complex process control, such as used in the chemical industry, may require algorithms and performance beyond the capability of even high-performance PLCs. Very high-speed or precision controls may also require customized solutions; for example, aircraft flight controls.

Programmable controllers are widely used in motion control, positioning control and torque control. Some manufacturers produce motion control units to be integrated with PLC so that G-code (involving a CNC machine) can be used to instruct machine movements.

PLCs may include logic for single-variable feedback analog control loop, a "proportional, integral, derivative" or "PID controller". A PID loop could be used to control the temperature of a manufacturing process, for example. Historically PLCs were usually configured with only a few analog control loops; where processes required hundreds or thousands of loops, a distributed control system (DCS) would instead be used. As PLCs have become more powerful, the boundary between DCS and PLC applications has become less distinct.

PLCs have similar functionality as Remote Terminal Units. An RTU, however, usually does not support control algorithms or control loops. As hardware rapidly becomes more powerful and cheaper, RTUs, PLCs and DCSs are increasingly beginning to overlap in responsibilities, and many vendors sell RTUs with PLC-like features and vice versa. The industry has standardized on the IEC 61131-3 functional block language for creating programs to run on RTUs and PLCs, although nearly all vendors also offer proprietary alternatives and associated development environments.

Digital and analog signals

Digital or discrete signals behave as binary switches, yielding simply an On or Off signal (1 or 0, True or False, respectively). Push buttons, limit switches, and photoelectric sensors are examples of devices providing a discrete signal. Discrete signals are sent using either voltage or current, where a specific range is designated as *On* and another as *Off*. For example, a PLC might use 24 V DC I/O, with values above 22 V DC representing *On*, values below 2VDC representing *Off*, and intermediate values undefined. Initially, PLCs had only discrete I/O.

Analog signals are like volume controls, with a range of values between zero and full-scale. These are typically interpreted as integer values (counts) by the PLC, with various ranges of accuracy depending on the device and the number of bits available to store the data. As PLCs typically use 16-bit signed binary processors, the integer values are limited between -32,768 and +32,767. Pressure, temperature, flow, and weight are often represented by analog signals. Analog signals can use voltage or current with a magnitude proportional to the value of the process signal. For example, an analog 0 - 10 V input or 4-20 mA would be converted into an integer value of 0 - 32767.

Current inputs are less sensitive to electrical noise (i.e. from welders or electric motor starts) than voltage inputs.

Example

As an example, say a facility needs to store water in a tank. The water is drawn from the tank by another system, as needed, and our example system must manage the water level in the tank.

Using only digital signals, the PLC has two digital inputs from float switches (Low Level and High Level). When the water level is above the switch it closes a contact and passes a signal to an input. The PLC uses a digital output to open and close the inlet valve into the tank.

When the water level drops enough so that the Low Level float switch is off (down), the PLC will open the valve to let more water in. Once the water level rises enough so that the High Level switch is on (up), the PLC will shut the inlet to stop the water from overflowing. This rung is an example of seal-in (latching) logic. The output is sealed in until some condition breaks the circuit.

```
|                                                              |
|   Low Level      High Level                 Fill Valve       |
|------[/]------|------[/]----------------------(OUT)---------|
|               |                                              |
|               |                                              |
|               |                                              |
|   Fill Valve  |                                              |
|------[ ]------|                                              |
|                                                              |
|                                                              |
```

An analog system might use a water pressure sensor or a load cell, and an adjustable (throttling) dripping out of the tank, the valve adjusts to slowly drip water back into the tank.

In this system, to avoid 'flutter' adjustments that can wear out the valve, many PLCs incorporate "hysteresis" which essentially creates a "deadband" of activity. A technician adjusts this deadband so the valve moves only for a significant change in rate. This will in turn minimize the motion of the valve, and reduce its wear.

A real system might combine both approaches, using float switches and simple valves to prevent spills, and a rate sensor and rate valve to optimize refill rates and prevent water hammer. Backup and maintenance methods can make a real system very complicated.

Chapter 3

Power Line Communication

Power line communication or **power line carrier** (**PLC**), also known as **Power line Digital Subscriber Line** (**PDSL**), **mains communication**, **power line telecom** (**PLT**), **power line networking** (**PLN**), or **Broadband over Power Lines** (**BPL**) are systems for carrying data on a conductor also used for electric power transmission.

Electrical power is transmitted over high voltage transmission lines, distributed over medium voltage, and used inside buildings at lower voltages. Powerline communications can be applied at each stage. Most PLC technologies limit themselves to one set of wires (for example, premises wiring), but some can cross between two levels (for example, both the distribution network and premises wiring). Typically the transformer prevents propagating the signal, which requires multiple PLC technologies to be used to form very large networks.

Basics

All power line communications systems operate by impressing a modulated carrier signal on the wiring system. Different types of powerline communications use different frequency bands, depending on the signal transmission characteristics of the power wiring used. Since the power wiring system was originally intended for transmission of AC power, in conventional use, the power wire circuits have only a limited ability to carry higher frequencies. The propagation problem is a limiting factor for each type of power line communications. A new discovery called E-Line that allows a single power conductor on an overhead power line to operate as a waveguide to provide low attenuation propagation of RF through microwave energy lines while providing information rate of multiple Gbps is an exception to this limitation.

Data rates over a power line communication system vary widely. Low-frequency (about 100-200 kHz) carriers impressed on high-voltage transmission lines may carry one or two analog voice circuits, or telemetry and control circuits with an equivalent data rate of a few hundred bits per second; however, these circuits may be many miles long. Higher data rates generally imply shorter ranges; a local area network operating at millions of bits per second may only cover one floor of an office building, but eliminates installation of dedicated network cabling.

Ultra-High-frequency communication (≥100 MHz)

The highest information rate transmissions over power line use RF through microwave frequencies transmitted via a transverse mode surface wave propagation mechanism that requires only a single conductor (U.S. Patent 7,567,154). An implementation of this technology called E-Line has been demonstrated using a single power line conductor. These systems have demonstrated symmetric and full duplex communication well in excess of 1 Gbit/s in each direction. Multiple Wi-Fi channels with simultaneous analog television in the 2.4 and 5.3 GHz unlicensed bands have been demonstrated operating over a single medium voltage line conductor. Because the underlying propagation mode is extremely broadband, it can operate anywhere in the 20 MHz - 20 GHz region. Also since it is not restricted to below 80 MHz, as is the case for high-frequency BPL, these systems can avoid the need to share spectrum with other licensed or unlicensed services and can completely avoid the interference issues associated with use of shared spectrum while offering complete flexibility for modulation and protocols of an RF-microwave system.

High-frequency communication (≥MHz)

High frequency communication may (re)use large portions of the radio spectrum for communication, or may use select (narrow) band(s), depending on the technology.

Home networking (LAN)

Power line communications can also be used in a home to interconnect home computers (and networked peripherals), as well as any home entertainment devices (including TVs, Blu-ray players, game consoles and Internet video boxes such as Apple TV, Roku, Kodak Theatre, etc.) that have an Ethernet port. Consumers can buy powerline adapter sets at most electronics retailers and use those to establish a wired connection using the existing electrical wiring in the home. The powerline adapters plug into a wall outlet (or into an extension cord or power strip, but not into any unit with surge suppression and filtering, as this may defeat the signal) and then are connected via CAT5 to the home's router. Then, a second (or third, fourth, fifth) adapter(s) can be plugged in at any other outlet to give instant networking and Internet access to an Ethernet-equipped Blu-ray player, a game console (PS3, Xbox 360, etc.) a laptop or an Internet TV box that can access and stream video content to the TV.

The most established and widely deployed powerline networking standard for these powerline adapter products is from the HomePlug Powerline Alliance. HomePlug AV is the most current of the HomePlug specifications (HomePlug 1.0, HomePlug AV and the new HomePlug Green PHY for smart grid comprise the set of published specifications) and was adopted by the IEEE P1901 group as a baseline technology for their standard, published 30 December 2010. HomePlug estimates that over 45 million HomePlug devices have been deployed worldwide. Other companies and organizations back different specifications for power line home networking and these include the Universal Powerline Association, the HD-PLC Alliance and the ITU-T's G.hn specification.

Internet access (broadband over powerlines)

Broadband over power lines (BPL), also known as power-line Internet or powerband, is the use of PLC technology to provide broadband Internet access through ordinary power lines. A computer (or any other device) would need only to plug a BPL "modem" into any outlet in an equipped building to have high-speed Internet access. International Broadband Electric Communications or IBEC and other companies currently offer BPL service to several electric cooperatives.

BPL may offer benefits over regular cable or DSL connections: the extensive infrastructure already available appears to allow people in remote locations to access the Internet with relatively little equipment investment by the utility. Also, such ubiquitous availability would make it much easier for other electronics, such as televisions or sound systems, to hook up. Cost of running wires such as ethernet in many buildings can be prohibitive; Relying on wireless has a number of predictable problems including security, limited maximum throughput and inability to power devices efficiently.

But variations in the physical characteristics of the electricity network and the current lack of IEEE standards mean that provisioning of the service is far from being a standard, repeatable process. And, the amount of bandwidth a BPL system can provide compared to cable and wireless is in question. The prospect of BPL could motivate DSL and cable operators to more quickly serve rural communities.

PLC modems transmit in medium and high frequency (1.6 to 80 MHz electric carrier). The asymmetric speed in the modem is generally from 256 kbit/s to 2.7 Mbit/s. In the repeater situated in the meter room the speed is up to 45 Mbit/s and can be connected to 256 PLC modems. In the medium voltage stations, the speed from the head ends to the Internet is up to 135 Mbit/s. To connect to the Internet, utilities can use optical fiber backbone or wireless link.

Deployment of BPL has illustrated a number of fundamental challenges, the primary one being that power lines are inherently a very noisy environment. Every time a device turns on or off, it introduces a pop or click into the line. Energy-saving devices often introduce noisy harmonics into the line. The system must be designed to deal with these natural signaling disruptions and work around them. For these reasons BPL can be thought of as a halfway between wireless transmission (where likewise there is little control of the medium through which signals propagate) and wired transmission (but not requiring any new cables).

Broadband over power lines has developed faster in Europe than in the United States due to a historical difference in power system design philosophies. Power distribution uses step-down transformers to reduce the voltage for use by customers. But BPL signals cannot readily pass through transformers, as their high inductance makes them act as low-pass filters, blocking high-frequency signals. So, repeaters must be attached to the transformers. In the U.S., it is common for a small transformer hung from a utility pole to service a single house or a small number of houses. In Europe, it is more common for a somewhat larger transformer to service 10 or 100 houses. For delivering power to customers, this difference in design makes little difference for power distribution. But for delivering BPL over the power grid in a typical U.S. city requires an order of magnitude more repeaters than in a comparable European city. On the other hand, since bandwidth to the transformer is limited, this can increase the speed at which each household can connect, due to fewer people sharing the same line. One possible solution is to use BPL as the backhaul for wireless communications, for instance by hanging Wi-Fi access points or cellphone base stations on utility poles, thus allowing end-users within a certain range to connect with equipment they already have.

The second major issue is signal strength and operating frequency. The system is expected to use frequencies of 10 to 30 MHz, which has been used for many decades by amateur radio operators, as well as international shortwave broadcasters and a variety of communications systems (military, aeronautical, etc.). Power lines are unshielded and will act as antennas for the signals they carry, and have the potential to interfere with shortwave radio communications. Modern BPL systems use OFDM modulation, which allows them to mitigate interference with radio services by removing specific frequencies used. A 2001 joint study by the American Radio Relay League (ARRL) and HomePlug Powerline Alliance showed that for modems using this technique "in general that with moderate separation of the antenna from the structure containing the HomePlug signal that interference was barely perceptible at the notched frequencies" and interference only happened when the "antenna was physically close to the power lines" (however other frequencies still suffer from interference).

Medium frequency (kHz)

Home control (narrowband)

Power line communications technology can use the household electrical power wiring as a transmission medium. This is a technique used in home automation for remote control of lighting and appliances without installation of additional control wiring.

Typically home-control power line communication devices operate by modulating in a carrier wave of between 20 and 200 kHz into the household wiring at the transmitter. The carrier is modulated by digital signals. Each receiver in the system has an address and can be individually commanded by the signals transmitted over the household wiring and decoded at the receiver. These devices may be either plugged into regular power outlets, or permanently wired in place. Since the carrier signal may propagate to nearby homes (or apartments) on the same distribution system, these control schemes have a "house address" that designates the owner.

Since 1999, a new power-line communication technology "universal powerline bus" has been developed, using pulse-position modulation (PPM). The physical layer method is a very different scheme than the modulated/demodulated RF techniques used by X-10. The promoters claim advantages in cost per node, and reliability.

Low-speed narrow-band communication

Narrowband power line communications began soon after electrical power supply became widespread. Around the year 1922 the first carrier frequency systems began to operate over high-tension lines with frequencies of 15 to 500 kHz for telemetry purposes, and this continues. Consumer products such as baby alarms have been available at least since 1940.

In the 1930s, ripple carrier signalling was introduced on the medium (10-20 kV) and low voltage (240/415 V) distribution systems. For many years the search continued for a cheap bi-directional technology suitable for applications such as remote meter reading. For example, the Tokyo Electric Power Co ran experiments in the 1970s which reported successful bi-directional operation with several hundred units. Since the mid-1980s, there has been a surge of interest in using the potential of digital communications techniques and digital signal processing. The drive is to produce a reliable system which is cheap enough to be widely installed and able to compete cost effectively with wireless solutions. But the narrowband powerline communications channel presents many technical challenges, a mathematical channel model and a survey of work is available.

Applications of mains communications vary enormously, as would be expected of such a widely available medium. One natural application of narrow band power line communication is the control and telemetry of electrical equipment such as meters, switches, heaters and domestic appliances. A number of active developments are considering such applications from a systems point of view, such as demand side management. In this, domestic appliances would intelligently co-ordinate their use of resources, for example limiting peak loads.

Control and telemetry applications include both 'utility side' applications, which involves equipment belonging to the utility company (i.e. between the supply transformer substation up to the domestic meter), and 'consumer-side' applications which involves equipment in the consumer's premises. Possible utility-side applications include automatic meter reading(AMR), dynamic tariff control, load management, load profile recording, credit control, pre-payment, remote connection, fraud detection and network management, and could be extended to include gas and water.

A project of EDF, France includes demand side management, street lighting control, remote metering and billing, customer specific tariff optimisation, contract management, expense estimation and gas applications safety.

There are also many specialised niche applications which use the mains supply within the home as a convenient data link for telemetry. For example, in the UK and Europe a TV audience monitoring system uses powerline communications as a convenient data path between devices that monitor TV viewing activity in different rooms in a home and a data concentrator which is connected to a telephone modem.

High-speed narrow-band powerline communication — distribution line carrier

DLC uses existing electrical distribution network in the medium voltage (MV) — i.e., 11 kV, Low Voltage (LV) as well as building voltages. It is very similar to the powerline carrier. DLC uses narrowband powerline communication frequency range of 9 to 500 kHz with data rate up to 576 kbit/s. DLC is suitable (even in very large networks) for multiple realtime energy management applications. It can be implemented under REMPLI System as well as SCADA, AMR and Power Quality Monitoring System. DLC complies with the following standards: EN 50065 (CENELEC), IEC 61000-3 and FCC Part 15 Subpart B.

Radio users may experience some interference to their systems when in the near proximity of overhead power lines. For two way radio systems utilizing digital schemas, such as the P25 systems, this may appear as loss of received signal caused by the radio's front end (desensitising the receiver). For analog radios the interference appears as a buzzing sound eminating from the radio's speaker. With external inductive or capacitive coupling, a distance more than 15 km can be achieved over a medium voltage network. On low voltage networks, a direct connection can be made since the DLC has a built-in capacitive coupler. This allows end-end communications from substation to the customer premises without repeaters.

The latest DLC systems significantly improve upon and differ from other powerline communication segments. DLC is mainly useful for last-mile and backhaul instrastucture that can be integrated with corporate wide area networks (WANs) via TCP/IP, serial communication or leased-line modem to cater for multi-services realtime energy management systems.

More recently, narrowband PLC communications techniques have also started to include implementations of more sophisticated communication technologies like OFDM, that were till date used in broadband domain. PRIME is one such system that operates within CENELEC A band and uses OFDM as the technology at physical layer to provide data rates of up to 128 kbit/s. The PRIME Alliance is an industrial consortium that is putting forth this open specifications of physical and MAC layers and allowing for utilities to pick solutions from different vendors.

Transmitting radio programs

Sometimes PLC was used for transmitting radio programs over powerlines. When operated in the AM radio band, it is known as a carrier current system. Such devices were in use in Germany, where it was called *Drahtfunk*, and in Switzerland, where it was called *Telefonrundspruch*, and used telephone lines. In the Soviet Union, PLC was very common for broadcasting since the 1930s because of its low cost and accessibility. In Norway the radiation of PLC systems from powerlines was sometimes used for radio supply. These facilities were called *Linjesender*. In all cases the radio programme was fed by special transformers into the lines. To prevent uncontrolled propagation, filters for the carrier frequencies of the PLC systems were installed in substations and at line branches.

An example of the programs carried by "wire broadcasting" in Switzerland:

- 175 kHz Swiss Radio International
- 208 kHz RSR1 "la première" (French)
- 241 kHz "classical music"
- 274 kHz RSI1 "rete UNO" (Italian)
- 307 kHz DRS 1 (German)
- 340 kHz "easy music"

Utility applications

Utility companies use special coupling capacitors to connect medium-frequency radio transmitters to the power-frequency AC conductors. Frequencies used are in the range of 24 to 500 kHz, with transmitter power levels up to hundreds of watts. These signals may be impressed on one conductor, on two conductors or on all three conductors of a high-voltage AC transmission line. Several PLC channels may be coupled onto one HV line. Filtering devices are applied at substations to prevent the carrier frequency current from being bypassed through the station apparatus and to ensure that distant faults do not affect the isolated segments of the PLC system. These circuits are used for control of switchgear, and for protection of transmission lines. For example, a protective relay can use a PLC channel to trip a line if a fault is detected between its two terminals, but to leave the line in operation if the fault is elsewhere on the system.

While utility companies use microwave and now, increasingly, fiber optic cables for their primary system communication needs, the power-line carrier apparatus may still be useful as a backup channel or for very simple low-cost installations that do not warrant installing fiber optic lines.

Low frequency (<kHz)

Utility

Power line carrier systems have long been a favorite at many utilities because it allows them to reliably move data over an infrastructure that they control. Many technologies are capable of performing multiple applications. For example, a communication system bought initially for automatic meter reading can sometimes also be used for load control or for demand response applications.

PLC is one of the technologies used in the automatic meter reading industry. Both one-way and two-way systems have been successfully used for decades. Interest in this application has grown substantially in recent history—not so much because there is an interest in automating a manual process, but because there is an interest in obtaining fresh data from all metered points in order to better control and operate the system. PLC is one of the technologies being used in Advanced Metering Infrastructure (AMI) systems.

In a one-way (inbound only) system, readings "bubble up" from end devices (i.e. meters), through the communication infrastructure, to a "master station" which publishes the readings. A one-way system might be lower-cost than a two-way system, but also is difficult to reconfigure should the operating environment change.

In a two-way system (supporting both outbound and inbound), commands can be broadcast out from the master station to end devices (meters) -- allowing for reconfiguration of the network, or to obtain readings, or to convey messages, etc. The device at the end of the network may then respond (inbound) with a message that carries the desired value. Outbound messages injected at a utility substation will propagate to all points downstream. This type of broadcast allows the communication system to simultaneously reach many thousands of devices—all of which are known to have power, and have been previously identified as candidates for load shed. PLC also may be a component of a smart power grid.

Broadband over power line (BPL)

US FCC

On 14 October 2004, the U.S. Federal Communications Commission adopted rules to facilitate the deployment of "Access BPL" -- i.e., use of BPL to deliver broadband service to homes and businesses. The technical rules are more liberal than those advanced by the US national amateur radio organization, the ARRL, and other spectrum users, but include provisions that require BPL providers to investigate and correct any interference they cause. These rules may be subject to future litigation.

On 8 August 2006 FCC adopted a memorandum opinion and an order on broadband over power lines, giving the go-ahead to promote broadband service to all Americans.The order rejects calls from aviation, business, commercial, amateur radio and other sectors of spectrum users to limit or prohibit deployment until further study is completed. FCC chief Kevin Martin said that BPL "holds great promise as a ubiquitous broadband solution that would offer a viable alternative to cable, digital subscriber line, fiber, and wireless broadband solutions", and that BPL was one of the agency's "top priorities".

'notching out' and dynamic adaptation to contention

New FCC rules (and the IEEE standards) require BPL systems to be capable of remotely notching out frequencies on which interference occurs, and of shutting down remotely if necessary to resolve the interference. BPL systems operating within FCC Part 15 emissions limits may still interfere with wireless radio communications and are required to resolve interference problems. A few early trials were shut down, though whether it was in response to complaints is debatable. The need to deal with signals that inevitably will propagate through thick metal wires hanging above crowded areas was always an issue in BPL standardization and the technologies to resolve it are those already used for wireless, so the issue was primarily one of thresholds and agreement on who had priority for spectrum.

In the US, simply ignoring wireless users was apparently not legal. The ARRL sued the FCC, claiming that the FCC violated the Administrative Procedure Act in creating its rules. On 25 April 2008, a US Court of Appeals agreed with the ARRL that the FCC violated the APA, especially by redacting data from the public that could have shed doubt on the FCC's decision.

"It is one thing for the Commission to give notice and make available for comment the studies on which it relied in formulating the rule while explaining its non-reliance on certain parts", D.C. Circuit Judge Judith Rogers wrote. "It is quite another thing to provide notice and an opportunity for comment on only those parts of the studies that the Commission likes best."

US power and telecommunications companies had meanwhile started tests of the BPL technology, over the protests of the radio groups. After claims of interference by these groups, many of the trials were ended early and proclaimed successes, though the ARRL and other groups claimed otherwise.

Some of the same providers conducting those trials later began commercial roll-outs in limited neighborhoods in selected cities, with some level of user acceptance but also many documented cases of interference reported to the FCC by Amateur Radio users. Some wireless users filed a petition for reconsideration with the FCC in February 2005.

Austria, Australia, New Zealand and other locations have also experienced early BPL's so-called "spectrum pollution" and raised concerns within their governing bodies. In the UK, the BBC has published the results of a number of tests (The effects of PLT on broadcast reception,PLT and Broadcasting, Co-existence of PLT and Radio Services) to detect interference from BPL installations. It has also made a video (Real Media format), showing broadcast of data and interference from in-home BPL devices.

In June 2007, NATO Research and Technology Organisation released a report titled HF Interference, Procedures and Tools (RTO-TR-IST-050) which concluded that widespread deployment of BPL may have a "possible detrimental effect upon military HF radio communications and COMINT systems."

Interference issue remains a challenge to PLC systems

These concerns remain a challenge to widespread PLC adoption, predating the IEEE standards and G.hn for in-home use. All new powerline modems are supposed to detect the existence of SW-Radio services at the location and time of operation by monitoring the ground noise at the socket where the modem is connected but in reality this is not being implemented.

Questions remain how effectively an interference-avoidance system will meet the requirements of SW-Radio services where reception is the first concern. Frequency avoidance schemes cannot adapt to the very low signal levels necessary for a radio receiver to operate reliably. By far, most SW-Radio services are receiving sites and not transmitting sites, so the interference issue remains significant. Current detection schemes are dependent upon transmitted signal levels as the triggering event to force equipment into a frequency avoidance scheme.

In April 2009 the Wireless Institute of Australia reported that radio amateurs in Australia appear to be safe from the rollout of a nationwide Broadband over Powerline or BPL system. Australia's government announced that it will be building a system based on fibre optic technology for its backbone - though it would likely still rely on BPL on high-voltage lines in remote areas. This decision would appear to remove the possibility of widespread interference to radio communications from any network-wide adoption of BPL technology, but still leaves as a concern the possibility of interference from in-home use of G.hn over AC.

The British communications regulator Ofcom has investigated a number of PLT-related complaints but nearly 20% of these remain unresolved. Ofcom maintains that "there does not at present appear to be significant public harm arising from this situation." Since publishing this statement, Ofcom was presented with evidence by the RSGB (Radio Society of Great Britain) that PLT is causing significant disruption to Amateur Radio and Shortwave broadcast resulting in Ofcom commissioning a report into the interference being caused by the technology.

The Electromagnetic Compatibility Industry Association (EMCIA), formed in March 2002 for the benefit of companies involved in the supply, design, test or manufacture of EMC products, or the provision of EMC Services and is a UKTI Accredited Trade Organisation, submitted a stern report to the Parliamentary Committee overseeing broadband, stating that they "..very strongly recommend that the Committee specifically excludes the use of PowerLine Telecommunication (PLT*)..."

It is reported, that these "In Home" Power Line Networking systems, can cause widespread disruption to nearby radio services that use the Shortwave radio spectrum (3 to 30 MHz); and now the VHF radio spectrum (30 to 300MHz). Though some systems when quiescent and not transferring data appear relatively quiet, others continue to send considerable RF energy into the mains wiring when no data is being transferred. All of them can create huge amounts of interference to nearby services (including it has been observed, ADSL2+ via overhead telco cable) when they transfer data. It does appear the problem is worse in some places than others; the local domestic mains wiring practices in different countries appear to have a marked effect on the level of the resulting local radio interference created.

The Radio Society of Great Britain is extremely concerned over PLT and has established a Spectrum Defence Fund.

There are now in-home PLT devices on the market that use both the HF radio spectrum and the VHF radio spectrum (with harmonics observed at 1GHz). This new breed of PLT still use the mains cabling for something it was never designed for. Mains cabling in all countries was only ever intended to carry 50 or 60Hz power. The result is disruption to local FM and DAB broadcast reception, with possible adverse effects to nearby emergency services who may use the VHF spectrum for their own communications.

Automotive uses

Power-line technology enables in-vehicle network communication of data, voice, music and video signals by digital means over direct current (DC) battery power-line. Advanced digital communication techniques tailored to overcome hostile and noisy environment are implemented in a small size silicon device. One power line can be used for multiple independent networks. The benefits would be lower cost and weight (compared to separate power and control wiring), flexible modification, and ease of installation. Potential problems in vehicle applications would include the higher cost of end devices, which must be equipped with active controls and communication, and the possibility of intereference with other radio frequency devices in the vehicle or other places.

Prototypes are successfully operational in vehicles, using automotive compatible protocols such as CAN-bus, LIN-bus over power line (DC-LIN) and [DC-bus].

LonWorks power line based control has been used for an HVAC system in a production model bus.

Failure Scenarios

There are many ways in which the communication signal may have error introduced into it. Interference, cross chatter, some active devices, and some passive devices all introduce noise or attenuation into the signal. When error becomes significant the devices controlled by the unreliable signal may fail, become inoperative, or operate in an undesirable fashion.

1. **Interference:** Interference from nearby systems can cause signal degradation as the modem may not be able to determine a specific frequency among many signals in the same bandwidth.
2. **Signal Attenuation by Active Devices**: Devices such as relays, transistors, and rectifiers create noise in their respective systems, increasing the likelihood of signal degradation. Arc-fault circuit interrupter (AFCI) devices, required by some recent electrical codes for living spaces, may also attenuate the signals.
3. **Signal Attenuation by Passive Devices**: Transformers and DC-DC converters attenuate the input frequency signal almost completely. "Bypass" devices become necessary for the signal to be passed on to the receiving node. A bypass device

may consist of three stages, a filter in series with a protection stage and coupler, placed in parallel with the passive device.

Standards

Two distinctly different sets of standards apply to powerline networking as of early 2010.

IEEE P1901, ITU G.hn home grids

Within homes, the HomePlug AV and IEEE P1901 standards specify how, globally, existing AC wires should be employed for data purposes. The IEEE 1901 includes HomePlug AV as a baseline technology, so any future IEEE 1901 products will be fully interoperable with HomePlug AV, HomePlug Green PHY or the forthcoming HomePlug AV2 specification (under development now and expected to be approved in Q1 2011).

Smart grids and use of BPL for telemetry and data provision by powercos

Power providers are also standardizing their internal and external communications including use of BPL technologies to provide direct links to power system components like transformers. In North America another IEEE standard group is supervising these activities.

Unlike home users, power providers are more able to consider widespread deployment of fiber optic cables immune to electromagnetic interference (and which do not generate any) and for which mature devices (switches, repeaters) are available. Accordingly there is no one single compelling reason to carry data on the existing power lines themselves as there is in homes, except in remote regions where fibre optic networks would not normally be deployed at all. Power network architectures with many transformers are more likely to be served using fibre.

Even if a home is using BPL it may not necessarily connect to the Internet using a BPL-based gateway (typically a smart meter), although this would have major advantages to both the consumer and provider. NIST and IEEE have considered whether requiring smart meters to all be fully functioning BPL gateways would not accelerate demand side management and create a uniform market into which security, home control and other providers can sell.

Standards organizations

Several competing organizations have developed specifications, including the HomePlug Powerline Alliance, Universal Powerline Association and HD-PLC Alliance. On December 2008, the ITU-T adopted Recommendation G.hn/G.9960 as a standard for high-speed powerline, coax and phoneline communications. The National Energy Marketers Association was also involved in advocating for standards. IEEE P1901 is an IEEE working group developing the global standard for high speed powerline communications. In July 2009, the working group approved its "IEEE 1901 Draft Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications" as an IEEE draft standard for broadband over power lines defining medium access control and physical layer specifications. The IEEE 1901 Draft Standard was published by the IEEE in January 2010 and the final standard is expected to be published and ratified in September or October of 2010.

NIST has included IEEE 1901, HomePlug AV and ITU-T G.hn as "Additional Standards Identified by NIST Subject to Further Review" for the Smart grid in the United States.

Chapter 4

Universal Powerline Bus and PLCBUS

Universal powerline bus

Universal powerline bus (or **UPB**) is a protocol for communication among devices used for home automation. It uses power line wiring for signaling and control.

UPB was developed by PCS Powerline Systems of Northridge, California and released in 1999. Based on the concept of the ubiquitous X10 standard, UPB has an improved transmission rate and higher reliability. While X10 without specialty firewalls has a reported reliability of 70-80%, UPB reportedly has a reliability of more than 99%.

Power-line carrier control overview

Household electrical wiring such as Romex or BX is used to send digital data between UPB devices.

While in the X10 protocol this digital data is encoded onto a 120 kHz carrier which is transmitted as bursts during the relatively quiet zero crossings of the 50 or 60 Hz AC alternating current waveform, the UPB protocol works differently.

The UPB communication method consists of a series of precisely timed electrical pulses (called UPB Pulses) that are superimposed on top of the normal AC power waveform (sine wave). Receiving UPB devices can easily detect and analyze these UPB Pulses and pull out the encoded digital information from them.

UPB Pulses are generated by charging a capacitor to a high voltage and then discharging that capacitor's voltage into the powerline at a precise time. This quick discharging of the capacitor creates a large "spike" (or pulse) on the powerline that is easily detectable by receiving UPB devices wired large distances away on the same powerline.

UPB protocol

While transmitting, one UPB Pulse is generated each half-cycle of the 60Hz AC electrical power cycle. The generation of each UPB Pulse is precisely timed to occur in one of four predefined positions in the half-cycle of the AC powerline. The position of each UPB Pulse determines its value as either 0, 1, 2, or 3. This method of encoding data as a relative position of a pulse is a well-known and used method in digital communications known as Pulse Position Modulation (PPM). Since each UPB Pulse can encode two bits of digital information and there are 120 AC half-cycles per second (at 60Hz), UPB communication has a raw speed of 240 bits per second. Although this speed isn't fast enough for doing high bandwidth applications it is perfectly adequate for doing command and control communication.

UPB Pulses are transmitted in a special region toward the end of the AC half-cycle known as the UPB Frame. This region was selected due to its relatively low noise characteristics and for other attributes that make it an optimum position for powerline communications. UPB Frames are synchronized to the low-to-high transition of the AC waveform (known as the AC zero-crossing point) such that one Frame starts T/Frame milliseconds after the zero crossing and the other Frame starts 8,333 milliseconds (one half-cycle at 60Hz) after the first one.

Controllers

UPB controllers range from extremely simple plug-in modules to very sophisticated whole house home automation controllers.

The simplest controllers are plug-in controllers that are recommended for a moderate amount of switches and devices as it becomes cumbersome to control a wide range of devices.

More sophisticated controllers can control more units and/or incorporate timers that perform pre-programmed functions at specific times each day. Units are also available that use passive infrared motion detectors or photocells to turn lights on and off based on external conditions.

Finally, whole house home automation controllers can be fully programmed. These systems can execute many different timed events, respond to external sensors, and execute, with the press of a single button, an entire *scene*, turning lights on, establishing brightness levels, and so on.

Things to consider

UPB is a powerline carrier technology which can be affected by devices on the powerline. However with the advance of the technology to Generation II there are only a few items that can affect the UPB Signal. The engineering team created specific devices to isolate these items.

PLCBUS

PLCBUS (Communication Protocol) or PLC-BUS is a power-line communication protocol for communication between electronic devices used for home automation. It primarily uses power line wiring for signaling and control.

PLCBUS is similar to the X10 (industry standard) power line communication protocol. Though PLCBUS uses the same addressing scheme it is not compatible with X10. PLCBUS and X10 can coexist in the same power-line network and can interact with the use of bridges (like the PLCBUS 4808 device).

History and adoptation

PLCBUS was developed in 2002 by ATS Ltd. in Amsterdam the Netherlands. Companies like Philips, Magma and KPN have agreements with ATS Ltd. regarding PLCBUS products. Also Microsoft, IBM, KPN, Nokia, Motorola, Hewlett Packard, Dell, Siemens and Intel have are said to have agreements with ATS Ltd.. Philips, Nokia, Siemens and the French power company Électricité de France are member of the PLC-BUS Union Commission.

In 2005 the Chinese company Shanghai Super Smart Electronics bought the PLCBUS Technology for their home automation products . Currently the use of PLCBUS, however, is not as widespread as the X10 protocol and there is no vibrant community of PLCBUS users.

Advantages

Advantages of are:

- Reliable two way communication: an ACK is being send back to the sender module to acknowledge command
- Possibility to query the status of a module (for example to determine if a device is switched on or what the dim level of a light is)
- Possibility to monitor the noise and signal levels per module
- Fast: the time between the sending of a command and the retuning of an ACK is ~500ms
- Scalability: up to 64000 module can be addressed. An address consists of a user code, house code and unit code to uniquely identify a module. The large number of addressable modules greatly decreases the chance of unwanted interactions with PLCBUS modules of neighbors, eliminating the need of filters.

Disadvantages

- The normal PLCBUS switches can only switch local appliances. Special scene controller switches are needed to switch appliances remotely.

- Modules no not report when operated locally, the module status has to be polled actively.

Typical devices

An **applicance switch** is used to both locally switch a device on/off andremote (from a scene controller or computer interface for example). Special micro modules are available that can be installed behind switches. Existing on/off switches or momentary (normal-open) switches can be used in conjunction with those micro modules. Also available are plugin appliance switches which don't have to be built-in and which can also be operated locally or remote.

A **light dimmer** is used to set a lights' lightlevel both locally and remote (from a scene controller or computer interface for example). Special micro modules are available that can be installed behind switches or in the ceiling above the light. Existing on/off switches or momentary (normal-open) switches can be used in conjunction with those micro modules. Also available are plugin light dimmers which don't have to be built-in and which can also be operated locally or remote.

A **scene controller** or scene switch is a switch which can operate appliances and lights remote but not locally. It can send macros to set light levels and switch appliances on or off. Scene controllers are typically used to perform activities. For example for watching TV lights are dimmed, the window blinds are closed and the TV is turned on.

A **computer interface** like the PLCBUS 1141, conntected to a serial RS-232 or USB port, can be used to operate appliances and lights and to read module status. Windows software is available and also Linux drivers do exist.

A **bridge** can be used to mix PLCBUS technology with other power-line communication technology. For example the PLCBUS 4808 device can be used to let PLCBUS devices interoperate with X10 devices.

A **phase coupler** can be used to couple up to three different electrical phases. In a normal house, typically only one phase is available.

Chapter 5

Insteon

Insteon (commonly written **INSTEON**) is a system for connecting lighting switches and loads without extra wiring, similar to the X10 standard, designed specifically to address the inherent limitations in the X10 standard but also to incorporate backward compatibility with X10.

Insteon is designed to enable simple devices - such as light switches - to be networked together using the powerline, radio frequency (RF), or both. All Insteon devices are peers, meaning each device can transmit, receive, and repeat any message of the Insteon protocol, without requiring a master controller or routing software.

The system is a dual-band mesh topology employing AC-power lines and a radio-frequency (RF) protocol to communicate with devices. It is a home automation networking technology designed by SmartLabs, Inc.

All Insteon powered devices act as repeaters, meaning that they repeat each message they hear. This is in contrast to other mesh networking topologies where only "advanced nodes" repeat. Automatic error detection and correction are included in all Insteon compatible products. The powerline protocol uses phase-shift keying and is designed so that the repetition is synchronized: all repeaters repeat the same message during precisely-defined time slots, so while the repetitions collide, they do so in harmony in a manner that preserves the message. The power line AC frequency is used as the synchronization source.

Network Topology

Insteon is an integrated dual-mesh network that combines wireless radio frequency (RF) with the home's existing electrical wiring. This is intended to improve reliability by providing a backup system in case of wireless interference. As a peer-to-peer network, devices do not require network supervision, thus dispensing with the need for controllers and routing tables.

Each transmission contains a two-bit "hops" field that starts at 3 and is decremented each time a node in the network repeats a message. The repetition scheme is designed so that all of the nodes repeat the messages in precise sync with one another, so the repetitions collide by design and strengthen one another in harmony.

Notable limitations

- Although the network is dual-mesh, many of the core Insteon compatible products on the market (such as the relay-based light switch for installation in junction boxes) can only communicate on one medium or the other (RF or powerline), rather than both. This negates the benefit of dual mesh for a significant portion of any given installation.
- As with X10, powerline communication is not always dependable, and messages can be lost, even with an acknowledgment and retry scheme. Powerline communication reliability can be hampered by household appliances that generate electrical noise on frequencies near those used by Insteon communication (131.65 kHz). This makes it necessary to purchase additional products to repeat signals and filter noise.
- No network troubleshooting tools exist for Insteon, as there are for X10. The only method for troubleshooting an installation is trial and error with filtering and repeater devices.
- Insteon is designed around 60 Hz power often called "two phase" where all circuits cross zero volts at the same time, as is the standard in North American homes. Almost all compatible products support only 110 volts AC. Three-phase power is not supported by the protocol. 220 volt power is only supported on a few products, but this is mainly a limitation of Insteon-compatible devices themselves, not the protocol.

Installation

Insteon devices are set up using a *Plug and Tap* method. Each device has its own unique ID. The procedure to link two Insteon devices can be done manually at the devices. Though a basic system can be deployed without a controller or PC, such a device may be added for advanced home management. Some such devices are able to save and restore the configuration of individual devices on the network.

Transmission

Insteon uses digital signal processing to encode and transmit messages, enabling rapid transmission of control data between Insteon devices. Individual Insteon messages can also carry up to 14 bytes of arbitrary user data to support home-control applications from developers.

X10 Compatibility

Insteon allows manufacturers to develop products that are both Insteon-compatible and X10-ready. Homeowners with existing X10 networks can migrate to an Insteon network without having to discard all their existing X10 devices. Insteon devices repeat Insteon signals and not X10.

Although both can be sent over the same powerline, Insteon commands are not similar to or compatible with X10, and X10 commands are not Insteon. Rather, Insteon driver chipsets simply include the capability of transmitting, receiving, and responding to X10 powerline messages in addition to Insteon messages. X10 compatibility is implemented in the Insteon-compatible chipsets made by SmartLabs which are offered for sale to other product vendors wishing to implement Insteon in their products. Other than requiring detection of X10 signals and taking steps to prevent collisions with X10 messages in transit, X10 compatibility is not part of the Insteon protocol itself.

Specifications

Data Rate

- Instantaneous 13,165 bit/s
- Sustained 2,880 bit/s

Message Types

- Standard 10 B
- Extended 24 B

Message Format/Structure

- Source Address 3 B
- Destination Address 3 B
- Flags 1 B
- Command 2 B
- User Data 14 B
- Message Integrity 1 B

Devices Supported

- Unique IDs 16,777,216
- Device Types 65,536
- Commands 65,536
- Group Members 256

Insteon Engine Memory Requirements

- RAM 80 B

- ROM 3 kB

Typical Application (Light Switch, Lamp Dimmer) Memory Requirements

- RAM 256 B
- EEPROM 256 B
- Flash 7 kB

Powerline Physical Layer

- Frequency 131.65 kHz
- Modulation BPSK
- Min Transmit Level 3.16 Vpp into 5 ohms
- Min Receive Level 10 mV
- Phase Bridging Insteon RF or hardware

RF Physical Layer

- Frequency 902 to 924 MHz
- Modulation FSK
- Sensitivity -103 dBm
- Range 150 ft unobstructed line-of-sight

Chapter 6

Bus SCS and C-Bus (Protocol)

Bus SCS

SCS is an acronym for "*Sistema Cablaggio Semplificato*" ("Simplified Wiring System"). It uses a fieldbus network protocol and has applications in the field of home automation and building automation.

General Features

An SCS bus is based on a sheathed twisted pair formed of two flexible conductors; these are braided and unshielded with isolation 300/500V – according to the rules adopted by CEI (Italian Electrotechnical Committee).

Communication

Across the Scs bus four different types of signals are transmitted in frequency modulation

- Electricity Supply
- Data
- Sound
- Video

The transmission protocol is the CSMA/CA.

Functions

Through the SCS bus you have the following functions:

- Automation
- Sound diffusion
- Energy management
- Thermoregulation
- Video intercom
- Alarm system

All the listed functions share the same technology and the same procedures for configuration / installation.

Certifications

Devices connected to the SCS bus are IMQ-certified and comply with these product standards (International Electrotechnical Commission (IEC) EN 50428 - IEC EN 60669-1/A1 - IEC EN 60669-2-1 - IEC EN 50090-2-2 - IEC EN 50090-2-3).

Integration

You can interact with the SCS bus through a gateway and an open high-level protocol called OpenWebNet.
These gateways are bidirectional; they translate SCS frames into OpenWebNet frames, and the other way round.

C-Bus (protocol)

C-Bus is a proprietary communications protocol for home and building automation that can handle cable lengths up to 1000 meter using Cat.5 cable. It is used in Australia, New Zealand, Asia, the Middle East, Russia, USA, South Africa, the UK and other parts of Europe including Greece and Romania. C-Bus was created by Clipsal's *Clipsal Integrated Systems* division for use with its brand of home automation and building lighting control system. C-Bus has recently become available in the USA under the 'SquareD Clipsal' brand name.

C-Bus is used in the control of domotics, or home automation systems, as well as commercial building lighting control systems. Unlike the more common X10 protocol which uses a signal imposed upon the AC power line, C-Bus uses a dedicated low-voltage cable or two-way wireless network to carry command and control signals. This improves the reliability of command transmission and makes C-Bus far more suitable for large, commercial applications than X10.

C-Bus System

The C-Bus System can be used to control lighting and other electrical systems and products via remote control and can also be interfaced to a home security system, AV products or other electrical items. The C-Bus system is available in a wired version and a wireless version, with a gateway available to allow messages to be sent between wired and wireless networks.

The wired C-Bus system uses a standard category 5 UTP (Unshielded Twisted Pair) cable as its network communications cable. Clipsal manufacture a specific category 5 cable for use within electrical distribution panels. This cable has a pink outer sheath which is rated to ensure adequate electrical isolation between the mains voltages found in distribution panels and the extra low voltage C-Bus. Outside of distribution panels standard category 5 UTP cable can be used.

The category 5 C-Bus network wiring uses a free topology architecture. The maximum length of cable used on a C-Bus network is 1000 metres; however this is easily extended using C-Bus Network Bridges. Up to 100 units can be installed on a C-Bus network and this can also be extended using Network Bridges.

The maximum number of C-Bus networks in one installation is 255 (note that this limitation does not apply if a C-Bus Ethernet Interface is utilised, the system size is then limited to IP Addressing only). The maximum number of networks connected in series to the local network via Network Bridges is seven (i.e. using six network bridges).

Each standard C-Bus unit requires 18mA @ 15-36Vdc to operate. However some C-Bus units require up to 40mA.

More than one C-Bus power supply can be connected to a C-Bus network to provide sufficient power to the C-Bus units, the C-Bus power supplies will share the load evenly.

Each C-Bus network requires a network burden. This network burden can be enabled on C-Bus output units through software or a hardware burden can be connected to the network.

Each C-Bus network requires at least one system clock generating unit for data synchronisation.

The isolation between the mains supply circuitry and the 36V dc C-Bus circuitry is greater than 3.5kV. This is achieved using double wound transformers and opto isolators. This means the C-Bus wiring, connections and circuitry can be considered Extra Low Voltage.

Wiring Design of C-Bus Systems

In C-Bus systems, the connections between the DB and (for example) the ceiling lights, and between the DB and the junction box (wall switch) are completely separate. In addition, there are no connections between the Junction Box and the respective ceiling lights. The Intelligence of a C-BUS system lies in a “Channel Dimmer” or “Channel Actuator” which is installed in the DB and would replace the traditional standard relay installed in existing homes today. This “Channel Dimmer” would have a 120/220V Line interconnection directly to the ceiling light and a neutral connection back from the ceiling light to the “Channel Dimmer”. The “Channel Dimmer” will control the light directly and will receive its commands either from a rail mounted controller that is connected to its communication port or bus port, or manually from a wall mounted light switch/keypad. This wall mounted light switch would not be connected to any load whatsoever, it would be directly connected with the “Channel Dimmer” by means of a control/signaling cable. The “Channel Dimmers” normally come as 4-channel or 8-channel, this means that they can be connected to 4 or 8 separate lighting circuits at the same time and this din-rail mounted device is also a single point of failure for all these 4 or 8 lighting circuits.

C-Bus Interoperability

As of 9th December 2008 Clipsal opened its C-Bus protocols to anyone who wants to interact with it programatically.

Using one of Clipsal C-Bus PC Modules: Serial (Comport rs232) or Ethernet (tcp/ip) modules, you can interact with other home automation systems, or interact with Andriod apps, and iPad/iPhone apps. All you do is plug a network cable from your Home ADSL WiFi router to the Clipsal C-Bus Ethernet module, and then any Android or iPad can control your home automation system. You can also use this same method to integrate C-bus with HomeSeer using MCSxAP. And in theory you can also do this to integrate C-Bus via a X10 module for the PC.

If you a .Net/Java/c++ software developer, you can find the C-Bus protocol information here to interact from your PC:

Even though C-Bus or Clipsal Bus is a closed protocol. The C-Bus was developed using the ISO 7 layer reference model. C-Bus supports a number of interfaces such as RS232 and TCP/IP and makes these protocols available to third party companies. Clipsal has also developed a server application called C-Gate, to facilitate software integration. The C-Bus interface specifications are available at no-cost through the C-Bus Enabled Program, however it is necessary to agree to a license agreement. It is also possible to become a C-Bus enabled partner; This requires payment but provides a greater level of support for product development and certification.

The future of C-Bus

C-Bus as a home automation and building lighting control system is used primarily in Australia (Sydney Opera House etc.). C-Bus is currently available in Asia, the United Kingdom (installed in Wembley Stadium and Manchester City Football Club), Russia, USA (named SquareD) and a number of other countries are now using this system. One major obstacle to widespread use of wired C-Bus is that it will not work with a standard mains wire installation, a completely new wiring system must be installed for a wired C-Bus system which means that it is normally only used for new builds. The C-Bus wireless (RF) system can however be retrofitted using the existing mains wiring.

C-Bus is compatible with BACnet, TCP/IP, Crestron, AMX, LonWorks, ModBus, Charmed Quark Controller, the Comfort Intelligent Home System and some other protocols through interfaces.

Chapter 7

X10 (Industry Standard)

X10 modules (clockwise from upper left): An original BSR lamp module, a "chime module", a recent lamp module, an outlet module

X10 is an international and open industry standard for communication among electronic devices used for home automation, also known as *domotics*. It primarily uses power line wiring for signaling and control, where the signals involve brief radio frequency bursts representing digital information. A wireless radio based protocol transport is also defined.

X10 was developed in 1975 by Pico Electronics of Glenrothes, Scotland, in order to allow remote control of home devices and appliances. It was the first general purpose domotic network technology and remains the most widely available.

Although a number of higher bandwidth alternatives exist, X10 remains popular in the home environment with millions of units in use worldwide, and inexpensive availability of new components.

History

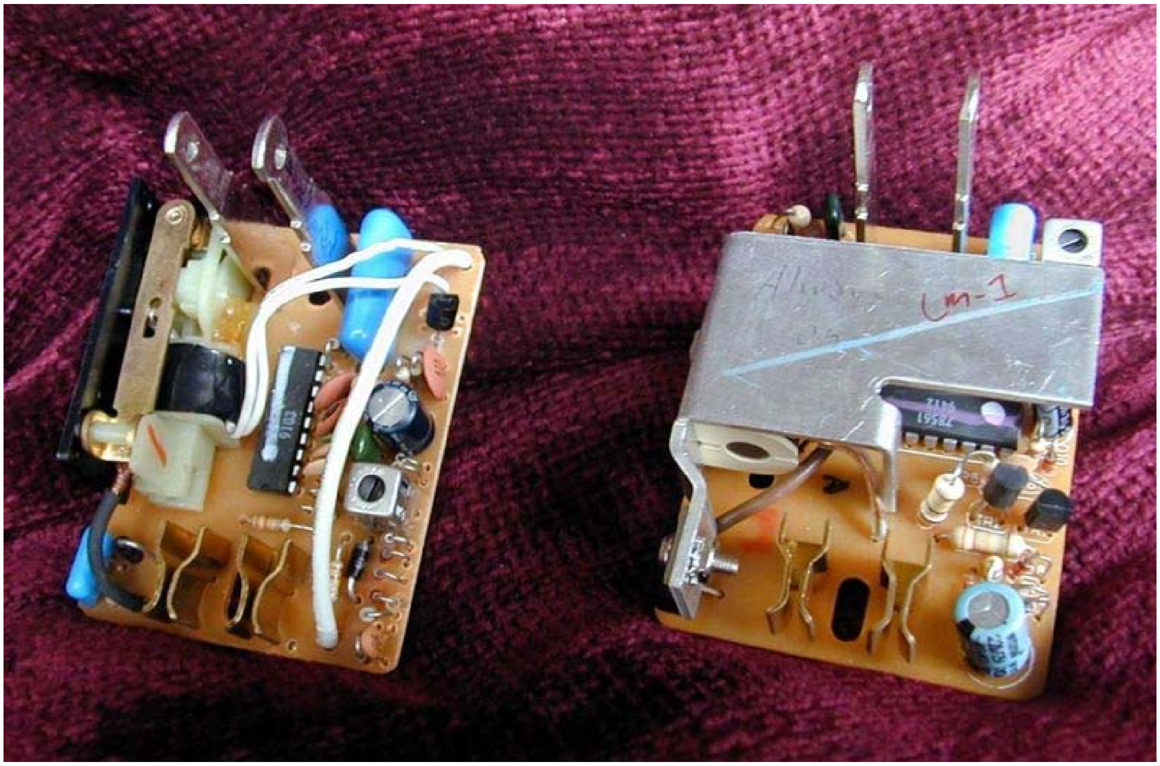
In 1970, a group of engineers started a company in Glenrothes, Scotland called Pico Electronics. The company revolutionized the calculator industry by developing the first single chip calculator. When the calculator IC prices started to fall. Pico refocused on commercial products rather than plain ICs.

In 1974, the Pico engineers jointly developed a vinyl LP changer with BSR, at the time the largest manufacturer of record changers in the world. It could be operated by a remote control using ultrasound signals. Which gave the idea of remote control for lights and appliances. By 1975, the X10 project was conceived, named so because it was the tenth project. In 1978, X10 products started to appear in Radio Shack and Sears stores. Together with BSR a partnership was formed, with the name X10 Ltd. At that time the system consisted of a 16 channel command console, a lamp module, and an appliance module. Soon after came the wall switch module and the first X10 timer.

In the 1980s the CP-290 computer interface was released. Software for the interface run on the Apple II, Macintosh, MS-DOS, and MS-Windows.

In 1984, BSR went out of business, and X10 (USA) Inc was formed. In the early 1990s, the consumer market was divided into two main categories, the ultra-high-end with a budget at > 100 000 USD and the mass market with budgets at 2000 - 35 000 USD. CEBus (1984) and LonWorks (1991) were attempts to improve reliability and replace X10, but have yet to succeed with market ubiquity.

Power line carrier control overview



X10 modules: The interior of an appliance module (note the impulse relay on the left) and a lamp module (note the TRIAC and heat sink)

Household electrical wiring (the same which powers lights and appliances) is used to send digital data between X10 devices. This digital data is encoded onto a 120 kHz carrier which is transmitted as bursts during the relatively quiet zero crossings of the 50 or 60 Hz AC alternating current waveform. One bit is transmitted at each zero crossing.

The digital data consists of an address and a command sent from a controller to a controlled device. More advanced controllers can also query equally advanced devices to respond with their status. This status may be as simple as "off" or "on", or the current dimming level, or even the temperature or other sensor reading. Devices usually plug into the wall where a lamp, television, or other household appliance plugs in; however some built-in controllers are also available for wall switches and ceiling fixtures.

The relatively high-frequency carrier frequency carrying the signal cannot pass through a power transformer or across the phases of a multiphase system. For split phase systems, the signal can be passively coupled from phase-to-phase using a passive capacitor, but for three phase systems or where the capacitor provides insufficient coupling, an active X10 repeater can be used. To allow signals to be coupled across phases and still match each phase's zero crossing point, each bit is transmitted three times in each half cycle, offset by 1/6th cycle.

It may also be desirable to block X10 signals from leaving the local area so, for example, the X10 controls in one house do not interfere with the X10 controls in a neighboring house. In this situation, inductive filters can be used to attenuate the X10 signals coming into or going out of the local area.

X10 protocol

Whether using power line or radio communications, packets transmitted using the X10 control protocol consist of a four bit *house code* followed by one or more four bit *unit code*, finally followed by a four bit command. For the convenience of users configuring a system, the four bit house code is selected as a letter from A through P while the four bit unit code is a number 1 through 16.

When the system is installed, each controlled device is configured to respond to one of the 256 possible addresses (16 house codes × 16 unit codes); each device reacts to commands specifically addressed to it, or possibly to several broadcast commands.

The protocol may transmit a message that says "select code A3", followed by "turn on", which commands unit "A3" to turn on its device. Several units can be addressed before giving the command, allowing a command to affect several units simultaneously. For example, "select A3", "select A15", "select A4", and finally, "turn on", causes units A3, A4, and A15 to all turn on.

Note that there is no restriction (except possibly consideration of the neighbors) that prevents using more than one house code within a single house. The "all lights on" command and "all units off" commands will only affect a single house code, so an installation using multiple house codes effectively has the devices divided into separate zones.

List of X10 commands:

Code	Function	Description
0 0 0 0	All units off	Switch off all devices with the house code indicated in the message
0 0 0 1	All lights on	Switches on all lighting devices (with the ability to control brightness)
0 0 1 0	On	Switches on a device
0 0 1 1	Off	Switches off a device
0 1 0 0	Dim	Reduces the light intensity
0 1 0 1	Bright	Increases the light intensity

0 1 1 1	Extended code	Extension code
1 0 0 0	Hail request	Requests a response from the device(s) with the house code indicated in the message
1 0 0 1	Hail acknowledge	Response to the previous command
1 0 1 x	Pre-set dim	Allows the selection of two predefined levels of light intensity
1 1 0 1	Status is on	Response to the Status Request indicating that the device is switched on
1 1 1 0	Status is off	Response indicating that the device is switched off
1 1 1 1	Status request	Request requiring the status of a device

Power line protocol physical layer details

In the 60 Hz AC current flow, a bit value of one is represented by a 1 millisecond burst of 120 kHz at the zero crossing point (nominally 0°, but within 200 microseconds of the zero crossing point), immediately followed by the absence of a pulse. A zero value is represented by the absence of 120 kHz at the zero crossing point (pulse), immediately followed by the presence of a pulse. All messages are sent twice to reduce false signaling. After allowing for retransmission, line control, etc., data rates are around 20 bit/s, making X10 data transmission so slow that the technology is confined to turning devices on and off or other very simple operations.

In order to provide a predictable start point, every data frame transmitted always begin with a *start code* of 1110. Immediately after the start code, a *house code* (A–P) appears, and after the letter code comes a *function code*. Function codes may specify a unit number code (1–16) or a command code, the selection between the two modes being determined by the last bit where 0=unit number and 1=command. One start code, one letter code, and one function code is known as an X10 **frame** and represent the minimum components of a valid X10 data packet.

Each frame is sent twice in succession to make sure the receivers understand it over any power line noise for purposes of redundancy, reliability, and to accommodate line repeaters.

Whenever the data changes from one address to another address, from an address to a command, or from one command to another command, the data frames must be separated by at least 6 clear zero crossings (or "000000"). The sequence of six zeros resets the device decoder hardware.

Later developments (1997) of hardware are improvements of the native X10 hardware. This is called "Advanced X10" or A10. These devices contain improved hardware with a receiver and transmitter allowing two-way communication between the devices. In Europe (2001) for the 230 VAC 50 Hz market, this improvement is called Xanura. All improved products use the same X10 protocol.

The radio protocol

A four-channel radio switch and radio-to-power-line transponder

To allow the operation of wireless keypads, remote switches, and the like, a radio protocol is also defined. Operating at a frequency of 310 MHz in the U.S. and 433 MHz in European systems, the wireless devices send data packets that are very similar to ordinary X10 power line control packets. A radio receiver then provides a bridge which translates these radio packets to ordinary X10 power line control packets.

The devices available using the radio protocol include:

- Keypad controllers ("clickers")
- Keychain controllers that can control one to four X10 devices
- Burglar alarm modules that can transmit sensor data
- Passive infrared switches to control lighting and X-10 chimes
- Non-passive information bursts

Device modules

X10 modules: A lamp socket module

Depending on the load that is to be controlled, different modules must be used. For incandescent lamp loads, a *lamp module* or *wall switch* module can be used. These modules switch the power using a TRIAC solid state switch and are also capable of dimming the lamp load. Lamp modules are almost silent in operation, and generally rated to control loads ranging from approximately 40 to 500 watts.

For loads other than incandescent lamps, such as fluorescent lamps, high-intensity discharge lamps, and electrical home appliances, the triac-based electronic switching in the lamp module is unsuitable and an *appliance module* must be used instead. These modules switch the power using an impulse relay. In the U.S., these modules are generally rated to control loads up to 15 amperes (1800 watts at 120V).

Many device modules offer a feature called *local control*. If the module is switched off, operating the power switch on the lamp or appliance will cause the module to turn on. In this way, a lamp can still be lit or a coffee pot turned on without the need to use an X10 controller. Wall switch modules may not offer this feature.

Some wall switch modules offer a feature called *local dimming*. Ordinarily, the local push button of a wall switch module simply offers on/off control with no possibility of locally dimming the controlled lamp. If local dimming is offered, holding down the push button will cause the lamp to cycle through its brightness range.

Higher end modules have more advanced features such as programmable on levels, customizable fade rates, the ability to transmit commands when used (referred to as 2-way devices), and *scene* support.

There are sensor modules that sense and report temperature, light, infra-red, motion, or contact openings and closures. Device modules include thermostats, audible alarms and controllers for low voltage switches.

Controllers

X10 controllers: A simple controller, a radio controller, and an original controller usable with an ultrasonic remote control

X10 controllers range from extremely simple to very sophisticated.

The simplest controllers are arranged to control four X10 devices at four sequential addresses (1–4 or 5–8). The controllers typically contain the following buttons:

- Unit 1 on/off
- Unit 2 on/off
- Unit 3 on/off
- Unit 4 on/off
- Brighten/dim (last selected unit)
- All lights on/all units off

More sophisticated controllers can control more units and/or incorporate timers that perform preprogrammed functions at specific times each day. Units are also available that use passive infrared motion detectors or photocells to turn lights on and off based on external conditions.

Finally, very sophisticated units are available that can be fully programmed or, like the X10 Firecracker, use a program running in an external computer. These systems can execute many different timed events, respond to external sensors, and execute, with the press of a single button, an entire *scene*, turning lights on, establishing brightness levels, and so on. Control programs are available for computers running Microsoft Windows, Apple's Macintosh, Linux and FreeBSD operating systems.

Burglar alarm systems are also available. These systems contain door/window sensors as well as motion sensors that use a coded RF signal to identify when they are tripped or just to routinely check-in and give a heart-beat signal to show that the system is still active. Users can arm and disarm their system via several different remote controls which also use a coded RF signal to ensure security. When an alarm is triggered the console will make an outbound phone call with a recorded message. The console will also use X10 protocols to flash lights when an alarm has been triggered while the security console sounds an external siren. Using X10 protocols signals will also be sent to remote sirens for additional security.

Weak points and limitations

Compatibility with installed wiring and appliances

One problem with X10 is excessive attenuation of signals between the two live conductors in the 3-wire 120/240 volt system used in typical North American residential construction. Signals from a transmitter on one live conductor may not propagate through the high impedance of the distribution transformer winding to the other live conductor. Often, there's simply no reliable path to allow the X10 signals to propagate from one transformer leg wire to the other; this failure may come and go as large 240 volt devices such as stoves or dryers are turned on and off. (When turned on, such devices provide a low-impedance bridge for the X10 signals between the two leg wires.) This problem can be permanently overcome by installing a capacitor between the leg wires as a path for the X10 signals; manufacturers commonly sell signal couplers that plug into 240 volt sockets that perform this function. More sophisticated installations install an active repeater device between the legs, while others combine signal amplifiers with a coupling device. A repeater is also needed for inter-phase communication in homes with three-phase electric power. In many countries outside North America, entire houses are typically wired from a single 240 volt single-phase wire, so this problem does not occur.

An RCD/GFCI can attenuate X10 signals passing through the device. This means that X10 signals passing through an RCD may not be strong enough to provide reliable communication.

Television receivers or household wireless devices may cause spurious "off" or "on" signals. Noise filtering (as installed on computers as well as many modern appliances) may help keep external noise out of X10 signals, but noise filters not designed for X10 may also attenuate X10 signals traveling on the branch circuit to which the appliance is connected.

Certain types of power supplies used in modern electronic equipment, such as computers, television receivers and satellite receivers, attenuate passing X10 signals by providing a low impedance path to high frequency signals. Typically, the capacitors used on the inputs to these power supplies short the X10 signal from line to neutral, suppressing any hope of X10 control on the circuit near that device. Filters are available that will block the X10 signals from ever reaching such devices; plugging offending devices into such filters can cure mysterious X10 intermittent failures.

Some X10 controllers may not work well or at all with low power devices (below 50 watts) or devices like fluorescent bulbs that do not present resistive loads. Use of an appliance module rather than a lamp module may resolve this problem.

Commands getting lost

X10 signals can only be transmitted one command at a time, first by addressing the device to control, and then sending an operation for that device to perform. If two X10 signals are transmitted at the same time they may collide or interleave, leading to commands that either cannot be decoded or that trigger incorrect operations. The CM15A and RR501 Transceiver can avoid these signal collisions that can sometimes occur with other models.

Relatively slow

The X10 protocol is slow. It takes roughly three quarters of a second to transmit a device address and a command. While generally not noticeable when using a tabletop controller, it becomes a noticeable problem when using 2-way switches or when utilizing some sort of computerized controller. The apparent delay can be lessened somewhat by using slower device dim rates. With more advanced modules another option is to use group control (lighting scene) extended commands. These allow to adjust several modules at once by a single command.

Limited functionality

X10 protocol does support more advanced control over the dimming speed, direct dim level setting and group control (scene settings). This is done via extended message set, which is an official part of X10 standard . However support for all extended messages is not mandatory, and a lot of cheaper modules implement only the basic message set. These require adjusting each lighting circuit one after the other, which can be visually unappealing and also very slow.

Interference and lack of encryption

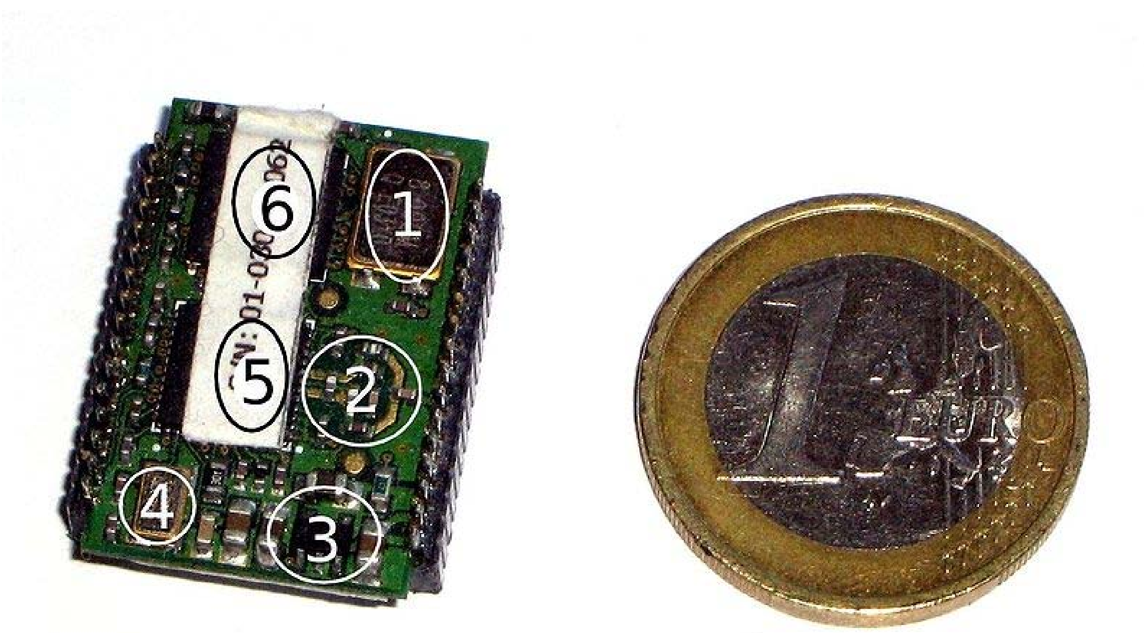
The standard X10 power line and RF protocols lack support for encryption, and can only address 256 devices. Unfiltered power line signals from close neighbors using the same X10 device addresses may interfere with each other. Interfering RF wireless signals may similarly be received, with it being easy for anyone nearby with an X10 RF remote to wittingly or unwittingly cause mayhem if an RF to power line device is being used on a premises.

Bridges

There are bridges to translate X10 to other domotic standards (e.g., KNX). ioBridge translates the X10 protocol to a web service API via the X10 PSC04 Powerline Interface Module.

Chapter 8

ZigBee



ZigBee module. The €1 coin, shown for size reference, is about 23 mm (0.9 inch) in diameter.

ZigBee is a specification for a suite of high level communication protocols using small, low-power digital radios based on the IEEE 802.15.4-2003 standard for Low-Rate Wireless Personal Area Networks (LR-WPANs), such as wireless light switches with lamps, electrical meters with in-home-displays, consumer electronics equipment via short-range radio needing low rates of data transfer. The technology defined by the ZigBee specification is intended to be simpler and less expensive than other WPANs, such as Bluetooth. ZigBee is targeted at radio-frequency (RF) applications that require a low data rate, long battery life, and secure networking.

Technical overview

ZigBee is a low-cost, low-power, wireless mesh networking standard. First, the low cost allows the technology to be widely deployed in wireless control and monitoring applications. Second, the low power-usage allows longer life with smaller batteries. Third, the mesh networking provides high reliability and more extensive range.

It is not capable of powerline networking though other elements of the OpenHAN standards suite promoted by openAMI and UtilityAMI deal with communications co-extant with AC power outlets. In other words, ZigBee is intended not to support powerline networking but to interface with it at least for smart metering and smart appliance purposes. Utilities, e.g. Penn Energy, have declared the intent to require them to interoperate again via the openHAN standards.

Trademark and Alliance

The ZigBee Alliance is an association of companies working together to enable reliable, cost-effective, and low-power wirelessly networked monitoring and control products based on an open global standard.

The ZigBee Alliance is a group of companies that maintain and publish the ZigBee standard. The term **ZigBee** is a registered trademark of this group, not a single technical standard.

As per its main role, it standardizes the body that defines ZigBee, and also publishes application profiles that allow multiple OEM vendors to create interoperable products. The current list of application profiles either published, or in the works are:

Released specifications

- ZigBee Home Automation
- ZigBee Smart Energy 1.0
- ZigBee Telecommunication Services
- ZigBee Health Care
- ZigBee Remote Control

Specifications under development

- ZigBee Smart Energy 2.0
- ZigBee Building Automation

- ZigBee Retail Services

The relationship between IEEE 802.15.4 and ZigBee is similar to that between IEEE 802.11 and the Wi-Fi Alliance. The ZigBee 1.0 specification was ratified on 14 December 2004 and is available to members of the ZigBee Alliance. Most recently, the ZigBee 2007 specification was posted on 30 October 2007. The first ZigBee Application Profile, Home Automation, was announced 2 November 2007. As amended by NIST, the Smart Energy Profile 2.0 specification will remove the dependency on IEEE 802.15.4. Device manufacturers will be able to implement any MAC/PHY, such as IEEE 802.15.4(x) and IEEE P1901, under an IP layer based on 6LoWPAN.

ZigBee operates in the industrial, scientific and medical (ISM) radio bands; 868 MHz in Europe, 915 MHz in the USA and Australia, and 2.4 GHz in most jurisdictions worldwide. The technology is intended to be simpler and less expensive than other WPANs such as Bluetooth. ZigBee chip vendors typically sell integrated radios and microcontrollers with between 60 KB and 256 KB flash memory.

Chip vendors/devices include

- Atmel ATmega128RFA1
- Digi International XBee XB24CZ7PIS-004
- Freescale MC13213
- Ember EM250
- Jennic JN5148
- Renesas uPD78F8056/57/58, M16C/6B3 and R8C/3MQ
- STMicroelectronics STM32W
- Samsung Electro-Mechanics ZBS240
- Texas Instruments CC2530 and CC2520

Radios are also available as stand-alone components to be used with any processor or microcontroller. Generally, the chip vendors also offer the ZigBee software stack, although independent ones are also available.

Because ZigBee can activate (go from sleep to active mode) in 30 msec or less, the latency can be very low and devices can be very responsive — particularly compared to Bluetooth wake-up delays, which are typically around three seconds. Because ZigBees can sleep most of the time, average power consumption can be very low, resulting in long battery life.

The first stack release is now called *ZigBee 2004*. The second stack release is called *ZigBee 2006*, and mainly replaces the MSG/KVP structure used in 2004 with a "cluster library". The 2004 stack is now more or less obsolete.

ZigBee 2007, now the current stack release, contains two stack profiles, stack profile 1 (simply called ZigBee), for home and light commercial use, and stack profile 2 (called ZigBee Pro). ZigBee Pro offers more features, such as multi-casting, many-to-one routing and high security with Symmetric-Key Key Exchange (SKKE), while ZigBee (stack profile 1) offers a smaller footprint in RAM and flash. Both offer full mesh networking and work with all ZigBee application profiles.

ZigBee 2007 is fully backward compatible with ZigBee 2006 devices: A ZigBee 2007 device may join and operate on a ZigBee 2006 network and vice versa. Due to differences in routing options, ZigBee Pro devices must become non-routing ZigBee End-Devices (ZEDs) on a ZigBee 2006 network, the same as for ZigBee 2006 devices on a ZigBee 2007 network must become ZEDs on a ZigBee Pro network. The applications running on those devices work the same, regardless of the stack profile beneath them.

Licensing

For non-commercial purposes, the ZigBee specification is available free to the general public. An entry level membership in the ZigBee Alliance, called Adopter, provides access to the as-yet unpublished specifications and permission to create products for market using the specifications.

The click through license on the ZigBee specification requires a commercial developer to join the ZigBee Alliance. "No part of this specification may be used in development of a product for sale without becoming a member of ZigBee Alliance." This causes problems for open-source developers because the annual fee conflicts with the GNU General Public License. From the GPL v2, "b) You must cause any work that you distribute or publish, that in whole or in part contains or is derived from the Program or any part thereof, to be licensed as a whole at no charge to all third parties under the terms of this License." Since the GPL makes no distinction between commercial and non-commercial use it is impossible to implement a GPL licensed ZigBee stack or combine a ZigBee implementation with GPL licensed code. The requirement for the developer to join the ZigBee Alliance similarly conflicts with most other Free software licenses.

Uses

ZigBee protocols are intended for use in embedded applications requiring low data rates and low power consumption. ZigBee's current focus is to define a general-purpose, inexpensive, self-organizing mesh network that can be used for industrial control, embedded sensing, medical data collection, smoke and intruder warning, building automation, home automation, etc. The resulting network will use very small amounts of power — individual devices must have a battery life of at least two years to pass ZigBee certification.

Typical application areas include

- **Home Entertainment and Control** — Smart lighting, advanced temperature control, safety and security, movies and music

- ***Wireless Sensor Networks'*** — Starting with individual sensors like Telosb/Tmote and Iris from Memsic.

Device types

There are three different types of ZigBee devices:

- *ZigBee coordinator (ZC)*: The most capable device, the coordinator forms the root of the network tree and might bridge to other networks. There is exactly one ZigBee coordinator in each network since it is the device that started the network originally. It is able to store information about the network, including acting as the Trust Center & repository for security keys.
- *ZigBee Router (ZR)*: As well as running an application function, a router can act as an intermediate router, passing on data from other devices.
- *ZigBee End Device (ZED)*: Contains just enough functionality to talk to the parent node (either the coordinator or a router); it cannot relay data from other devices. This relationship allows the node to be asleep a significant amount of the time thereby giving long battery life. A ZED requires the least amount of memory, and therefore can be less expensive to manufacture than a ZR or ZC.

Protocols

The protocols build on recent algorithmic research (Ad-hoc On-demand Distance Vector, neuRFon) to automatically construct a low-speed ad-hoc network of nodes. In most large network instances, the network will be a cluster of clusters. It can also form a mesh or a single cluster. The current profiles derived from the ZigBee protocols support beacon and non-beacon enabled networks.

In non-beacon-enabled networks (those whose beacon order is 15), an unslotted CSMA/CA channel access mechanism is used. In this type of network, ZigBee Routers typically have their receivers continuously active, requiring a more robust power supply. However, this allows for heterogeneous networks in which some devices receive continuously, while others only transmit when an external stimulus is detected. The typical example of a heterogeneous network is a wireless light switch: The ZigBee node at the lamp may receive constantly, since it is connected to the mains supply, while a battery-powered light switch would remain asleep until the switch is thrown. The switch then wakes up, sends a command to the lamp, receives an acknowledgment, and returns to sleep. In such a network the lamp node will be at least a ZigBee Router, if not the ZigBee Coordinator; the switch node is typically a ZigBee End Device.

In beacon-enabled networks, the special network nodes called ZigBee Routers transmit periodic beacons to confirm their presence to other network nodes. Nodes may sleep between beacons, thus lowering their duty cycle and extending their battery life. Beacon intervals may range from 15.36 milliseconds to 15.36 ms * 2^{14} = 251.65824 seconds at 250 kbit/s, from 24 milliseconds to 24 ms * 2^{14} = 393.216 seconds at 40 kbit/s and from 48 milliseconds to 48 ms * 2^{14} = 786.432 seconds at 20 kbit/s. However, low duty cycle operation with long beacon intervals requires precise timing, which can conflict with the need for low product cost.

In general, the ZigBee protocols minimize the time the radio is on so as to reduce power use. In beaconing networks, nodes only need to be active while a beacon is being transmitted. In non-beacon-enabled networks, power consumption is decidedly asymmetrical: some devices are always active, while others spend most of their time sleeping.

Except for the Smart Energy Profile 2.0, which will be MAC/PHY agnostic, ZigBee devices are required to conform to the IEEE 802.15.4-2003 Low-Rate Wireless Personal Area Network (WPAN) standard. The standard specifies the lower protocol layers—the physical layer (PHY), and the media access control (MAC) portion of the data link layer (DLL). This standard specifies operation in the unlicensed 2.4 GHz (worldwide), 915 MHz (Americas) and 868 MHz (Europe) ISM bands. In the 2.4 GHz band there are 16 ZigBee channels, with each channel requiring 5 MHz of bandwidth. The center frequency for each channel can be calculated as, $F_C = (2405 + 5 * (ch - 11))$ MHz, where ch = 11, 12, ..., 26.

The radios use direct-sequence spread spectrum coding, which is managed by the digital stream into the modulator. BPSK is used in the 868 and 915 MHz bands, and OQPSK that transmits four bits per symbol is used in the 2.4 GHz band. The raw, over-the-air data rate is 250 kbit/s per channel in the 2.4 GHz band, 40 kbit/s per channel in the 915 MHz band, and 20 kbit/s in the 868 MHz band. Transmission range is between 10 and 75 meters (33 and 246 feet) and up to 1500 meters for zigbee pro, although it is heavily dependent on the particular environment. The output power of the radios is generally 0 dBm (1 mW).

The basic channel access mode is "carrier sense, multiple access/collision avoidance" (CSMA/CA). That is, the nodes talk in the same way that people converse; they briefly check to see that no one is talking before they start. There are three notable exceptions to the use of CSMA. Beacons are sent on a fixed timing schedule, and do not use CSMA. Message acknowledgments also do not use CSMA. Finally, devices in Beacon Oriented networks that have low latency real-time requirements may also use Guaranteed Time Slots (GTS), which by definition do not use CSMA.

ZigBee RF4CE

On March 3, 2009 the RF4CE (Radio Frequency for Consumer Electronics) Consortium agreed to work with the ZigBee Alliance to jointly deliver a standardized specification for radio frequency-based remote controls. ZigBee RF4CE is designed to be deployed in a wide range of remotely-controlled audio/visual consumer electronics products, such as TVs and set-top boxes. It promises many advantages over existing remote control solutions, including richer communication and increased reliability, enhanced features and flexibility, interoperability, and no line-of-sight barrier.

Software and hardware

The software is designed to be easy to develop on small, inexpensive microprocessors. The radio design used by ZigBee has been carefully optimized for low cost in large scale production. It has few analog stages and uses digital circuits wherever possible.

Even though the radios themselves are inexpensive, the ZigBee Qualification Process involves a full validation of the requirements of the physical layer. This amount of concern about the Physical Layer has multiple benefits, since all radios derived from that semiconductor mask set would enjoy the same RF characteristics. On the other hand, an uncertified physical layer that malfunctions could cripple the battery lifespan of other devices on a ZigBee network. Where other protocols can mask poor sensitivity or other esoteric problems in a fade compensation response, ZigBee radios have very tight engineering constraints: they are both power and bandwidth constrained. Thus, radios are tested to the ISO 17025 standard with guidance given by Clause 6 of the 802.15.4-2006 Standard. Most vendors plan to integrate the radio and microcontroller onto a single chip getting smaller devices .

History

- ZigBee-style networks began to be conceived around 1998, when many installers realized that both Wi-Fi and Bluetooth were going to be unsuitable for many applications. In particular, many engineers saw a need for self-organizing ad-hoc digital radio networks.
- The IEEE 802.15.4-2003 standard was completed in May 2003 and has been superseded by the publication of IEEE 802.15.4-2006.
- In the summer of 2003, Philips Semiconductors, a major mesh network supporter, ceased the investment. Philips Lighting has, however, continued Philips' participation, and Philips remains a promoter member on the ZigBee Alliance Board of Directors.
- The ZigBee Alliance announced in October 2004 that the membership had more than doubled in the preceding year and had grown to more than 100 member companies, in 22 countries. By April 2005 membership had grown to more than 150 companies, and by December 2005 membership had passed 200 companies.
- The ZigBee specifications were ratified on 14 December 2004.
- The ZigBee Alliance announces public availability of Specification 1.0 on 13 June 2005, known as ZigBee 2004 Specification.
- The ZigBee Alliance announces the completion and immediate member availability of the enhanced version of the ZigBee Standard in September 2006, known as ZigBee 2006 Specification.
- During the last quarter of 2007, ZigBee PRO, the enhanced ZigBee specification was finalized.

Origin of the ZigBee name

The name of the brand is originated with reference to the behaviour of honey bees after their return to the beehive.

Chapter 9

Z-Wave

Z-Wave is a proprietary wireless communications protocol designed for home automation, specifically to remote control applications in residential and light commercial environments. The technology uses a low-power RF radio embedded or retrofitted into home electronics devices and systems, such as lighting, home access control, entertainment systems and household appliances.

The Z-Wave Alliance is an international consortium of manufacturers that provide interoperable Z-Wave enabled devices.

Overview

Z-Wave is a low-power wireless technology designed specifically for remote control applications. Unlike Wi-Fi and other IEEE 802.11-based wireless LAN systems that are designed primarily for high-bandwidth data flow, the Z-Wave RF system operates in the sub gigahertz frequency range and is optimized for low-overhead commands such as on-off (as in a light switch or an appliance) and raise-lower (as in a thermostat or volume control), with the ability to include device metadata in the communications.

Because Z-Wave operates apart from the crowded 2.4 GHz frequency, it is largely unaffected by interference from common household wireless electronics that operate in this range. Z-Wave does share a range (900 MHz) used by some cell-phones and would be susceptible to interference from such devices. However, this freedom from normal household interference allows for a standardized low-bandwidth control medium that can be reliable alongside common wireless devices.

As a result of its low power consumption and low cost of manufacture, Z-Wave is easily embedded in consumer electronics products, including battery operated devices such as remote controls, smoke alarms and security sensors. Z-Wave is currently supported by over 200 manufacturers worldwide and appears in a broad range of consumer products in the U.S. and Europe.

The standard itself is not open and is available only to Zensys customers under non-disclosure agreement. Some Z-Wave product vendors have embraced the open source and hobbyist communities.

Applications

Z-Wave is a mesh networking technology where each node or device on the network is capable of sending and receiving control commands through walls or floors and use intermediate nodes to route around household obstacles or radio dead spots that might occur in the home. Z-Wave devices can work individually or in groups, and can be programmed into scenes or events that trigger multiple devices, either automatically or via remote control. Some common applications for Z-Wave include:

Remote home control and management

By adding Z-Wave to home electronics such as lighting, climate and security systems, it is possible to control and monitor these household functions via remote control, based on manual or automated decisions. The control can be applied to a single device or group of devices, in a single room or zone or throughout the entire home. One of the benefits of Z-Wave over power line communication technologies is the ability to function in older houses lacking a neutral wire. Z-Wave devices can also be monitored and controlled from outside of the home by way of a gateway that combines Z-Wave with broadband Internet access.

Energy Conservation

Z-Wave is envisioned as a key enabling technology for energy management in the green home. As an example, Z-Wave-enabled thermostats are able to raise or lower automatically, based on commands from Z-Wave enabled daylight sensors. Grouped scene controls can ensure that unnecessary energy consumption is minimized by various all-off states for systems throughout the home, such as lighting, appliances and home entertainment systems.

Home safety and security systems

Because Z-Wave can transceive commands based on real time conditions, and is able to control devices in intelligent groupings, it allows novel extensions of traditional home security concepts. As an example, the opening of a Z-Wave enabled door lock can de-activate a security system and turn on lights when children arrive home from school, and send a notification to a parent's PC or cell phone via the Internet. Opening a Z-Wave enabled garage door can trigger exterior and interior home lights, while a Z-Wave motion detector can trigger an outdoor security light and a webcam, which would allow the end user to monitor the home while away.

Home entertainment

Z-Wave's ability to command multiple devices as a unified event makes it well suited for home audio and video applications. For example, a simple "Play DVD" command on the remote control could turn on the needed components, set them to the correct inputs and even lower motorized shades and dim the room lights. Z-Wave's RF technology is also well suited as an evolution of conventional infrared (IR) based remote controls for home electronics, as it is not constrained by IR's line of sight and distance limitations. In January of 2008, Zensys announced a single-chip solution that pairs Z-Wave with IR control, positioning the technology as an all encompassing solution for home remote controls.

Setting up a Z-Wave network

Z-Wave mesh networks can begin with a single controllable device and a controller. Additional devices can be added at any time, as can multiple controllers, including traditional hand-held controllers, key-fob controllers, wall-switch controllers and PC applications designed for management and control of a Z-Wave network.

A device must be "included" to the Z-Wave network before it can be controlled via Z-Wave. This process (also known as "pairing" and "adding") is usually achieved by pressing a sequence of buttons on the controller and the device being added to the network. This sequence only needs to be performed once, after which the device is always recognized by the controller. Devices can be removed from the Z-Wave network by a similar process of button strokes.

This inclusion process is repeated for each device in the system. Because the controller is learning the signal strength between the devices during the inclusion process, the devices themselves should be in their intended final location before they are added to the system.

However, once a device has been introduced into a network, it can become troublesome to remove the unit without actually having the functional unit present. A number of Z-Wave users have complained that a Z-Wave controller can be functionally destroyed by the bulb that it controls blowing and any controlling units then report errors every time a command that would affect that unit is sent, *i.e.*, group commands / scene commands / all-on / all-off, etc. The only way to restore the service to a non-error reporting state is to factory reset all controllers and then relearn all Z-Wave devices.

Z-Wave Alliance

The Z-Wave Alliance is a consortium of over 160 independent manufacturers who have agreed to build wireless home control products based on the Z-Wave standard. Principal members include Cooper Wiring Devices, Danfoss, Fakro, Ingersoll-Rand, Intermatic, Leviton, Universal Electronics, Wayne-Dalton, Z-Wave and Zensys.

Products and applications from the Z-Wave Alliance fall into all major market sectors for residential and light commercial control applications. These include lighting, HVAC and security control, as well as home theaters, automated window treatments, pool and spa controls, garage and access controls and more.

Radio specifications

Bandwidth: 9,600 bit/s or 40 kbit/s, fully interoperable

Modulation: GFSK

Range: Approximately 100 feet (or 30 meters) assuming "open air" conditions, with reduced range indoors depending on building materials, etc.

Frequency band: The Z-Wave Radio uses the 900 MHz ISM band: 908.42 MHz (United States); 868.42 MHz (Europe); 919.82 MHz (Hong Kong); 921.42 MHz (Australia/New Zealand).

Radio specifics

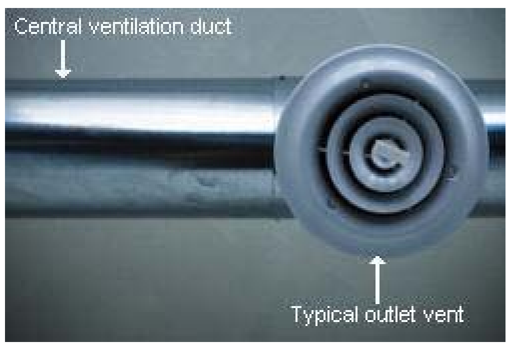
In Europe, the 868 MHz band has a 1% duty cycle limitation, meaning that a Z-Wave unit can only transmit 1% of the time. This limitation is not present in the U.S. 908 MHz band, but U.S. legislation imposes a 1 mW transmission power limit, as opposed to 25 mW in Europe. Z-Wave units can be in power-save mode and only be active 0.1% of the time, thus reducing power consumption dramatically.

Topology and routing

Z-Wave uses a source-routed mesh network topology and has one or more master controllers that control routing and security. Devices can communicate to another by using intermediate nodes to actively route around household obstacles or radio dead spots that might occur. A message from node A to node C can be successfully delivered even if the two nodes are not within range, providing that a third node B can communicate with nodes A and C. If the preferred route is unavailable, the message originator will attempt other routes until a path is found to the "C" node. Therefore a Z-Wave network can span much farther than the radio range of a single unit; however with several of these hops a delay may be introduced between the control command and the desired result. In order for Z-Wave units to be able to route unsolicited messages, they cannot be in sleep mode. Therefore, most battery-operated devices are not designed as repeater units. A Z-Wave network can consist of up to 232 devices with the option of bridging networks if more devices are required.

Chapter 10

HVAC

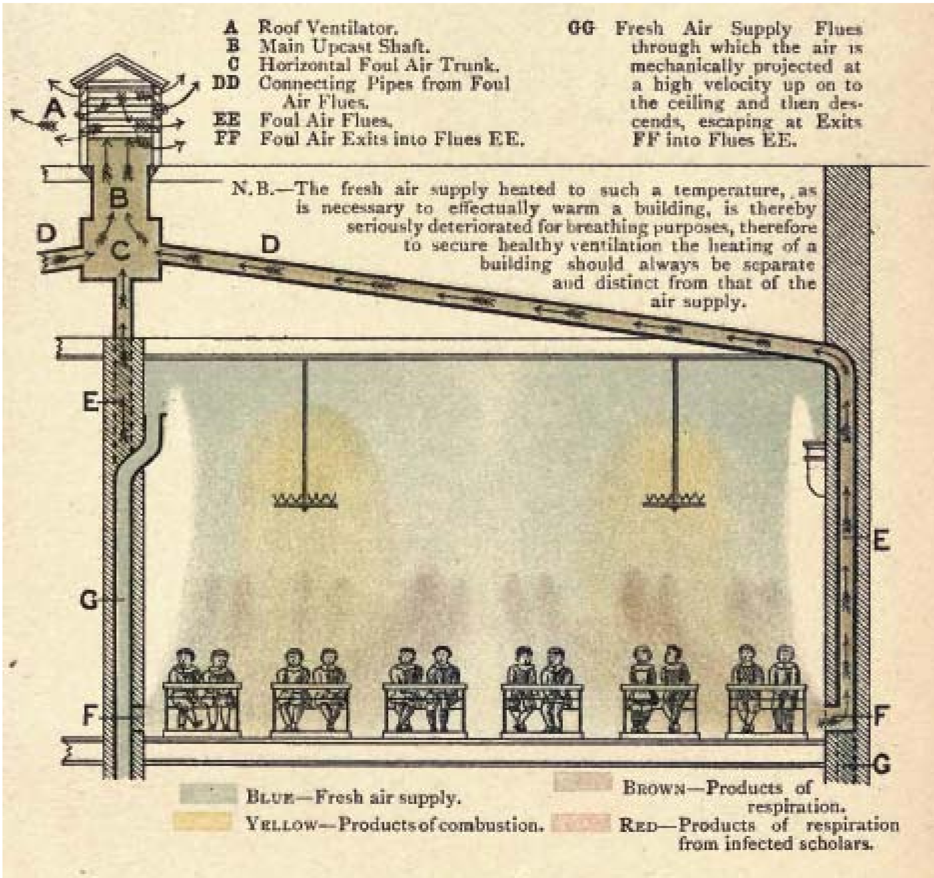


HVAC systems use ventilation air ducts installed throughout a building that supply conditioned air to a room through rectangular or round outlet vents, called diffusers; and ducts that remove air through return-air grilles

HVAC (Heating, Ventilating, and Air Conditioning) refers to technology of indoor or automotive environmental comfort. HVAC system design is a major subdiscipline of mechanical engineering, based on the principles of thermodynamics, fluid mechanics, and heat transfer. Refrigeration is sometimes added to the field's abbreviation as HVAC&R or HVACR, or ventilating is dropped as in HACR (such as the designation of HACR-rated circuit breakers).

HVAC is important in the design of medium to large industrial and office buildings such as skyscrapers and in marine environments such as aquariums, where safe and healthy building conditions are regulated with temperature and humidity, as well as "fresh air" from outdoors.

Background



Ventilation (architecture) on the downdraught system, by impulsion, or the 'plenum' principle, applied to schoolrooms (1899)

Heating, ventilating, and air conditioning is based on inventions and discoveries made by Nikolay Lvov, Michael Faraday, Willis Carrier, Reuben Trane, James Joule, William Rankine, Sadi Carnot, and many others.

The invention of the components of HVAC systems went hand-in-hand with the industrial revolution, and new methods of modernization, higher efficiency, and system control are constantly introduced by companies and inventors all over the world. The three central functions of heating, ventilating, and air-conditioning are interrelated, providing thermal comfort, acceptable indoor air quality, within reasonable installation, operation, and maintenance costs. HVAC systems can provide ventilation, reduce air infiltration, and maintain pressure relationships between spaces. How air is delivered to, and removed from spaces is known as room air distribution.

In modern buildings the design, installation, and control systems of these functions are integrated into one or more HVAC systems. For very small buildings, contractors normally "size" and select HVAC systems and equipment. For larger buildings, building services designers and engineers, such as mechanical, architectural, or building services engineers analyze, design, and specify the HVAC systems, and specialty mechanical contractors build and commission them. Building permits and code-compliance inspections of the installations are normally required for all sizes of buildings.

The HVAC industry is a worldwide enterprise, with career opportunities including operation and maintenance, system design and construction, equipment manufacturing and sales, and in education and research. The HVAC industry had been historically regulated by the manufacturers of HVAC equipment, but Regulating and Standards organizations such as HARDI, ASHRAE, SMACNA, ACCA, Uniform Mechanical Code, International Mechanical Code, and AMCA have been established to support the industry and encourage high standards and achievement.

Design of the HVAC system.

The starting point in carrying out a heat estimate both for cooling and heating will depends on the ambient and inside conditions specified. However before taking up the heat load calculation, it is necessary to work out the fresh air requirement for each area in details, as pressurization is an important requirement.

Heating

Central heating unit

There are many different types of standard heating systems. Central heating is often used in cold climates to heat private houses and public buildings. Such a system contains a boiler, furnace, or heat pump to heat water, steam, or air, all in a central location such as a furnace room in a home or a mechanical room in a large building. The use of water as the heat transfer medium is known as hydronics. The system also contains either ductwork, for forced air systems, or piping to distribute a heated fluid and radiators to transfer this heat to the air. The term *radiator* in this context is misleading since most heat transfer from the heat exchanger is by convection, not radiation. The radiators may be mounted on walls or buried in the floor to give under-floor heat.

In boiler fed or radiant heating systems, all but the simplest systems have a pump to circulate the water and ensure an equal supply of heat to all the radiators. The heated water can also be fed through another (secondary) heat exchanger inside a storage cylinder to provide hot running water.

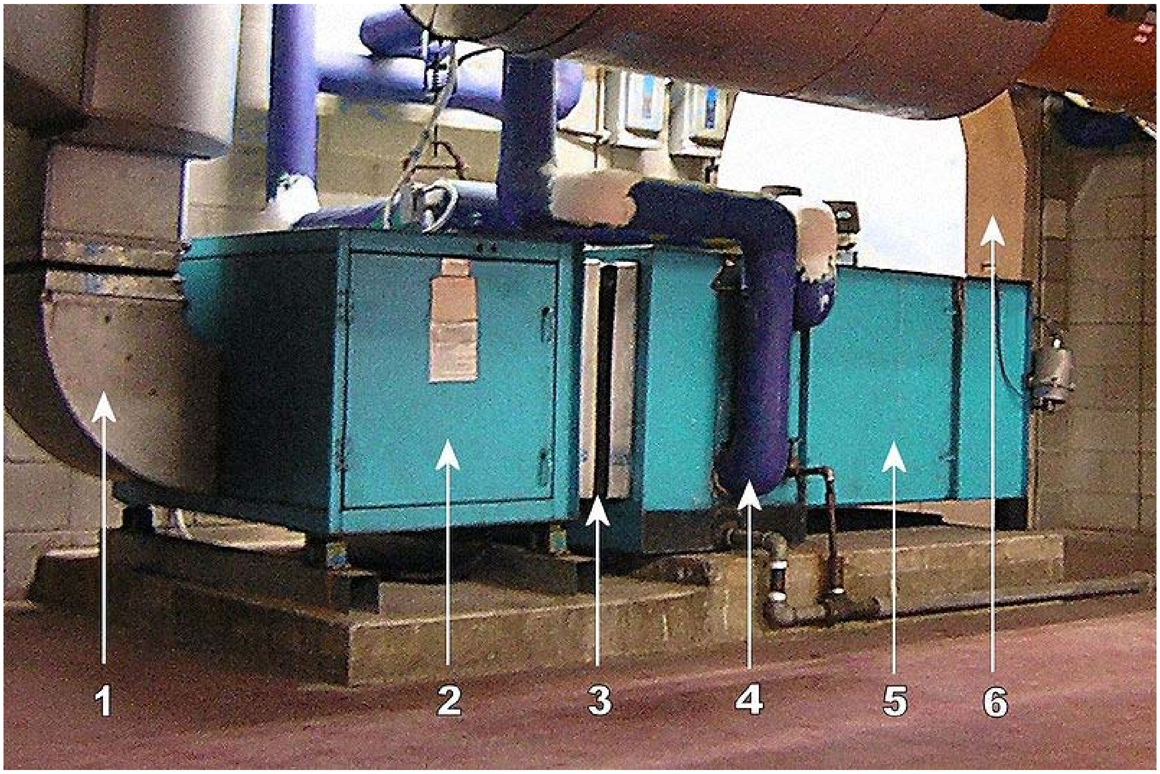
Forced air systems send heated air through ductwork. During warm weather the same ductwork can be used for air conditioning. The forced air can also be filtered or put through air cleaners.

Heating can also be provided from electric, or resistance heating using a filament that becomes hot when electric current is caused to pass through it. This type of heat can be found in electric baseboard heaters, portable electric heaters, and as backup or supplemental heating for heat pump (or reverse heating) system.

The heating elements (radiators or vents) should be located in the coldest part of the room, typically next to the windows to minimize condensation and offset the convective air current formed in the room due to the air next to the window becoming negatively buoyant due to the cold glass. Devices that direct vents away from windows to prevent "wasted" heat defeat this design intent. Cold air drafts can contribute significantly to subjectively feeling colder than the average room temperature. Therefore, it is important to control the air leaks from outside in addition to proper design of the **heating system**.

The invention of central heating is often credited to the ancient Romans, who installed a system of air ducts called a hypocaust in the walls and floors of public baths and private villas.

Ventilating



An air handling unit is used for the heating and cooling of air in a central location

Ventilating is the process of "changing" or replacing air in any space to control temperature or remove moisture, odors, smoke, heat, dust, airborne bacteria, carbon dioxide, and to replenish oxygen. Ventilation includes both the exchange of air to the outside as well as circulation of air within the building. It is one of the most important factors for maintaining acceptable indoor air quality in buildings. Methods for ventilating a building may be divided into *mechanical/forced* and *natural* types. Ventilation is used to remove unpleasant smells and excessive moisture, introduce outside air, to keep interior building air circulating, and to prevent stagnation of the interior air.

Mechanical or forced ventilation

"Mechanical" or "forced" ventilation is provided by an air handler and used to control indoor air quality. Excess humidity, odors, and contaminants can often be controlled via dilution or replacement with outside air. However, in humid climates much energy is required to remove excess moisture from ventilation air.

Kitchens and bathrooms typically have mechanical exhaust to control odors and sometimes humidity. Factors in the design of such systems include the flow rate (which is a function of the fan speed and exhaust vent size) and noise level. If ducting for the fans traverse unheated space (e.g., an attic), the ducting should be insulated as well to prevent condensation on the ducting. Direct drive fans are available for many applications, and can reduce maintenance needs.

Ceiling fans and table/floor fans circulate air within a room for the purpose of reducing the perceived temperature because of evaporation of perspiration on the skin of the occupants. Because hot air rises, ceiling fans may be used to keep a room warmer in the winter by circulating the warm stratified air from the ceiling to the floor. Ceiling fans do not provide ventilation as defined as the introduction of outside air.

Natural ventilation

Natural ventilation is the ventilation of a building with outside air without the use of a fan or other mechanical system. It can be achieved with openable windows or trickle vents when the spaces to ventilate are small and the architecture permits. In more complex systems warm air in the building can be allowed to rise and flow out upper openings to the outside (stack effect) thus forcing cool outside air to be drawn into the building naturally through openings in the lower areas. These systems use very little energy but care must be taken to ensure the occupants' comfort. In warm or humid months, in many climates, maintaining thermal comfort solely via natural ventilation may not be possible so conventional air conditioning systems are used as backups. Air-side economizers perform the same function as natural ventilation, but use mechanical systems' fans, ducts, dampers, and control systems to introduce and distribute cool outdoor air when appropriate.

Air conditioning

Air conditioning and refrigeration are provided through the removal of heat. The definition of cold is the absence of heat and all air conditioning systems work on this basic principle. Heat can be removed through the process of radiation, convection, and Heat cooling through a process called the refrigeration cycle. The conduction mediums such as water, air, ice, and chemicals are referred to as refrigerants.

An air conditioning system, or a standalone air conditioner, provides cooling, ventilation, and humidity control for all or part of a house or building.

The refrigerant cycle consists of four essential elements to create a cooling effect. The system refrigerant starts its cycle in a gaseous state. The compressor pumps the refrigerant gas up to a high pressure and temperature. From there it enters a heat exchanger (sometimes called a "condensing coil") where it loses energy (heat) to the outside. In the process the refrigerant condenses into a liquid. The liquid refrigerant is returned indoors to another heat exchanger ("evaporating coil"). A metering device allows the liquid to flow in at a low pressure at the proper rate. As the liquid refrigerant evaporates it aborbs energy (heat) from the inside air, returns to the compressor, and the cycle repeats. In the process, heat is absorbed from indoors, and transferred outdoors, resulting in cooling of the building.

Central, 'all-air' air conditioning systems are often installed in modern residences, offices, and public buildings, but are difficult to retrofit (install in a building that was not designed to receive it) because of the bulky air ducts required. A duct system must be carefully maintained to prevent the growth of pathogenic bacteria in the ducts. An alternative to large ducts to carry the needed air to heat or cool an area is the use of remote fan coils or split systems. These systems, although most often seen in residential applications, are gaining popularity in small commercial buildings. The evaporator coil is connected to a remote condenser unit using piping instead of ducts.

Dehumidification in an air conditioning system is provided by the evaporator. Since the evaporator operates at a temperature below dew point, moisture in the air condenses on the evaporator coil tubes. This moisture is collected at the bottom of the evaporator in a condensate pan and is removed by piping it to a central drain or onto the ground outside. A dehumidifier is an air-conditioner-like device that controls the humidity of a room or building. It is often employed in basements which have a higher relative humidity because of their lower temperature (and propensity for damp floors and walls). In food retailing establishments, large open chiller cabinets are highly effective at dehumidifying the internal air. Conversely, a humidifier increases the humidity of a building.

Air-conditioned buildings often have sealed windows, because open windows would disrupt the attempts of the HVAC system to maintain constant indoor air conditions.

All modern air conditioning systems, down to small "window" units, are equipped with internal air filters. These are generally of a light weight gauze-type element, and must be replaced as conditions warrant (some models may be washable). For example, a building in a high-dust environment, or a home with furry pets, will need to have the filters changed more often than buildings without these dirt loads. Failure to replace these filters as needed will contribute to a lower heat-exchange rate, resulting in wasted energy, shortened equipment life, and higher energy bills; also low air flow can result in "iced-up" or "iced-over" evaporator coils, and then there is no air flow at all. Additionally, very dirty or plugged filters can cause overheating during a heating cycle, and can possibly result in damage to the furnace unit or even fire.

It is important to keep in mind that because an air conditioner moves heat from the indoor (evaporator) coil to the outdoor (condenser) coil, the latter must be kept just as clean as the former. This means that, in addition to replacing the air filter at the evaporator coil, it is also necessary to regularly clean the condenser coil. Failure to keep the condenser clean will eventually result in harm to the compressor, because the condenser coil is responsible for discharging both the indoor heat (as picked up by the evaporator) plus the heat generated by the electric motor driving the compressor.

Outside, "fresh" air is generally drawn into the system by a vent into the evaporator section. Adjustment of the percentage of return air made up of fresh air can usually be adjusted by manipulating the opening of this vent.

Energy efficiency

For the last 20 to 30 years, manufacturers of HVAC equipment have been making an effort to make the systems they manufacture more efficient. This was originally driven by rising energy costs, and has more recently been driven by increased awareness of environmental issues. In the USA, the EPA has also imposed tighter restrictions. There are several methods for making HVAC systems more efficient.

Heating energy

Water heating is more efficient for heating buildings and was the standard many years ago. Today forced air systems can double for air conditioning and are more popular.

A couple of benefits of forced air systems, which are now widely applied in churches, schools and high-end residences,are 1) better air conditioned effect 2) up to 15-20% energy saving, and 3) evenly conditioned effect. A drawback is the installation cost, which might be slightly higher than traditional HVAC system.

Energy efficiency can be improved even more in central heating systems by introducing zoned heating. This allows a more granular application of heat, similar to non-central heating systems. Zones are controlled by multiple thermostats. In water heating systems the thermostats control zone valves, and in forced air systems they control zone dampers inside the vents which selectively block the flow of air. In this case, the control system is very critical to maintain a proper temperature.

Geothermal Heat Pump

Geothermal heat pumps are similar to ordinary heat pumps, but instead of using heat found in outside air, they rely on the stable, even heat of the earth to provide heating, air conditioning and, in most cases, hot water. From Montana's −70 °F (−57 °C) temperature, to the highest temperature ever recorded in the U.S.—134 °F (56.7 °C) in Death Valley, California, in 1913—many parts of the country experience seasonal temperature extremes. A few feet below the earth's surface, however, the ground remains at a relatively constant temperature. Although the temperatures vary according to latitude, at 6 feet (1.83 m) underground, temperatures range from 45 to 75 °F (7.2 to 23.9 °C).

While they may be more costly to install initially than regular heat pumps, they can produce markedly lower energy bills—30 percent to 40 percent lower, according to estimates from the U.S. Environmental Protection Agency.

Ventilation energy recovery

Energy recovery systems sometimes utilize heat recovery ventilation or energy recovery ventilation systems that employ heat exchangers or enthalpy wheels to recover sensible or latent heat from exhausted air. This is done by transfer of energy to the incoming outside fresh air.

Air conditioning energy

The performance of vapor compression refrigeration cycles is limited by thermodynamics. These air conditioning and heat pump devices *move* heat rather than convert it from one form to another, so *thermal efficiencies* do not appropriately describe the performance of these devices. The **Coefficient-of-Performance** (COP) measures performance, but this dimensionless measure has not been adopted, but rather the **Energy Efficiency Ratio** (*EER*). EER is the Energy Efficiency Ratio based on a 35 °C (95 °F) outdoor temperature. To more accurately describe the performance of air conditioning equipment over a typical cooling season a modified version of the EER is used, and is the **Seasonal Energy Efficiency Ratio** (*SEER*). SEER ratings are based on seasonal temperature averages instead of a constant 35 °C outdoor temperature. The current industry minimum SEER rating is 13 SEER. The SEER article describes it further, and presents some economic comparisons using this useful performance measure.

Engineers have pointed out some areas where efficiency of the existing hardware could be improved. For example, the fan blades used to move the air are usually stamped from sheet metal, an economical method of manufacture, but as a result they are not aerodynamically efficient. A well-designed blade could reduce electrical power required to move the air by a third.

- Chilled beam
- Circulator pump
- Cooling tower
- Damper (flow)
- Dedicated outdoor air system
- Diffuser
- Displacement Ventilation
- Duct
- Economizer
- Evaporative cooler
- Fan coil unit
- Fan (mechanical)
- Heater
- Heat exchanger, including 'coils'
- Heat Pump
- Heat recovery ventilator
- Humidifier / Dehumidifier
- HVAC control system
- Piping
- Valve
- Variable air volume
- Variable-frequency drive, for fine control of pumps
- Underfloor air distribution

HVAC industry and standards

North America

USA

In the United States, HVAC engineers generally are members of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). ASHRAE is an international technical society for all individuals and organizations interested in HVAC. The Society, organized into Regions, Chapters, and Student Branches, allows exchange of HVAC knowledge and experiences for the benefit of the field's practitioners and the public. ASHRAE provides many opportunities to participate in the development of new knowledge via, for example, research and its many Technical Committees. These committees meet typically twice per year at the ASHRAE Annual and Winter Meetings. A popular product show, the AHR Expo, is held in conjunction with each Winter Meeting. The Society has approximately 50,000 members and has headquarters at Atlanta, Georgia, USA.

The most recognized standards for HVAC design is based on ASHRAE data. ASHRAE is the American Society of Heating, Refrigerating and Air-Conditioning Engineers. The ASHRAE Handbook's most general volume, of four, is Fundamentals; it includes heating and cooling calculations. Each volume of the ASHRAE Handbook is updated every four years. The design professional must consult ASHRAE data for the standards of design and care as the typical building codes provides little to no information on HVAC design practices; such codes, such as the UMC and IMC, do include much details on installation requirements, however. Other useful reference materials include items from SMACNA, ACCA, and technical trade journals.

American design standards are legislated in the Uniform Mechanical Code or International Mechanical Code. In certain states, counties, or cities, either of these codes may be adopted and amended via various legislative processes. These codes are updated and published by the International Association of Plumbing and Mechanical Officials (IAPMO) or the International Code Council (ICC) respectively, on a 3-year code development cycle. Typically, local Building Permit Departments are charged with enforcement of these standards on private and certain public properties.

In the United States, as well as throughout the world, HVAC contractors and companies are members of NADCA, the National Air Duct Cleaners Association. NADCA was formed in 1989 as a non-profit association of companies engaged in the cleaning of HVAC systems. Its mission was to promote source removal as the only acceptable method of cleaning and to establish industry standards for the association. NADCA has expanded its mission to include the representation of qualified companies engaged in the assessment, cleaning, and restoration of HVAC systems, and to assist its members in providing high quality service to their customers. The goal of the association is to be the number one source for the HVAC cleaning and restoration services: first time, every time. NADCA has experienced phenomenal membership growth and has been extremely successful with the training and certification of air systems cleaning specialists, mold remediators, and HVAC inspectors. The association has also published important standards and guidelines, educational materials, and other useful information for the consumer and members of NADCA. Their headquarters are located in Washington, D.C.

Europe

United Kingdom

The Chartered Institute of Building Services Engineers is a body that covers the essential Service (systems architecture) that allow buildings to operate. It includes the electrotechnical, heating, ventilating, air conditioning, refrigeration and plumbing industries. To train as a building services engineer, the academic requirement are GCSEs (A-C) / Standard Grades (1-3) in Maths and Science, which are important in measurements, planning and theory. Employers will often want a degree in a branch of engineering, such as building environment engineering, electrical engineering or mechanical engineering. To become a full member of CIBSE, and so also to be registered by the Engineering Council UK as a chartered engineer, one must also attain an Honours Degree and a Masters Degree in a relevent engineering subject.

CIBSE publishes several guides to HVAC design relevent to the UK market, and also the Republic of Ireland, Australia, New Zealand and Hong Kong. These guides include for various recommended design criteria and standards, some of which are cited within the UK building regulations, and therefore form a legislative requirment for major building services works. The main guides are:

- Guide A: Environmental Design
- Guide B: Heating, Ventilating, Air Conditioning and Refrigeration
- Guide C: Reference Data
- Guide D: Transportation systems in Buildings
- Guide E: Fire Safety Engineering
- Guide F: Energy Efficiency in Buildings
- Guide G: Public Health Engineering
- Guide H: Building Control Systems
- Guide J: Weather, Solar and Illuminance Data
- Guide K: Electricity in Buildings
- Guide L: Sustainability
- Guide M: Maintenance ENgineering and Management

Within the construction sector, it is the job of the building services engineer to design and oversee the installation and maintenance of the essential services such as gas, electricity, water, heating and lighting, as well as many others. These all help to make buildings comfortable and healthy places to live and work in. Building Services is part of a sector that has over 51,000 businesses and employs represents 2%-3% of the GDP.

Australia

Air Conditioning and Mechanical Contractors Association of Australia (AMCA)
Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH),
CIBSE

Asia

India

The Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE) was established to promote the HVAC industry in India. ISHRAE is an associate of

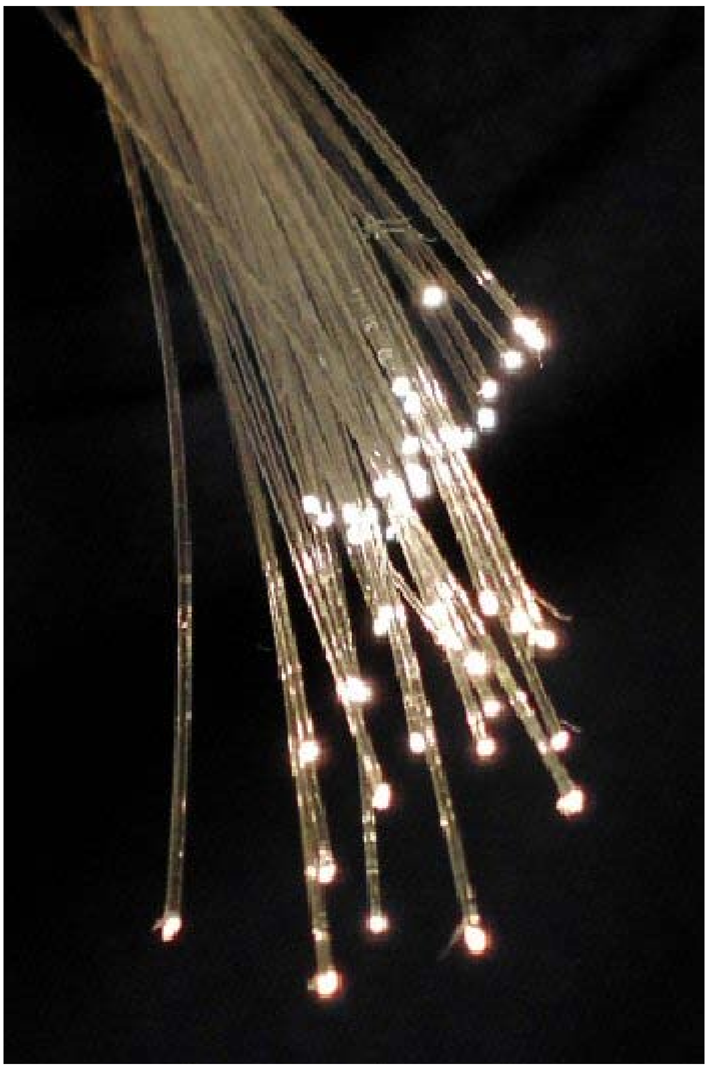
ASHRAE. ISHRAE was started at Delhi in 1981 and a chapter was started in Bangalore in 1989. Between 1989 & 1993, ISHRAE chapters were formed in all major cities in India and also in the Middle East.

Pakistan

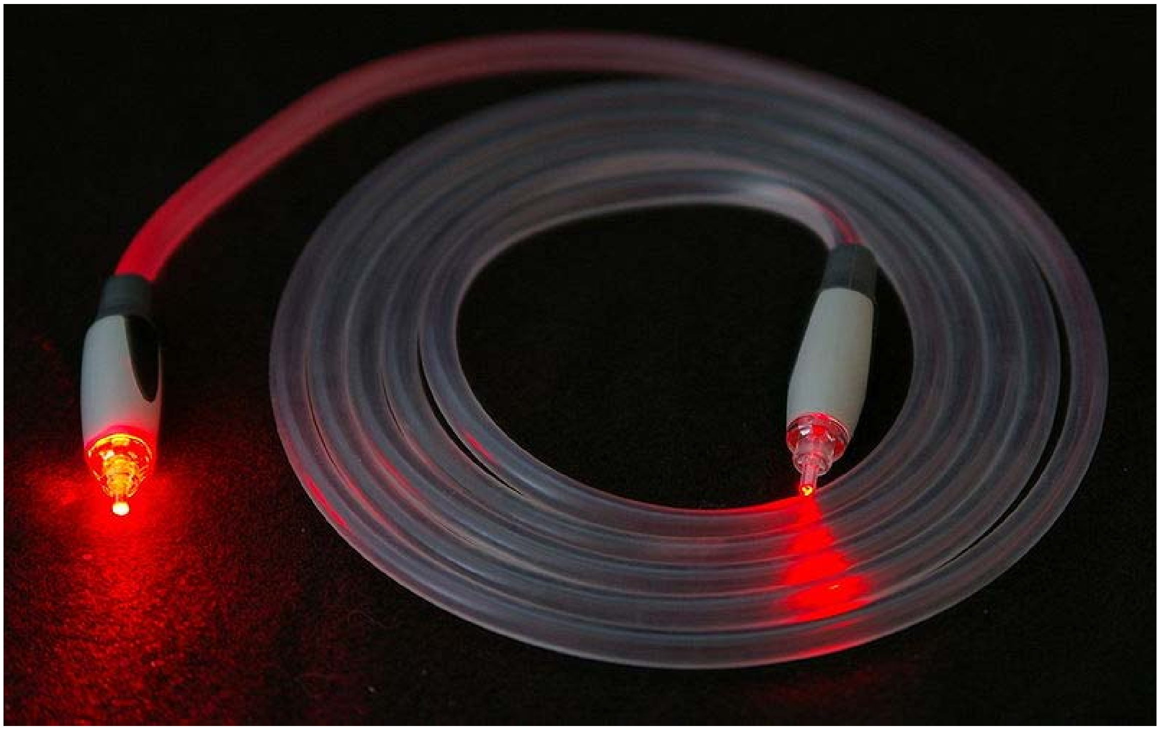
Air-conditioning technology has been in use in Pakistan since 1947, the time of its independence. At that point local expertise was dependent on the supply and installation of imported equipment in accordance with the system designs from abroad. Once Pakistani engineers recognized the importance of the field they became active in developing expertise in design, manufacture, installation, operation, and maintenance. In 1995 the Pakistan HVACR Society was formed. Since then, the Society started organizing various disciplines of the field under its umbrella.

Chapter 11

Optical Fiber



A bundle of optical fibers



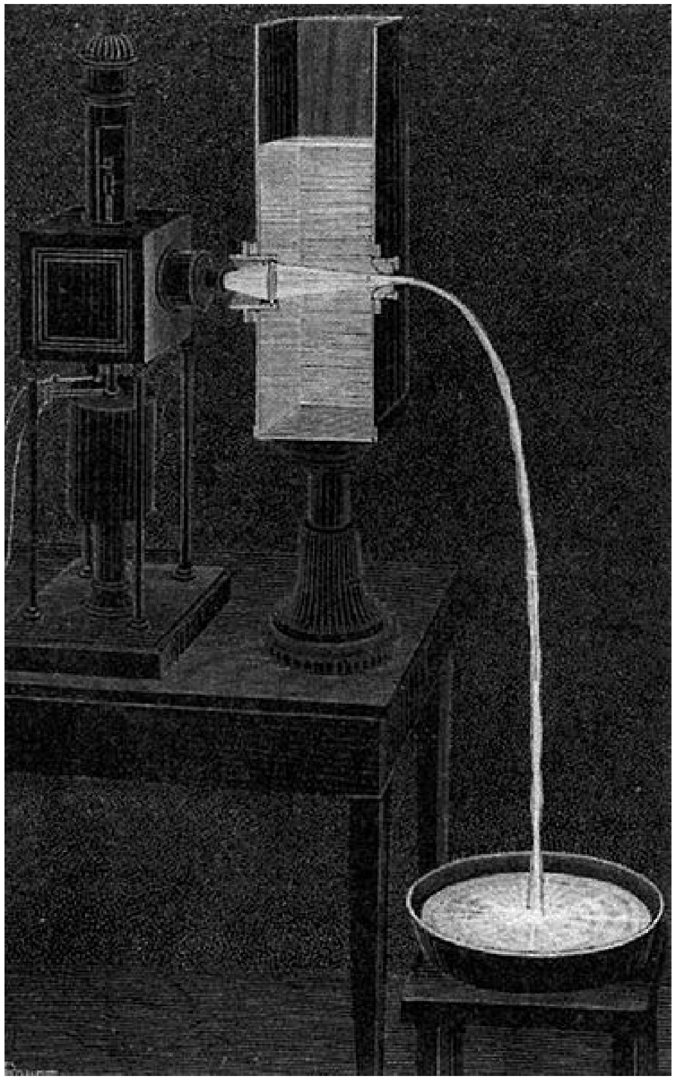
A TOSLINK fiber optic audio cable being illuminated at one end

An **optical fiber** or **optical fibre** is a thin, flexible, transparent fiber that acts as a waveguide, or "light pipe", to transmit light between the two ends of the fiber. The field of applied science and engineering concerned with the design and application of optical fibers is known as **fiber optics**. Optical fibers are widely used in fiber-optic communications, which permits transmission over longer distances and at higher bandwidths (data rates) than other forms of communication. Fibers are used instead of metal wires because signals travel along them with less loss and are also immune to electromagnetic interference. Fibers are also used for illumination, and are wrapped in bundles so they can be used to carry images, thus allowing viewing in tight spaces. Specially designed fibers are used for a variety of other applications, including sensors and fiber lasers.

Optical fiber typically consists of a transparent core surrounded by a transparent cladding material with a lower index of refraction. Light is kept in the core by total internal reflection. This causes the fiber to act as a waveguide. Fibers which support many propagation paths or transverse modes are called multi-mode fibers (MMF), while those which can only support a single mode are called single-mode fibers (SMF). Multi-mode fibers generally have a larger core diameter, and are used for short-distance communication links and for applications where high power must be transmitted. Single-mode fibers are used for most communication links longer than 1,050 meters (3,440 ft).

Joining lengths of optical fiber is more complex than joining electrical wire or cable. The ends of the fibers must be carefully cleaved, and then spliced together either mechanically or by fusing them together with heat. Special optical fiber connectors are used to make removable connections.

History



Daniel Colladon first described this "light fountain" or "light pipe" in an 1842 article titled *On the reflections of a ray of light inside a parabolic liquid stream*. This particular illustration comes from a later article by Colladon, in 1884.

Fiber optics, though used extensively in the modern world, is a fairly simple and old technology. Guiding of light by refraction, the principle that makes fiber optics possible, was first demonstrated by Daniel Colladon and Jacques Babinet in Paris in the early 1840s. John Tyndall included a demonstration of it in his public lectures in London a dozen years later. Tyndall also wrote about the property of total internal reflection in an introductory book about the nature of light in 1870: "When the light passes from air into water, the refracted ray is bent *towards* the perpendicular... When the ray passes from water to air it is bent *from* the perpendicular... If the angle which the ray in water encloses with the perpendicular to the surface be greater than 48 degrees, the ray will not quit the water at all: it will be *totally reflected* at the surface.... The angle which marks the limit where total reflection begins is called the limiting angle of the medium. For water this angle is 48°27', for flint glass it is 38°41', while for diamond it is 23°42'."

Practical applications, such as close internal illumination during dentistry, appeared early in the twentieth century. Image transmission through tubes was demonstrated independently by the radio experimenter Clarence Hansell and the television pioneer John Logie Baird in the 1920s. The principle was first used for internal medical examinations by Heinrich Lamm in the following decade. In 1952, physicist Narinder Singh Kapany conducted experiments that led to the invention of optical fiber. Modern optical fibers, where the glass fiber is coated with a transparent cladding to offer a more suitable refractive index, appeared later in the decade. Development then focused on fiber bundles for image transmission. The first fiber optic semi-flexible gastroscope was patented by Basil Hirschowitz, C. Wilbur Peters, and Lawrence E. Curtiss, researchers at the University of Michigan, in 1956. In the process of developing the gastroscope, Curtiss produced the first glass-clad fibers; previous optical fibers had relied on air or impractical oils and waxes as the low-index cladding material. A variety of other image transmission applications soon followed.

In the late 19th and early 20th centuries, light was guided through bent glass rods to illuminate body cavities. Alexander Graham Bell invented a 'Photophone' to transmit voice signals over an optical beam.

Jun-ichi Nishizawa, a Japanese scientist at Tohoku University, also proposed the use of optical fibers for communications in 1963, as stated in his book published in 2004 in India. Nishizawa invented other technologies which contributed to the development of optical fiber communications, such as the graded-index optical fiber as a channel for transmitting light from semiconductor lasers. Charles K. Kao and George A. Hockham of the British company Standard Telephones and Cables (STC) were the first to promote the idea that the attenuation in optical fibers could be reduced below 20 decibels per kilometer (dB/km), allowing fibers to be a practical medium for communication. They proposed that the attenuation in fibers available at the time was caused by impurities, which could be removed, rather than fundamental physical effects such as scattering. They correctly and systematically theorized the light-loss properties for optical fiber, and pointed out the right material to manufacture such fibers — silica glass with high purity. This discovery led to Kao being awarded the Nobel Prize in Physics in 2009.

NASA used fiber optics in the television cameras sent to the moon. At the time such use in the cameras was 'classified confidential' and only those with the right security clearance or those accompanied by someone with the right security clearance were permitted to handle the cameras.

The crucial attenuation limit of 20 dB/km was first achieved in 1970, by researchers Robert D. Maurer, Donald Keck, Peter C. Schultz, and Frank Zimar working for American glass maker Corning Glass Works, now Corning Incorporated. They demonstrated a fiber with 17 dB/km attenuation by doping silica glass with titanium. A few years later they produced a fiber with only 4 dB/km attenuation using germanium dioxide as the core dopant. Such low attenuation ushered in optical fiber telecommunication. In 1981, General Electric produced fused quartz ingots that could be drawn into fiber optic strands 25 miles (40 km) long.

Attenuation in modern optical cables is far less than in electrical copper cables, leading to long-haul fiber connections with repeater distances of 70–150 kilometers (43–93 mi). The erbium-doped fiber amplifier, which reduced the cost of long-distance fiber systems by reducing or eliminating optical-electrical-optical repeaters, was co-developed by teams led by David N. Payne of the University of Southampton and Emmanuel Desurvire at Bell Labs in 1986. Robust modern optical fiber uses glass for both core and sheath and is therefore less prone to aging processes. It was invented by Gerhard Bernsee of Schott Glass in Germany in 1973.

The emerging field of photonic crystals led to the development in 1991 of photonic-crystal fiber which guides light by diffraction from a periodic structure, rather than by total internal reflection. The first photonic crystal fibers became commercially available in 2000. Photonic crystal fibers can carry higher power than conventional fibers and their wavelength-dependent properties can be manipulated to improve performance.

Applications

Optical fiber communication

Optical fiber can be used as a medium for telecommunication and networking because it is flexible and can be bundled as cables. It is especially advantageous for long-distance communications, because light propagates through the fiber with little attenuation compared to electrical cables. This allows long distances to be spanned with few repeaters. Additionally, the per-channel light signals propagating in the fiber have been modulated at rates as high as 111 gigabits per second by NTT, although 10 or 40 Gbit/s is typical in deployed systems. Each fiber can carry many independent channels, each using a different wavelength of light (wavelength-division multiplexing (WDM)). The net data rate (data rate without overhead bytes) per fiber is the per-channel data rate reduced by the FEC overhead, multiplied by the number of channels (usually up to eighty in commercial dense WDM systems as of 2008). The current laboratory fiber optic data rate record, held by Bell Labs in Villarceaux, France, is multiplexing 155 channels, each carrying 100 Gbit/s over a 7000 km fiber. Nippon Telegraph and Telephone Corporation have also managed 69.1 Tbit/s over a single 240 km fiber (multiplexing 432 channels, equating to 171 Gbit/s per channel). Bell Labs also broke a 100 Petabit per second *kilometer* barrier (15.5 Tbit/s over a single 7000 km fiber).

For short distance applications, such as creating a network within an office building, fiber-optic cabling can be used to save space in cable ducts. This is because a single fiber can often carry much more data than many electrical cables, such as 4 pair Cat-5 Ethernet cabling. Fiber is also immune to electrical interference; there is no cross-talk between signals in different cables and no pickup of environmental noise. Non-armored fiber cables do not conduct electricity, which makes fiber a good solution for protecting communications equipment located in high voltage environments such as power generation facilities, or metal communication structures prone to lightning strikes. They can also be used in environments where explosive fumes are present, without danger of ignition. Wiretapping is more difficult compared to electrical connections, and there are concentric dual core fibers that are said to be tap-proof.

Fiber optic sensors

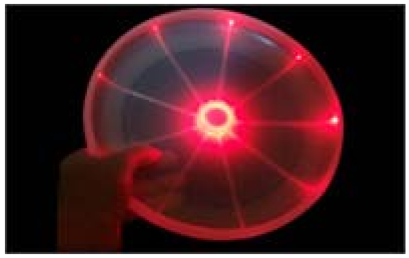
Fibers have many uses in remote sensing. In some applications, the sensor is itself an optical fiber. In other cases, fiber is used to connect a non-fiberoptic sensor to a measurement system. Depending on the application, fiber may be used because of its small size, or the fact that no electrical power is needed at the remote location, or because many sensors can be multiplexed along the length of a fiber by using different wavelengths of light for each sensor, or by sensing the time delay as light passes along the fiber through each sensor. Time delay can be determined using a device such as an optical time-domain reflectometer.

Optical fibers can be used as sensors to measure strain, temperature, pressure and other quantities by modifying a fiber so that the quantity to be measured modulates the intensity, phase, polarization, wavelength or transit time of light in the fiber. Sensors that vary the intensity of light are the simplest, since only a simple source and detector are required. A particularly useful feature of such fiber optic sensors is that they can, if required, provide distributed sensing over distances of up to one meter.

Extrinsic fiber optic sensors use an optical fiber cable, normally a multi-mode one, to transmit modulated light from either a non-fiber optical sensor, or an electronic sensor connected to an optical transmitter. A major benefit of extrinsic sensors is their ability to reach places which are otherwise inaccessible. An example is the measurement of temperature inside aircraft jet engines by using a fiber to transmit radiation into a radiation pyrometer located outside the engine. Extrinsic sensors can also be used in the same way to measure the internal temperature of electrical transformers, where the extreme electromagnetic fields present make other measurement techniques impossible. Extrinsic sensors are used to measure vibration, rotation, displacement, velocity, acceleration, torque, and twisting. A solid state version of the gyroscope using the interference of light has been developed. The fiber optic gyroscope (FOG) has no moving parts and exploits the Sagnac effect to detect mechanical rotation.

A common use for fiber optic sensors are in advanced intrusion detection security systems, where the light is transmitted along the fiber optic sensor cable, which is placed on a fence, pipeline or communication cabling, and the returned signal is monitored and analysed for disturbances. This return signal is digitally processed to identify if there is a disturbance, and if an intrusion has occurred an alarm is triggered by the fiber optic security system.

Other uses of optical fibers



A frisbee illuminated by fiber optics

Light reflected from optical fiber illuminates exhibited model

Fiber optic front sight on a hand gun

Fibers are widely used in illumination applications. They are used as light guides in medical and other applications where bright light needs to be shone on a target without a clear line-of-sight path. In some buildings, optical fibers are used to route sunlight from the roof to other parts of the building. Optical fiber illumination is also used for decorative applications, including signs, art, and artificial Christmas trees. Swarovski boutiques use optical fibers to illuminate their crystal showcases from many different angles while only employing one light source. Optical fiber is an intrinsic part of the light-transmitting concrete building product, LiTraCon.

Optical fiber is also used in imaging optics. A coherent bundle of fibers is used, sometimes along with lenses, for a long, thin imaging device called an endoscope, which is used to view objects through a small hole. Medical endoscopes are used for minimally invasive exploratory or surgical procedures (endoscopy). Industrial endoscopes are used for inspecting anything hard to reach, such as jet engine interiors.

In spectroscopy, optical fiber bundles are used to transmit light from a spectrometer to a substance which cannot be placed inside the spectrometer itself, in order to analyze its composition. A spectrometer analyzes substances by bouncing light off of and through them. By using fibers, a spectrometer can be used to study objects that are too large to fit inside, or gasses, or reactions which occur in pressure vessels.

An optical fiber doped with certain rare earth elements such as erbium can be used as the gain medium of a laser or optical amplifier. Rare-earth doped optical fibers can be used to provide signal amplification by splicing a short section of doped fiber into a regular (undoped) optical fiber line. The doped fiber is optically pumped with a second laser wavelength that is coupled into the line in addition to the signal wave. Both wavelengths of light are transmitted through the doped fiber, which transfers energy from the second pump wavelength to the signal wave. The process that causes the amplification is stimulated emission.

Optical fibers doped with a wavelength shifter are used to collect scintillation light in physics experiments.

Optical fiber can be used to supply a low level of power (around one watt) to electronics situated in a difficult electrical environment. Examples of this are electronics in high-powered antenna elements and measurement devices used in high voltage transmission equipment.

A growing trend in iron sights for arms, is the use of short pieces of optical fiber for contrast enhancement dots, made in such a way that ambient light falling on the length of the fiber is concentrated at the tip, making the dots slightly brighter than the surroundings. This method is most commonly used in front sights, but many makers offer sights that use fiber optics on front and rear sights. Fiber optic sights can now be found on handguns, rifles, and shotguns, both as aftermarket accessories and a growing number of factory guns.

Principle of operation

An optical fiber is a cylindrical dielectric waveguide (nonconducting waveguide) that transmits light along its axis, by the process of total internal reflection. The fiber consists of a *core* surrounded by a cladding layer, both of which are made of dielectric materials. To confine the optical signal in the core, the refractive index of the core must be greater than that of the cladding. The boundary between the core and cladding may either be abrupt, in *step-index fiber*, or gradual, in *graded-index fiber*.

Index of refraction

The index of refraction is a way of measuring the speed of light in a material. Light travels fastest in a vacuum, such as outer space. The speed of light in a vacuum is about 300,000 kilometres (186 thousand miles) per second. Index of refraction is calculated by dividing the speed of light in a vacuum by the speed of light in some other medium. The index of refraction of a vacuum is therefore 1, by definition. The typical value for the cladding of an optical fiber is 1.46. The core value is typically 1.48. The larger the index of refraction, the slower light travels in that medium. From this information, a good rule of thumb is that signal using optical fiber for communication will travel at around 200 million meters per second. Or to put it another way, to travel 1000 kilometers in fiber, the signal will take 5 milliseconds to propagate. Thus a phone call carried by fiber between

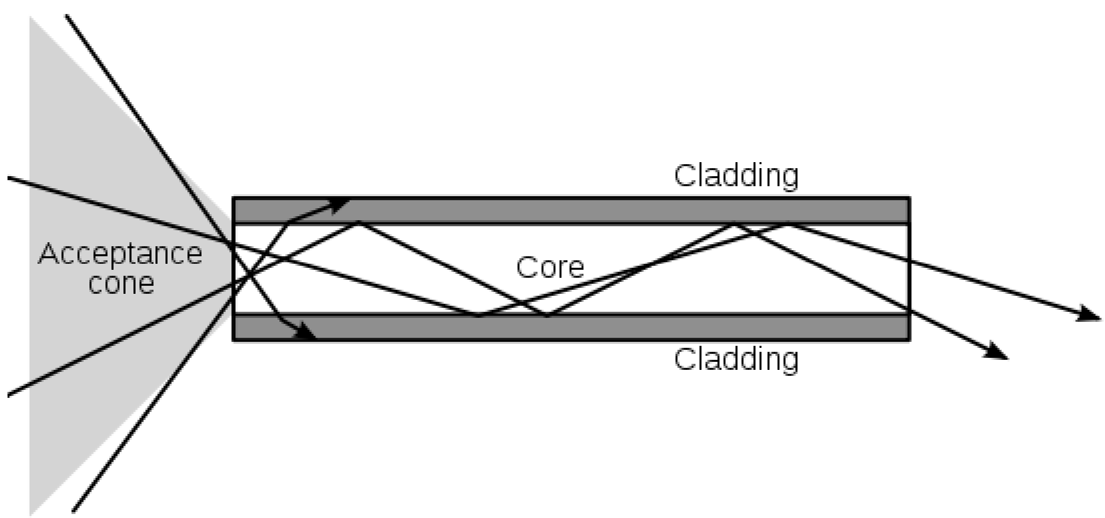
Sydney and New York, a 12000 kilometer distance, means that there is an absolute minimum delay of 60 milliseconds (or around 1/16 of a second) between when one caller speaks to when the other hears. (Of course the fiber in this case will probably travel a longer route, and there will be additional delays due to communication equipment switching and the process of encoding and decoding the voice onto the fiber).

Total internal reflection

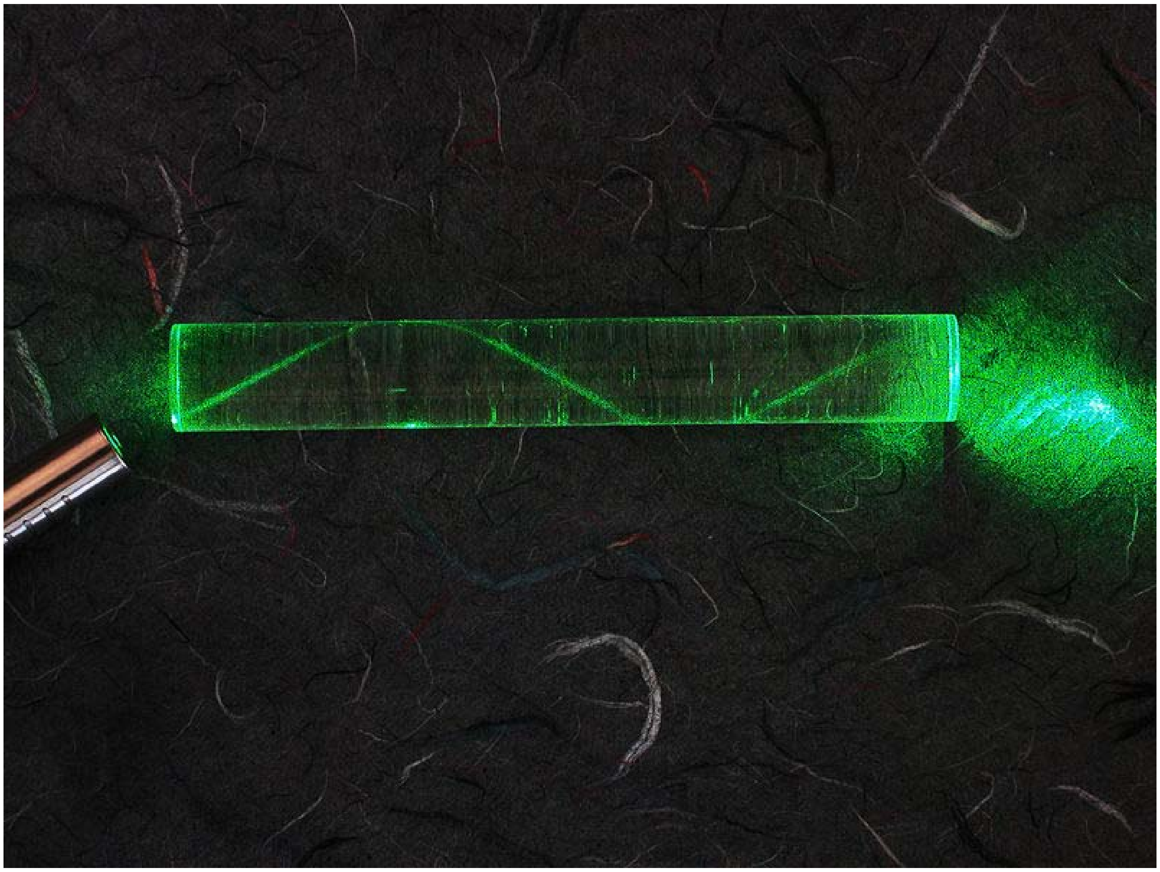
When light traveling in a dense medium hits a boundary at a steep angle (larger than the "critical angle" for the boundary), the light will be completely reflected. This effect is used in optical fibers to confine light in the core. Light travels along the fiber bouncing back and forth off of the boundary. Because the light must strike the boundary with an angle greater than the critical angle, only light that enters the fiber within a certain range of angles can travel down the fiber without leaking out. This range of angles is called the acceptance cone of the fiber. The size of this acceptance cone is a function of the refractive index difference between the fiber's core and cladding.

In simpler terms, there is a maximum angle from the fiber axis at which light may enter the fiber so that it will propagate, or travel, in the core of the fiber. The sine of this maximum angle is the numerical aperture (NA) of the fiber. Fiber with a larger NA requires less precision to splice and work with than fiber with a smaller NA. Single-mode fiber has a small NA.

Multi-mode fiber

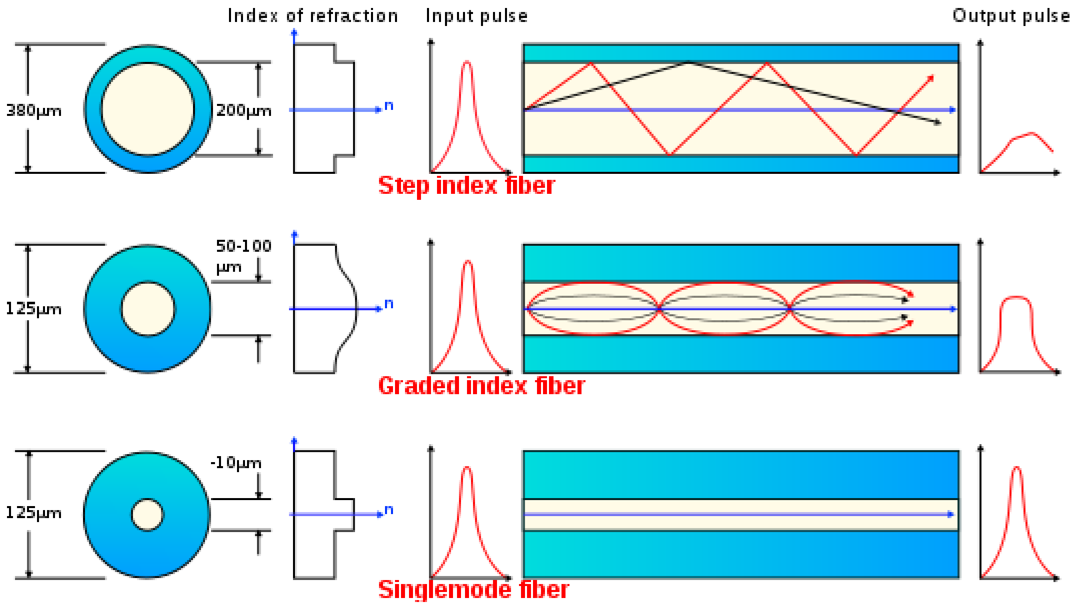


The propagation of light through a multi-mode optical fiber.



A laser bouncing down an acrylic rod, illustrating the total internal reflection of light in a multi-mode optical fiber.

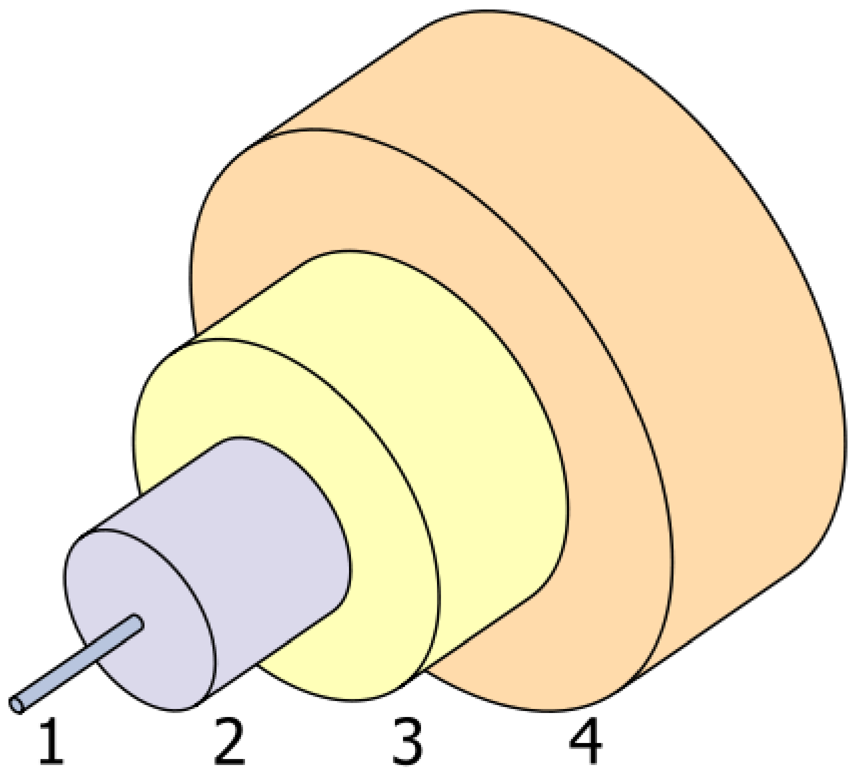
Fiber with large core diameter (greater than 10 micrometers) may be analyzed by geometrical optics. Such fiber is called *multi-mode fiber*, from the electromagnetic analysis (see below). In a step-index multi-mode fiber, rays of light are guided along the fiber core by total internal reflection. Rays that meet the core-cladding boundary at a high angle (measured relative to a line normal to the boundary), greater than the critical angle for this boundary, are completely reflected. The critical angle (minimum angle for total internal reflection) is determined by the difference in index of refraction between the core and cladding materials. Rays that meet the boundary at a low angle are refracted from the core into the cladding, and do not convey light and hence information along the fiber. The critical angle determines the acceptance angle of the fiber, often reported as a numerical aperture. A high numerical aperture allows light to propagate down the fiber in rays both close to the axis and at various angles, allowing efficient coupling of light into the fiber. However, this high numerical aperture increases the amount of dispersion as rays at different angles have different path lengths and therefore take different times to traverse the fiber.



Optical fiber types.

In graded-index fiber, the index of refraction in the core decreases continuously between the axis and the cladding. This causes light rays to bend smoothly as they approach the cladding, rather than reflecting abruptly from the core-cladding boundary. The resulting curved paths reduce multi-path dispersion because high angle rays pass more through the lower-index periphery of the core, rather than the high-index center. The index profile is chosen to minimize the difference in axial propagation speeds of the various rays in the fiber. This ideal index profile is very close to a parabolic relationship between the index and the distance from the axis.

Single-mode fiber



The structure of a typical single-mode fiber.
1. Core: 8 µm diameter
2. Cladding: 125 µm dia.
3. Buffer: 250 µm dia.
4. Jacket: 400 µm dia.

Fiber with a core diameter less than about ten times the wavelength of the propagating light cannot be modeled using geometric optics. Instead, it must be analyzed as an electromagnetic structure, by solution of Maxwell's equations as reduced to the electromagnetic wave equation. The electromagnetic analysis may also be required to understand behaviors such as speckle that occur when coherent light propagates in multi-mode fiber. As an optical waveguide, the fiber supports one or more confined transverse modes by which light can propagate along the fiber. Fiber supporting only one mode is called *single-mode* or *mono-mode fiber*. The behavior of larger-core multi-mode fiber can also be modeled using the wave equation, which shows that such fiber supports more than one mode of propagation (hence the name). The results of such modeling of multi-mode fiber approximately agree with the predictions of geometric optics, if the fiber core is large enough to support more than a few modes.

The waveguide analysis shows that the light energy in the fiber is not completely confined in the core. Instead, especially in single-mode fibers, a significant fraction of the energy in the bound mode travels in the cladding as an evanescent wave.

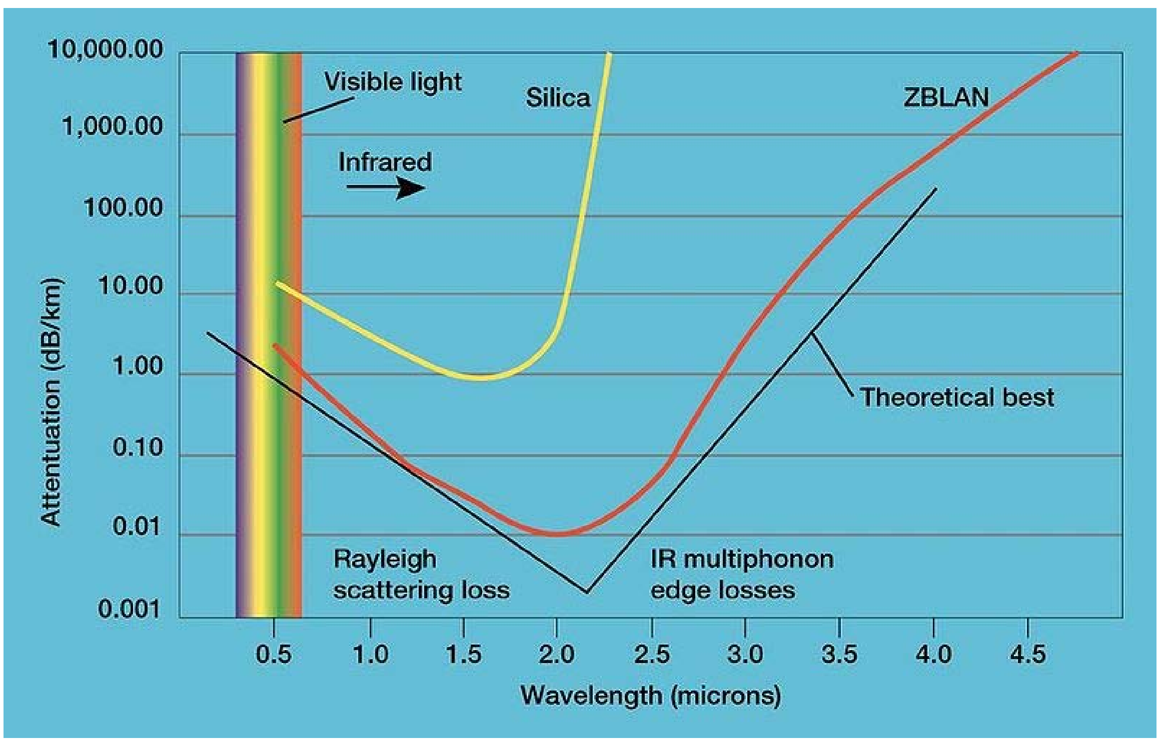
The most common type of single-mode fiber has a core diameter of 8–10 micrometers and is designed for use in the near infrared. The mode structure depends on the wavelength of the light used, so that this fiber actually supports a small number of additional modes at visible wavelengths. Multi-mode fiber, by comparison, is manufactured with core diameters as small as 50 micrometers and as large as hundreds of micrometers. The normalized frequency V for this fiber should be less than the first zero of the Bessel function J_0 (approximately 2.405).

Special-purpose fiber

Some special-purpose optical fiber is constructed with a non-cylindrical core and/or cladding layer, usually with an elliptical or rectangular cross-section. These include polarization-maintaining fiber and fiber designed to suppress whispering gallery mode propagation.

Photonic-crystal fiber is made with a regular pattern of index variation (often in the form of cylindrical holes that run along the length of the fiber). Such fiber uses diffraction effects instead of or in addition to total internal reflection, to confine light to the fiber's core. The properties of the fiber can be tailored to a wide variety of applications.

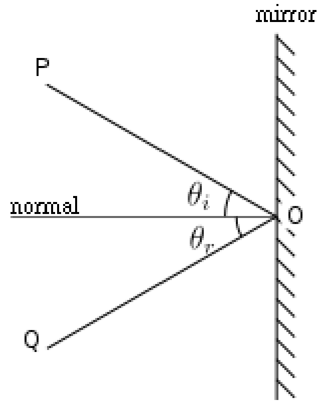
Mechanisms of attenuation



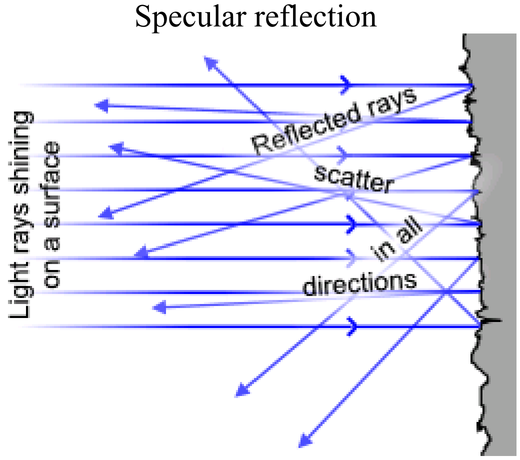
Light attenuation by ZBLAN and silica fibers

Attenuation in fiber optics, also known as transmission loss, is the reduction in intensity of the light beam (or signal) with respect to distance traveled through a transmission medium. Attenuation coefficients in fiber optics usually use units of dB/km through the medium due to the relatively high quality of transparency of modern optical transmission media. The medium is usually a fiber of silica glass that confines the incident light beam to the inside. Attenuation is an important factor limiting the transmission of a digital signal across large distances. Thus, much research has gone into both limiting the attenuation and maximizing the amplification of the optical signal. Empirical research has shown that attenuation in optical fiber is caused primarily by both scattering and absorption.

Light scattering



Specular reflection



Diffuse reflection

The propagation of light through the core of an optical fiber is based on total internal reflection of the lightwave. Rough and irregular surfaces, even at the molecular level, can cause light rays to be reflected in random directions. This is called diffuse reflection or scattering, and it is typically characterized by wide variety of reflection angles.

Light scattering depends on the wavelength of the light being scattered. Thus, limits to spatial scales of visibility arise, depending on the frequency of the incident light-wave and the physical dimension (or spatial scale) of the scattering center, which is typically in the form of some specific micro-structural feature. Since visible light has a wavelength of the order of one micrometre (one millionth of a meter) scattering centers will have dimensions on a similar spatial scale.

Thus, attenuation results from the incoherent scattering of light at internal surfaces and interfaces. In (poly)crystalline materials such as metals and ceramics, in addition to pores, most of the internal surfaces or interfaces are in the form of grain boundaries that separate tiny regions of crystalline order. It has recently been shown that when the size of the scattering center (or grain boundary) is reduced below the size of the wavelength of the light being scattered, the scattering no longer occurs to any significant extent. This phenomenon has given rise to the production of transparent ceramic materials.

Similarly, the scattering of light in optical quality glass fiber is caused by molecular level irregularities (compositional fluctuations) in the glass structure. Indeed, one emerging school of thought is that a glass is simply the limiting case of a polycrystalline solid. Within this framework, "domains" exhibiting various degrees of short-range order become the building blocks of both metals and alloys, as well as glasses and ceramics. Distributed both between and within these domains are micro-structural defects which will provide the most ideal locations for the occurrence of light scattering. This same phenomenon is seen as one of the limiting factors in the transparency of IR missile domes.

At high optical powers, scattering can also be caused by nonlinear optical processes in the fiber.

UV-Vis-IR absorption

In addition to light scattering, attenuation or signal loss can also occur due to selective absorption of specific wavelengths, in a manner similar to that responsible for the appearance of color. Primary material considerations include both electrons and molecules as follows:

1) At the electronic level, it depends on whether the electron orbitals are spaced (or "quantized") such that they can absorb a quantum of light (or photon) of a specific wavelength or frequency in the ultraviolet (UV) or visible ranges. This is what gives rise to color.

2) At the atomic or molecular level, it depends on the frequencies of atomic or molecular vibrations or chemical bonds, how close-packed its atoms or molecules are, and whether or not the atoms or molecules exhibit long-range order. These factors will determine the capacity of the material transmitting longer wavelengths in the infrared (IR), far IR, radio and microwave ranges.

The design of any optically transparent device requires the selection of materials based upon knowledge of its properties and limitations. The lattice absorption characteristics observed at the lower frequency regions (mid IR to far-infrared wavelength range) define the long-wavelength transparency limit of the material. They are the result of the interactive coupling between the motions of thermally induced vibrations of the constituent atoms and molecules of the solid lattice and the incident light wave radiation. Hence, all materials are bounded by limiting regions of absorption caused by atomic and molecular vibrations (bond-stretching)in the far-infrared (>10 μm).

Thus, multi-phonon absorption occurs when two or more phonons simultaneously interact to produce electric dipole moments with which the incident radiation may couple. These dipoles can absorb energy from the incident radiation, reaching a maximum coupling with the radiation when the frequency is equal to the fundamental vibrational mode of the molecular dipole (e.g. Si-O bond) in the far-infrared, or one of its harmonics.

The selective absorption of infrared (IR) light by a particular material occurs because the selected frequency of the light wave matches the frequency (or an integer multiple of the frequency) at which the particles of that material vibrate. Since different atoms and molecules have different natural frequencies of vibration, they will selectively absorb different frequencies (or portions of the spectrum) of infrared (IR) light.

Reflection and transmission of light waves occur because the frequencies of the light waves do not match the natural resonant frequencies of vibration of the objects. When IR light of these frequencies strikes an object, the energy is either reflected or transmitted.

Manufacturing

Materials

Glass optical fibers are almost always made from silica, but some other materials, such as fluorozirconate, fluoroaluminate, and chalcogenide glasses as well as crystalline materials like sapphire, are used for longer-wavelength infrared or other specialized applications. Silica and fluoride glasses usually have refractive indices of about 1.5, but some materials such as the chalcogenides can have indices as high as 3. Typically the index difference between core and cladding is less than one percent.

Plastic optical fibers (POF) are commonly step-index multi-mode fibers with a core diameter of 0.5 millimeters or larger. POF typically have higher attenuation coefficients than glass fibers, 1 dB/m or higher, and this high attenuation limits the range of POF-based systems.

Silica

Silica exhibits fairly good optical transmission over a wide range of wavelengths. In the near-infrared (near IR) portion of the spectrum, particularly around 1.5 μm, silica can have extremely low absorption and scattering losses of the order of 0.2 dB/km. A high transparency in the 1.4-μm region is achieved by maintaining a low concentration of hydroxyl groups (OH). Alternatively, a high OH concentration is better for transmission in the ultraviolet (UV) region.

Silica can be drawn into fibers at reasonably high temperatures, and has a fairly broad glass transformation range. One other advantage is that fusion splicing and cleaving of silica fibers is relatively effective. Silica fiber also has high mechanical strength against both pulling and even bending, provided that the fiber is not too thick and that the surfaces have been well prepared during processing. Even simple cleaving (breaking) of the ends of the fiber can provide nicely flat surfaces with acceptable optical quality. Silica is also relatively chemically inert. In particular, it is not hygroscopic (does not absorb water).

Silica glass can be doped with various materials. One purpose of doping is to raise the refractive index (e.g. with Germanium dioxide (GeO_2) or Aluminium oxide (Al_2O_3)) or to lower it (e.g. with fluorine or Boron trioxide (B_2O_3)). Doping is also possible with laser-active ions (for example, rare earth-doped fibers) in order to obtain active fibers to be used, for example, in fiber amplifiers or laser applications. Both the fiber core and cladding are typically doped, so that the entire assembly (core and cladding) is effectively the same compound (e.g. an aluminosilicate, germanosilicate, phosphosilicate or borosilicate glass).

Particularly for active fibers, pure silica is usually not a very suitable host glass, because it exhibits a low solubility for rare earth ions. This can lead to quenching effects due to clustering of dopant ions. Aluminosilicates are much more effective in this respect.

Silica fiber also exhibits a high threshold for optical damage. This property ensures a low tendency for laser-induced breakdown. This is important for fiber amplifiers when utilized for the amplification of short pulses.

Because of these properties silica fibers are the material of choice in many optical applications, such as communications (except for very short distances with plastic optical fiber), fiber lasers, fiber amplifiers, and fiber-optic sensors. The large efforts which have been put forth in the development of various types of silica fibers have further increased the performance of such fibers over other materials.

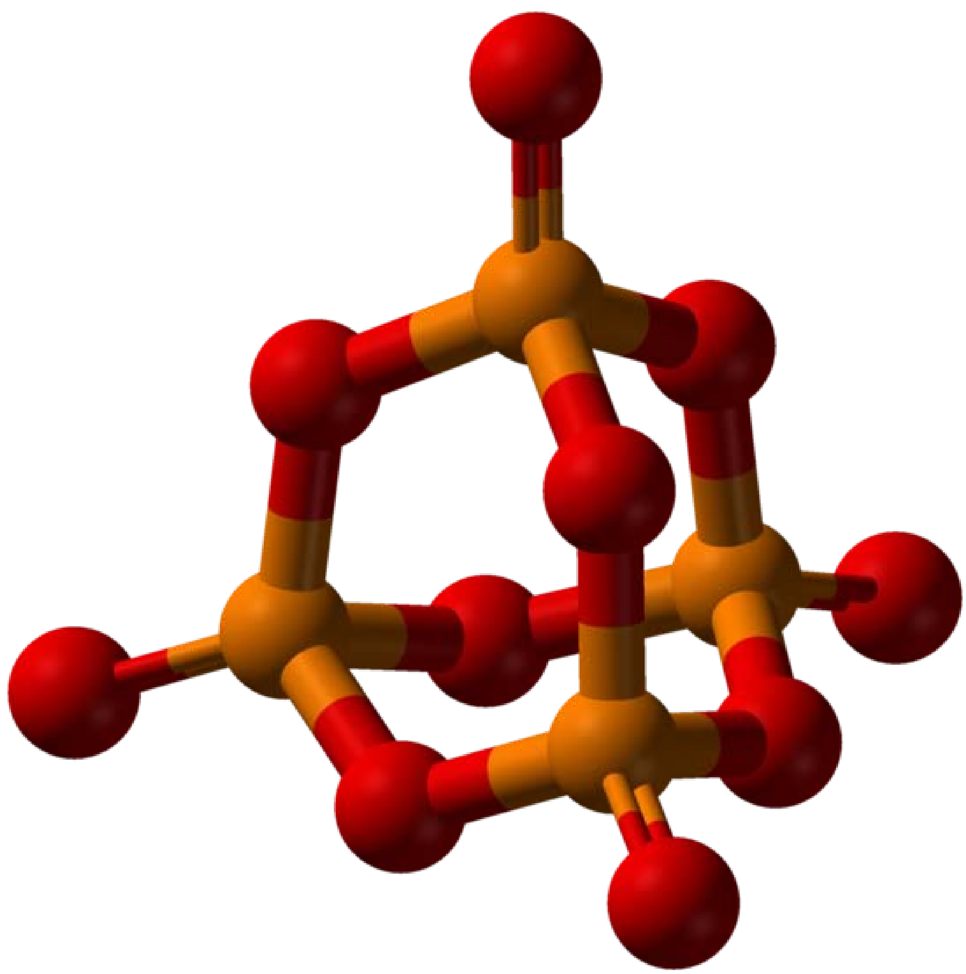
Fluorides

Fluoride glass is a class of non-oxide optical quality glasses composed of fluorides of various metals. Because of their low viscosity, it is very difficult to completely avoid crystallization while processing it through the glass transition (or drawing the fiber from the melt). Thus, although heavy metal fluoride glasses (HMFG) exhibit very low optical attenuation, they are not only difficult to manufacture, but are quite fragile, and have poor resistance to moisture and other environmental attacks. Their best attribute is that they lack the absorption band associated with the hydroxyl (OH) group (3200–3600 cm^{-1}), which is present in nearly all oxide-based glasses.

An example of a heavy metal fluoride glass is the ZBLAN glass group, composed of zirconium, barium, lanthanum, aluminium, and sodium fluorides. Their main technological application is as optical waveguides in both planar and fiber form. They are advantageous especially in the mid-infrared (2000–5000 nm) range.

HMFGs were initially slated for optical fiber applications, because the intrinsic losses of a mid-IR fiber could in principle be lower than those of silica fibers, which are transparent only up to about 2 µm. However, such low losses were never realized in practice, and the fragility and high cost of fluoride fibers made them less than ideal as primary candidates. Later, the utility of fluoride fibers for various other applications was discovered. These include mid-IR spectroscopy, fiber optic sensors, thermometry, and imaging. Also, fluoride fibers can be used for guided lightwave transmission in media such as YAG (yttria-alumina garnet) lasers at 2.9 µm, as required for medical applications (e.g. ophthalmology and dentistry).

Phosphates



The P_4O_{10} cagelike structure—the basic building block for phosphate glass.

Phosphate glass constitutes a class of optical glasses composed of metaphosphates of various metals. Instead of the SiO_4 tetrahedra observed in silicate glasses, the building block for this glass former is Phosphorus pentoxide (P_2O_5), which crystallizes in at least four different forms. The most familiar polymorph (see figure) comprises molecules of P_4O_{10}.

Phosphate glasses can be advantageous over silica glasses for optical fibers with a high concentration of doping rare earth ions. A mix of fluoride glass and phosphate glass is fluorophosphate glass.

Chalcogenides

The chalcogens—the elements in group 16 of the periodic table—particularly sulfur (S), selenium (Se) and tellurium (Te)—react with more electropositive elements, such as silver, to form chalcogenides. These are extremely versatile compounds, in that they can be crystalline or amorphous, metallic or semiconducting, and conductors of ions or electrons.

Process

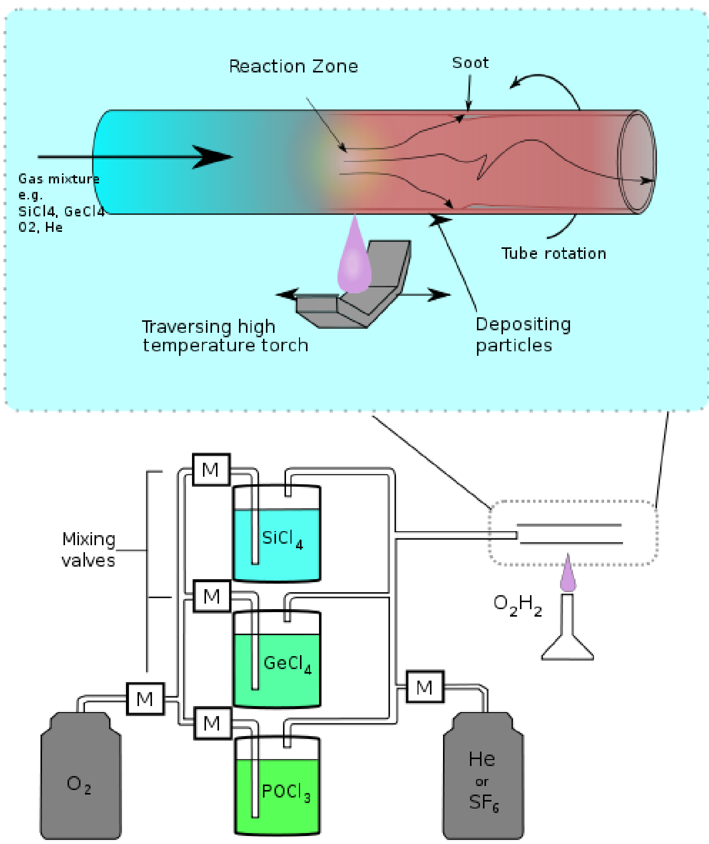


Illustration of the modified chemical vapor deposition (inside) process

Standard optical fibers are made by first constructing a large-diameter *preform*, with a carefully controlled refractive index profile, and then *pulling* the preform to form the long, thin optical fiber. The preform is commonly made by three chemical vapor deposition methods: *inside vapor deposition*, *outside vapor deposition*, and *vapor axial deposition*.

With *inside vapor deposition*, the preform starts as a hollow glass tube approximately 40 centimeters (16 in) long, which is placed horizontally and rotated slowly on a lathe. Gases such as silicon tetrachloride ($SiCl_4$) or germanium tetrachloride ($GeCl_4$) are injected with oxygen in the end of the tube. The gases are then heated by means of an external hydrogen burner, bringing the temperature of the gas up to 1900 K (1600 °C, 3000 °F), where the tetrachlorides react with oxygen to produce silica or germania (germanium dioxide) particles. When the reaction conditions are chosen to allow this reaction to occur in the gas phase throughout the tube volume, in contrast to earlier techniques where the reaction occurred only on the glass surface, this technique is called *modified chemical vapor deposition (MCVD)*.

The oxide particles then agglomerate to form large particle chains, which subsequently deposit on the walls of the tube as soot. The deposition is due to the large difference in temperature between the gas core and the wall causing the gas to push the particles outwards (this is known as thermophoresis). The torch is then traversed up and down the length of the tube to deposit the material evenly. After the torch has reached the end of the tube, it is then brought back to the beginning of the tube and the deposited particles are then melted to form a solid layer. This process is repeated until a sufficient amount of material has been deposited. For each layer the composition can be modified by varying the gas composition, resulting in precise control of the finished fiber's optical properties.

In outside vapor deposition or vapor axial deposition, the glass is formed by *flame hydrolysis*, a reaction in which silicon tetrachloride and germanium tetrachloride are oxidized by reaction with water (H_2O) in an oxyhydrogen flame. In outside vapor deposition the glass is deposited onto a solid rod, which is removed before further processing. In vapor axial deposition, a short *seed rod* is used, and a porous preform, whose length is not limited by the size of the source rod, is built up on its end. The porous preform is consolidated into a transparent, solid preform by heating to about 1800 K (1500 °C, 2800 °F).

The preform, however constructed, is then placed in a device known as a drawing tower, where the preform tip is heated and the optic fiber is pulled out as a string. By measuring the resultant fiber width, the tension on the fiber can be controlled to maintain the fiber thickness.

Coatings

The light is "guided" down the core of the fiber by an optical "cladding" with a lower refractive index that traps light in the core through "total internal reflection."

The cladding is coated by a "buffer" that protects it from moisture and physical damage. The buffer is what gets stripped off the fiber for termination or splicing. These coatings are UV-cured urethane acrylate composite materials applied to the outside of the fiber during the drawing process. The coatings protect the very delicate strands of glass fiber—about the size of a human hair—and allow it to survive the rigors of manufacturing, proof testing, cabling and installation.

Today's glass optical fiber draw processes employ a dual-layer coating approach. An inner primary coating is designed to act as a shock absorber to minimize attenuation caused by microbending. An outer secondary coating protects the primary coating against mechanical damage and acts as a barrier to lateral forces. Sometimes a metallic armour layer is added to provide extra protection.

These fiber optic coating layers are applied during the fiber draw, at speeds approaching 100 kilometers per hour (60 mph). Fiber optic coatings are applied using one of two methods: wet-on-dry, in which the fiber passes through a primary coating application, which is then UV cured, then through the secondary coating application which is subsequently cured; and wet-on-wet, in which the fiber passes through both the primary and secondary coating applications and then goes to UV curing.

Fiber optic coatings are applied in concentric layers to prevent damage to the fiber during the drawing application and to maximize fiber strength and microbend resistance. Unevenly coated fiber will experience non-uniform forces when the coating expands or contracts, and is susceptible to greater signal attenuation. Under proper drawing and coating processes, the coatings are concentric around the fiber, continuous over the length of the application and have constant thickness.

Fiber optic coatings protect the glass fibers from scratches that could lead to strength degradation. The combination of moisture and scratches accelerates the aging and deterioration of fiber strength. When fiber is subjected to low stresses over a long period, fiber fatigue can occur. Over time or in extreme conditions, these factors combine to cause microscopic flaws in the glass fiber to propagate, which can ultimately result in fiber failure.

Three key characteristics of fiber optic waveguides can be affected by environmental conditions: strength, attenuation and resistance to losses caused by microbending. External fiber optic coatings protect glass optical fiber from environmental conditions that can affect the fiber's performance and long-term durability. On the inside, coatings ensure the reliability of the signal being carried and help minimize attenuation due to microbending.

Practical issues

Optical fiber cables

An optical fiber cable

In practical fibers, the cladding is usually coated with a tough resin *buffer* layer, which may be further surrounded by a *jacket* layer, usually glass. These layers add strength to the fiber but do not contribute to its optical wave guide properties. Rigid fiber assemblies sometimes put light-absorbing ("dark") glass between the fibers, to prevent light that leaks out of one fiber from entering another. This reduces cross-talk between the fibers, or reduces flare in fiber bundle imaging applications.

Modern cables come in a wide variety of sheathings and armor, designed for applications such as direct burial in trenches, high voltage isolation, dual use as power lines, installation in conduit, lashing to aerial telephone poles, submarine installation, and insertion in paved streets. The cost of small fiber-count pole-mounted cables has greatly decreased due to the high demand for fiber to the home (FTTH) installations in Japan and South Korea.

Fiber cable can be very flexible, but traditional fiber's loss increases greatly if the fiber is bent with a radius smaller than around 30 mm. This creates a problem when the cable is bent around corners or wound around a spool, making FTTX installations more complicated. "Bendable fibers", targeted towards easier installation in home environments, have been standardized as ITU-T G.657. This type of fiber can be bent with a radius as low as 7.5 mm without adverse impact. Even more bendable fibers have been developed. Bendable fiber may also be resistant to fiber hacking, in which the signal in a fiber is surreptitiously monitored by bending the fiber and detecting the leakage.

Another important feature of cable is cable withstanding against the horizontally applied force. It is technically called max tensile strength defining how much force can applied to the cable during the installation period.

Telecom Anatolia fiber optic cable versions are reinforced with aramid yarns or glass yarns as intermediary strength member. In commercial terms, usage of the glass yarns are more cost effective while no loss in mechanical durability of the cable. Glass yarns also protect the cable core against rodents and termites.

Termination and splicing

ST connectors on multi-mode fiber.

Optical fibers are connected to terminal equipment by optical fiber connectors. These connectors are usually of a standard type such as *FC*, *SC*, *ST*, *LC*, or *MTRJ*.

Optical fibers may be connected to each other by connectors or by *splicing*, that is, joining two fibers together to form a continuous optical waveguide. The generally accepted splicing method is arc fusion splicing, which melts the fiber ends together with an electric arc. For quicker fastening jobs, a "mechanical splice" is used.

Fusion splicing is done with a specialized instrument that typically operates as follows: The two cable ends are fastened inside a splice enclosure that will protect the splices, and the fiber ends are stripped of their protective polymer coating (as well as the more sturdy outer jacket, if present). The ends are *cleaved* (cut) with a precision cleaver to make them perpendicular, and are placed into special holders in the splicer. The splice is usually inspected via a magnified viewing screen to check the cleaves before and after the splice. The splicer uses small motors to align the end faces together, and emits a small spark between electrodes at the gap to burn off dust and moisture. Then the splicer generates a larger spark that raises the temperature above the melting point of the glass, fusing the ends together permanently. The location and energy of the spark is carefully controlled so that the molten core and cladding do not mix, and this minimizes optical loss. A splice loss estimate is measured by the splicer, by directing light through the cladding on one side and measuring the light leaking from the cladding on the other side. A splice loss under 0.1 dB is typical. The complexity of this process makes fiber splicing much more difficult than splicing copper wire.

Mechanical fiber splices are designed to be quicker and easier to install, but there is still the need for stripping, careful cleaning and precision cleaving. The fiber ends are aligned and held together by a precision-made sleeve, often using a clear index-matching gel that enhances the transmission of light across the joint. Such joints typically have higher optical loss and are less robust than fusion splices, especially if the gel is used. All splicing techniques involve the use of an enclosure into which the splice is placed for protection afterward.

Fibers are terminated in connectors so that the fiber end is held at the end face precisely and securely. A fiber-optic connector is basically a rigid cylindrical barrel surrounded by a sleeve that holds the barrel in its mating socket. The mating mechanism can be "push and click", "turn and latch" ("bayonet"), or screw-in (threaded). A typical connector is installed by preparing the fiber end and inserting it into the rear of the connector body. Quick-set adhesive is usually used so the fiber is held securely, and a strain relief is secured to the rear. Once the adhesive has set, the fiber's end is polished to a mirror finish. Various polish profiles are used, depending on the type of fiber and the application. For single-mode fiber, the fiber ends are typically polished with a slight curvature, such that when the connectors are mated the fibers touch only at their cores. This is known as a "physical contact" (PC) polish. The curved surface may be polished at an angle, to make an "angled physical contact" (APC) connection. Such connections have higher loss than PC connections, but greatly reduced back reflection, because light that reflects from the angled surface leaks out of the fiber core; the resulting loss in signal strength is known as gap loss. APC fiber ends have low back reflection even when disconnected.

In the 1990s, terminating fiber optic cables was very labor intensive. The number of parts per connector, polishing of the fibers, and the need to oven-bake the epoxy in each connector made terminating fiber optic cables very difficult. Today, many different connectors are on the market and offer an easier, less labor intensive way of terminating the cables. Some of the most popular connectors have already been polished from the factory and include a gel inside the connector and those two steps help save money on labor especially on large projects. A cleave is made at a required length in order to get as close to the polished piece already inside the connector, with the gel surrounding the point where the two piece meet inside the connector very little light loss is exposed.

Free-space coupling

It is often necessary to align an optical fiber with another optical fiber, or with an optoelectronic device such as a light-emitting diode, a laser diode, or a modulator. This can involve either carefully aligning the fiber and placing it in contact with the device, or can use a lens to allow coupling over an air gap. In some cases the end of the fiber is polished into a curved form that is designed to allow it to act as a lens.

In a laboratory environment, a bare fiber end is coupled using a fiber launch system, which uses a microscope objective lens to focus the light down to a fine point. A precision translation stage (micro-positioning table) is used to move the lens, fiber, or device to allow the coupling efficiency to be optimized. Fibers with a connector on the end make this process much simpler: the connector is simply plugged into a pre-aligned fiberoptic collimator, which contains a lens that is either accurately positioned with respect to the fiber, or is adjustable. To achieve the best injection efficiency into single-mode fiber, the direction, position, size and divergence of the beam must all be optimized. With good beams, 70 to 90% coupling efficiency can be achieved.

With properly polished single-mode fibers, the emitted beam has an almost perfect Gaussian shape—even in the far field—if a good lens is used. The lens needs to be large enough to support the full numerical aperture of the fiber, and must not introduce aberrations in the beam. Aspheric lenses are typically used.

Fiber fuse

At high optical intensities, above 2 megawatts per square centimeter, when a fiber is subjected to a shock or is otherwise suddenly damaged, a *fiber fuse* can occur. The reflection from the damage vaporizes the fiber immediately before the break, and this new defect remains reflective so that the damage propagates back toward the transmitter at 1–3 meters per second (4−11 km/h, 2–8 mph). The open fiber control system, which ensures laser eye safety in the event of a broken fiber, can also effectively halt propagation of the fiber fuse. In situations, such as undersea cables, where high power levels might be used without the need for open fiber control, a "fiber fuse" protection device at the transmitter can break the circuit to prevent any damage.

Example

Fiber connections can be used for various types of connections. For example, most high definition televisions offer a digital audio optical connection. This allows the streaming of audio over light, using the TOSLink protocol.

Electric power transmission

Optical fiber can be used to transmit electricity. While the efficiency is not nearly that of traditional copper wire, it is especially useful in situations where it is desirable to not have a metallic conductor as in the case of use near MRI machines which produce strong magnetic currents.