

Must Science and Religion Be Enemies? (see page 88)

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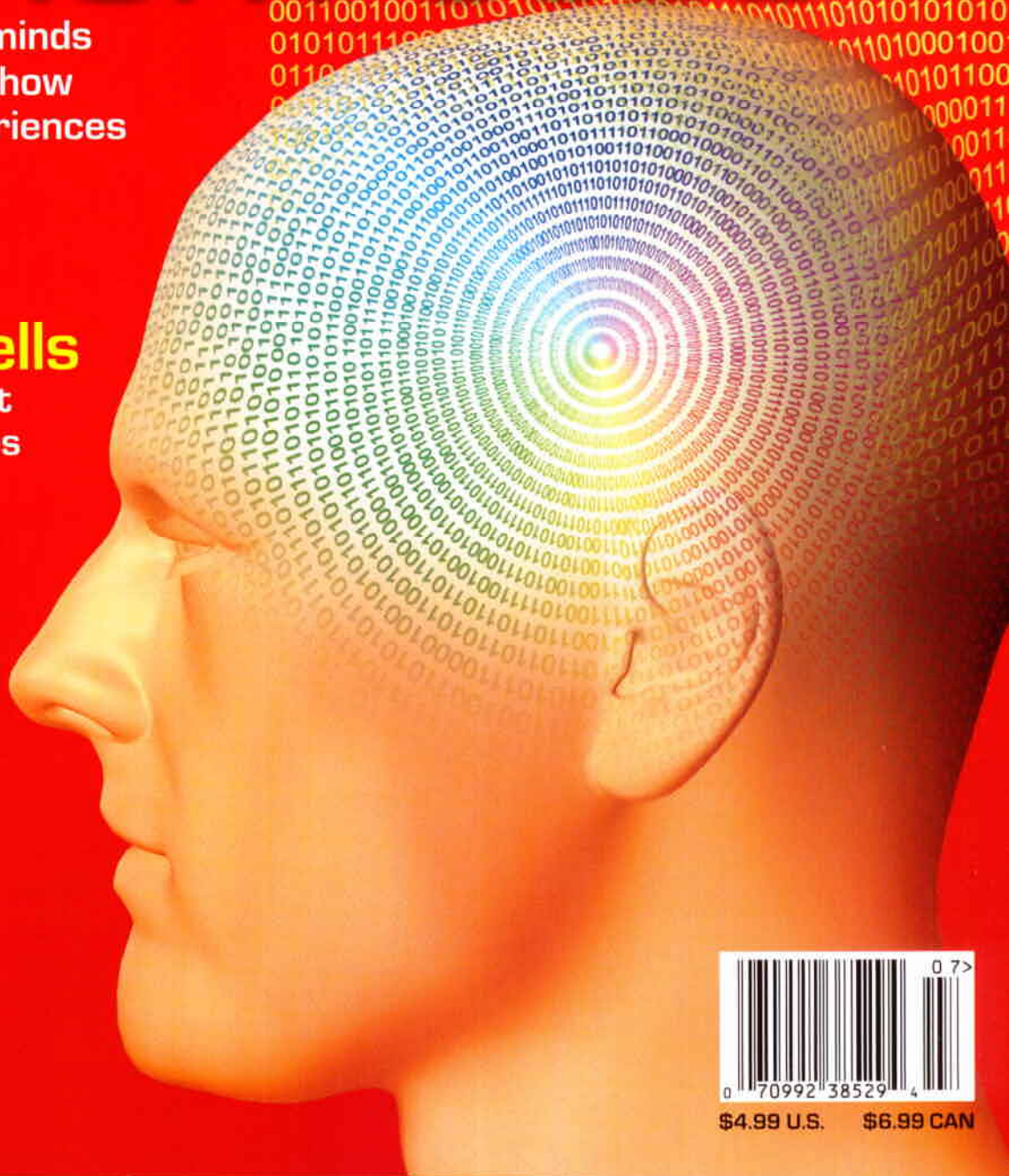
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# BROADBAND ROOM SERVICE BY LIGHT

Encoded light transmissions can provide the wireless devices in a room with multimedia Web services such as videoconferencing, movies on demand and more **By Mohsen Kavehrad**

## KEY CONCEPTS

- Wireless delivery of multimedia Internet services to multiple users indoors may best be accomplished using light beams rather than radio waves.
- Optical wireless local-area networks employ encoded invisible infrared or visible light rays to transmit broadband data to mobile and fixed users inside homes and offices.
- Unlike the radio waves used by Wi-Fi, WiMAX and other similar networks, light photons offer a broader bandwidth that lets many users operate simultaneously. In addition, photons do not interfere with one another, nor do they pass through walls, thereby preventing eavesdropping.

—The Editors

**E**lectronics engineers have long dreamed of ubiquitous connectivity—wireless data delivery for everyone and everything, everywhere, all the time. And they have made significant strides toward their goal: more than two billion people today have cell phones, and hundreds of millions send and receive messages and files via laptops, handhelds and other digital devices using Wi-Fi, the radio-frequency-based wireless local-area network (“hot spot”) technology.

In addition, more and more Wi-Fi users enjoy the convenience of employing wireless mobile devices anywhere indoors. At the same time, manufacturers are installing wireless communications capabilities in traditionally stationary electronic devices and appliances to enable consumers to communicate with them remotely. Increasingly, these users also want to access broadband services without the fixed wire links they typically must have to receive them. But because of the limited availability of radio bandwidth in desired frequency ranges, Wi-Fi suffers from insufficient transmission speed and channel capacity, which slows the wireless access of Web-based multimedia services such as Internet

browsing and video conferencing, as well as television and movies on demand. And even the new higher-speed, wide-area radio systems, such as WiMAX, are not well suited to wireless broadband communications inside structures because they can handle only a few users in a confined space and, more important, cannot provide secure communications.

An intriguing alternative is optical wireless technology. Rather than transmitting radio waves, optical wireless local-area networks send data in coded beams of white or infrared light—the latter being the same invisible wavelengths found in TV remote controls. Optical systems can connect wireless digital devices to a data port in a room, which in turn can be hooked into whatever high-speed broadband data network serves the house or building. This fast-developing technology offers several benefits: its focused, interference-free cells (or basic service areas) afford almost limitless bandwidth for multiple users. It also provides near-total security because, unlike radio waves, light does not pass through walls. And optical wireless is especially appropriate for large business spaces with many high-bandwidth users in close prox-



LIGHT WAVES can bring broadband data to and from mobile digital devices indoors at high speed no matter where the user moves.

imity, such as a factory floor or an office with many reconfigurable cubicles.

### Data via Light

You may have heard of the “last mile” problem—the high cost of delivering broadband services from the nation’s high-speed data infrastructure to fixed users. Optical wireless technology, in contrast, addresses the “last few feet” problem—the difficulty of sending broadband traffic from the terminus of the hardwired information backbone to wireless devices indoors.

Researchers have investigated the concept of indoor optical communications since the early 1980s, when engineers at IBM Zurich built the first working system. The technology languished for a decade because the Internet was still in its infancy and demand for wireless broadband systems did not yet exist. With the astounding growth of the Web in recent years, however, all that has changed.

Engineers describe infrared and white light-

emitting diode (LED) wireless local-area networks as “optical” systems because they transmit data via invisible and visible light waves (or photons) rather than longer radio waves or microwaves. Current optical wireless systems use very low intensity infrared radiation—the “optical” segment of the electromagnetic spectrum with wavelengths longer than those of visible light but shorter than those of radio waves—which people cannot sense. When infrared light is emitted at higher intensities, we feel it as heat.

Optical links operate best when the transmitter aims directly at the receiver, as they do in the familiar point-and-shoot systems of TV remotes and digital cameras. But this arrangement would be impractical when connecting up an entire office or providing network access in a public place such as an airport or a restaurant. To get full coverage in a room, optical networks disperse their data-containing beams throughout the space [see box on page 85]. Encoded infrared beams can bounce off all the surfaces—the walls,

# 20 MILLION+

WIRELESS BROADBAND USERS BY 2010

will access high-speed data via WiMAX and other radio-based wide-area networks, according to Visant Strategies, a market research firm. Optical wireless systems may better serve indoor users.

## RADIO VS. INFRARED

Nondirected (or diffuse) infrared systems, which disperse coded light beams by reflecting them off room surfaces, offer advantages over radio-frequency-based systems for delivering wireless broadband data indoors.

### TRANSMISSION SPEED

**Radio:** Ensuring safe power levels that do not hurt indoor occupants limits the maximum data-transfer rate to several hundred megabits per second.

**Infrared:** Gigabit-per-second data-transfer speeds.

### BANDWIDTH LIMITATION

**Radio:** Because radio signals sent at the same frequency interfere with one another, the Federal Communications Commission regulates transmission bands, which curbs available bandwidth.

**Infrared:** Photons do not interfere with one another. Usable bandwidth is limited by the maximum rate at which the receiver's photodiodes can register incoming data and prepare to receive more.



Infrared TV remote

### SECURITY

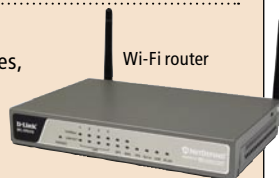
**Radio:** Radio waves pass through walls, opening up chances for eavesdroppers.

**Infrared:** Light waves cannot pass through walls, preventing others from snooping.

### MULTIPATH FADING

**Radio:** As coded radio waves bounce off conductive surfaces, they often arrive at different times. Sometimes the reflections are sufficiently out of phase so that the troughs line up with the rises, canceling one another out.

**Infrared:** Destructive interference is impossible with light waves. The sensors on the active area of a photodiode absorb the waves separately and then average out the incoming energy, so no canceling can result.



Wi-Fi router

### PRINCIPAL NOISE SOURCE

**Radio:** Co-channel interference from other users transmitting on the same frequency slows transmission speed.

**Infrared:** Spurious signals from ambient light sources—sun, lamps, and so forth—slow transmission speed.

the desk, the coffee machine, even occupants' faces. The resulting reflections scatter around the interior, so receivers can point in any direction. Although some commercially available infrared networking products already use this method, the ricocheting beams create something akin to echoes, which complicates the signal receiver technology's determination of whether it is capturing accurate data. The echoes can lead to loss of data and can significantly limit the network's data-transmission speed.

### Making Infrared Work

To address the echo issue, my research team at Pennsylvania State University developed an optical wireless system that sends out multiple copies of the data as an array, or grid, of pencil-thin infrared beams that fill the volume of an interior

space [see box on page 86]. The low-power beams, each repeating the same signals, connect an access port, which is wired to the high-speed data infrastructure, to all the digital devices in the room fitted with infrared receivers. Repetition of the coded beam permits users to move around the room and still stay hooked up to the system because they can link to new beams as they lose connection with others. Because a device receives multiple identical data streams simultaneously, it can perform error checking by simply comparing the data from several beams to ensure the data's accuracy. The grid of pencil beams enables rapid signal transmission—a gigabit per second, several hundred times as much data as a DSL modem—with few transmission errors. Such a system can make indoor wireless broadband access a breeze.

We create the light grid by sending the encoded infrared signal out through a so-called beam former—a special holographic filter—that disperses the beams in the desired directions. To make the holographic filter, we first illuminate an inexpensive photosensitive plastic sheet with an image of a grid from two directions. To accomplish this task, we split the image-containing beam into two with a half-silvered mirror and then recombine them using a couple of beam directors. This setup lights the photosensitive sheet with the same grid image from different angles, creating a three-dimensional, or volumetric, image. When the infrared wireless transmitter sends a coded light beam through the holographic filter, many copies of the beam emerge in a three-dimensional grid pattern.

The beam pattern we use depends on the configuration of the room; different areas can be illuminated as needed—with a fan shape, a rectangular grid shape, concentric circles, and so forth. For instance, whereas general-use spaces such as offices and factories usually have uniform lighting, an art museum typically requires lights to be focused on the paintings and the sculptures. In the same way, optical wireless installations can be optimized so that the beams are concentrated in areas where many broadband users labor and less so where there are fewer workers.

A room's infrared wireless receiver is fitted with a similar so-called fly-eye holographic filter that helps to collect the "reply," or return-path, beams emitted by digital devices. The filter funnels the signals received from many directions into separate photodetectors and improves reception by combining the energies of the beams.

## White LED Wireless

These infrared-based optical wireless systems will most likely be supplanted at some point by local-area networks based on white LEDs, which offer still more bandwidth, along with other benefits. LED technology is increasingly being seen as a replacement for conventional lighting, and it could provide an additional broadband function at the same time.

White LEDs combine the low power consumption and long life of fluorescent bulbs with the pleasing light spectrum of incandescent bulbs. According to industry experts, within a few years these white light-creating silicon chips will be mass-produced using traditional integrated-circuit fabrication techniques cheaply enough to allow them to overtake compact fluorescents, the currently favored low-energy lighting option. What is not yet widely appreciated, though, is that the same white LED technology that could one day brighten rooms and other interior spaces very inexpensively and efficiently could simultaneously provide all the suitably equipped digital devices inside those spaces with wireless digital broadband access. When you turn on a white LED lamp, your wireless device could simultaneously receive broadband transmissions via the same white light that illuminates the room.

**A white LED lamp could transmit broadband via the same light that illuminates the room.**

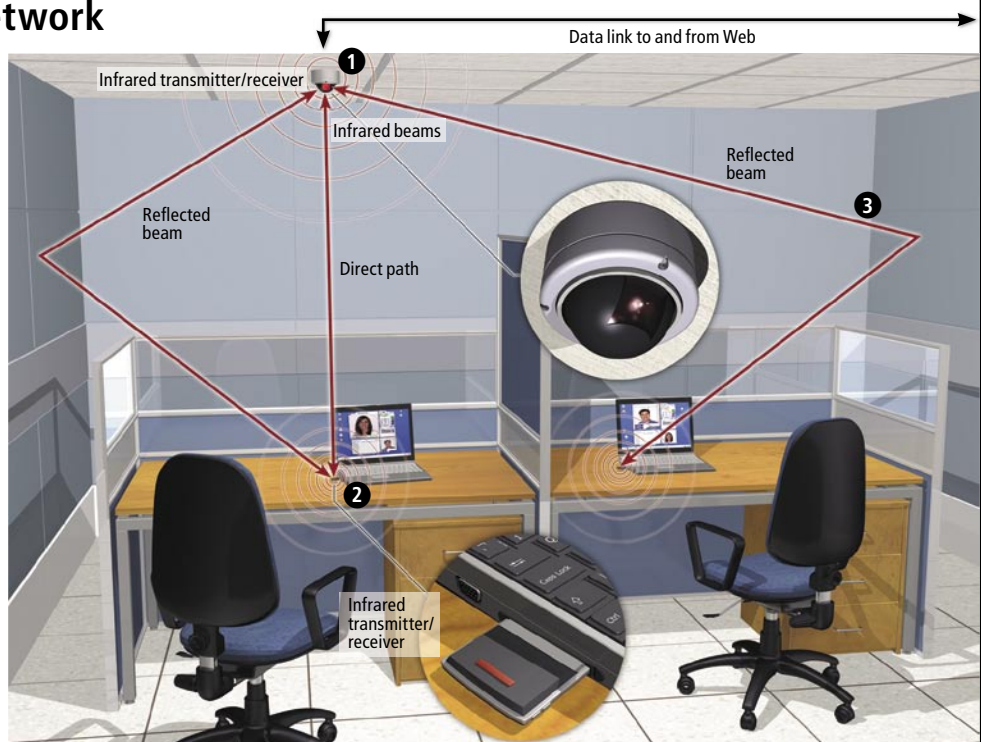
Unlike other existing lighting sources, an LED can be readily adapted to operate as a visible-light wireless communications transmitter, a concept first suggested a few years ago by a team of researchers at Keio University in Japan. The LED's rapid on-and-off response time (a kind of high-tech semaphore operating in the millions of cycles per second, or megahertz, range) enables it to modulate visible light for encoding wireless communications. According to my research group's preliminary experimental results, a commercially available white LED element can be modulated for signaling by up to about 100 megahertz. This high-frequency semaphore is far too fast for the human eye to see.

White LEDs offer a number of advantages for indoor wireless communications over Wi-Fi and even infrared networks. Because white LEDs may end up providing interior lighting in the future, installation of a wireless system based on them would probably be easier than setting up most other wireless systems. Plus, signal degradation caused by everyday objects in rooms blocking point-to-point transmissions—known as the shadowing effect—would be minimal because white LED light fixtures would typically be distributed throughout a room. Ceiling installations would be particularly useful because the beams would be less likely to be obstructed.

### [HOW IT WORKS]

## Optical Wireless Network

In contrast to radio-wave-based technology, such as Wi-Fi or the new WiMAX systems, optical wireless networks can connect multiple indoor portable devices to the Internet at broadband speeds using infrared light. Inexpensive infrared transmitters/receivers beam signals into a room ① to link with devices fitted with plug-in cards that can both receive and transmit the coded infrared light ②. Because light signals do not interfere with one another—as radio signals can—and offer greater bandwidth, many more devices can share the optical network. Barriers such as partitions do not halt reception because beams reflect off room surfaces ③. Engineers are working on similar systems that use white LED lamps, flickering in code faster than the human eye can detect.



**[THE AUTHOR]**



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As with all optical systems, white LED technology is not susceptible to interference from other light signals of other colors and offers a huge communications bandwidth.

It is important to note that room occupants will be able to shut off the lights at night and still use their laptops and other devices, because even when LEDs are “off” and dark, a low-current power supply could still allow them to release enough so-called residual photons to communicate wirelessly. An alternative approach would be to design white LED systems to include low-cost light sources that emit invisible frequencies to accomplish this function when the room lights are switched off.

Researchers need to resolve several remaining concerns with white LED wireless local-area network technology. A key step will be the design of the return, or uplink, signal systems by which the wireless devices communicate with the white LEDs and thus the backbone infrastructure. Engineers could, for instance, equip devices with emitters (on plug-in cards for retrofitting) that produce a different, invisible (perhaps infrared) wavelength. These light sources would send coded beams to white LED lamps fitted with small photodiode receivers. Or the system could operate on a single visible wavelength and take ad-

vantage of the fact that LEDs are pulsed at very high frequencies (they are “occulted,” or mostly on with very brief off periods). The return signals from wireless devices could be transmitted to receivers during the LEDs’ predetermined off cycles. Engineers call this technique “split time,” or time-division duplex. Whatever the eventual solution, the added equipment will raise the cost of the system somewhat.

Developers of white LED systems will also have to account for the possible and still uninvestigated negative effects of natural and artificial light entering through windows and other sources. And before engineers can formulate practical designs, they must conduct additional simulations and experiments to determine the optimal balance between indoor illumination and communications. Finally, researchers will have to produce effective visual-spectrum encoding, decoding, modulation, and diversity-combining techniques that are compatible with both illumination and communications functions.

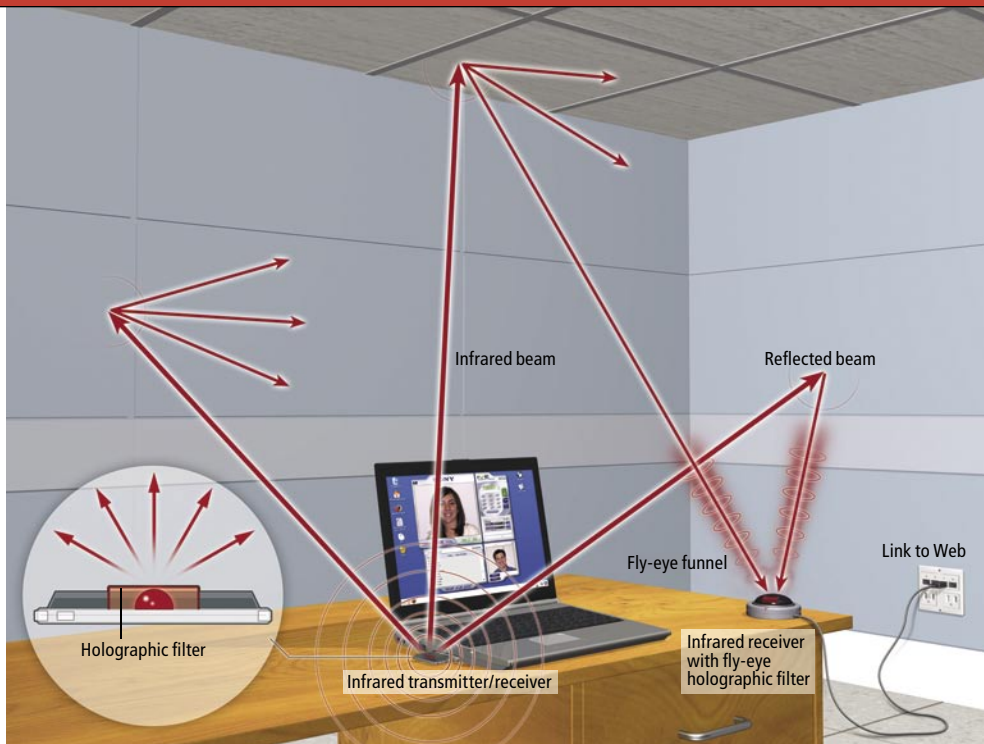
**Power-Line Broadband**

Adoption of both variants of optical wireless technology would benefit greatly from of an up-and-coming way to deliver broadband access over the last mile to fixed users—broadband

**[AUTHOR'S INNOVATION]**

# HOLOGRAPHIC FILTERS DEFEAT ECHOES

Existing optical wireless systems bounce infrared beams off room surfaces, scattering the reflections around the interior. Because the scattered beams travel unequal path lengths, they arrive at the receiver at slightly different times, creating an effect similar to echoes. The coded beams thus overlap randomly, making it difficult for the network to recognize incoming data accurately. Information loss and speed reduction result. One solution is to place a special holographic filter on the transmitter; the filter multiplies each encoded beam into many identical copies in a wide-ranging grid pattern that fills the entire room. A similar holographic “fly-eye” filter (lower right) on the receiver funnels signals from various sectors into separate sensors on the active area of the photodiode, which makes it easy to verify one beam-borne data stream against another.

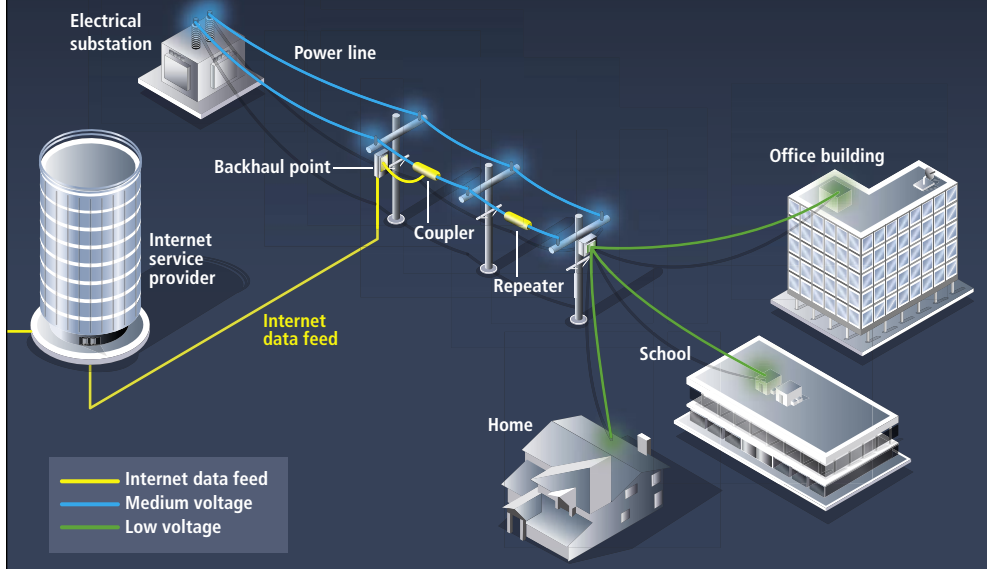


DEPARTMENT OF PUBLIC INFORMATION, PENNSYLVANIA STATE UNIVERSITY (Kavehrad); SW INFO GRAPHICS (illustration)

[THE NEXT STEP]

## BROADBAND VIA THE WALL PLUG

Optical wireless becomes more practical if the broadband data travel the “last mile” over electric power lines, via a new technology that can deliver data at rates between 500 and 50,000 kilobits per second—equivalent to the performance of DSL or cable. An Internet service provider feeds high-speed data to a backhaul point, a gateway to the local medium-voltage grid. Afterward, a coupler injects the data signal into the electric current flowing in the power line. Repeaters amplify the data at various points as the current makes its way to customers. Inexpensive “broadband over power lines” modems plugged into wall sockets in homes, schools and offices then convert the electrical signals into a form suitable for digital devices.



### MORE TO EXPLORE

**Spot-Diffusing and Fly-Eye Receivers for Indoor Infrared Wireless Communications.** G. Yun and M. Kavehrad in *Conference Proceedings, IEEE Wireless Communications*, June 1992.

**Fundamental Analysis for Visible-Light Communication System Using LED Lights.** T. Komine and M. Nakagawa in *IEEE Transactions on Consumer Electronics*, Vol. 50, No. 1, pages 100–107; February 2004.

**Short-Range Optical Wireless Communications.** Dominic C. O’Brien and Marcos Katz. *Wireless World Research Forum (WWRF11)*, Oslo, June 2004.

**Hybrid MV-LV Power Lines and White Light Emitting Diodes for Triple-Play Broadband Access Communications.** M. Kavehrad and P. Amirshahi in *Achieving the Triple Play: Technologies and Business Models for Success*. International Engineering Consortium, 2005.

**Transmission Channel Model and Capacity of Overhead Multi-Conductor Medium-Voltage Power-Lines for Broadband Communications.** P. Amirshahi and M. Kavehrad. *IEEE Consumer Communications and Networking Conference*, Las Vegas, January 2005.

over power lines (BoPL) technology, which sends high-speed data over medium- or low-voltage electric power grids to room wall sockets [see box above]. BoPL exploits the existing power network to piggyback broadband information on the same wires that bring electricity to consumers [see “The Network in Every Room,” by W. Wayt Gibbs; *SCIENTIFIC AMERICAN*, February 2002]. Utilities in Ohio, Texas, and elsewhere in the U.S. already offer BoPL service to consumers at rates comparable to that of DSL. And many users receive Internet services via BoPL in Europe and Asia (in Spain, Sweden, Norway, the Netherlands, South Korea and Japan, for instance), where the grid architecture makes it easier to adapt the existing power grid technology to this application. The optical wireless application of this broadband “bridge” emerges when users plug into electrical wall sockets small, inexpensive adapters that can deliver data via embedded infrared transmitters to any digital device in the room equipped with an optical receiver. In buildings illuminated by white LEDs, adapters would not be necessary.

My research team has shown that a white

LED system for lighting and high-data-rate wireless communications, coupled with BoPL technology, could provide data-transmission capacities as high as a gigabit (a billion bits) per second, which surpasses those offered by conventional DSL (two to four megabits, or millions of bits, per second at the maximum) or cable (about 50 megabits per second on average). This maximum rate is limited only by optical path differences within a room of a particular shape and size, which can contribute to signal distortions. Multiple receptions of the same message, if not properly processed, cause such problems. If engineers design a system appropriately, however, they can keep this distortion to acceptable levels or even exploit the multiple copies to provide a better quality of delivery of broadband service to the end users.

Whether their system uses infrared or visible light, operators of wireless digital devices indoors will soon have a new way to ride the broadband wave into the future. Optical wireless technology is well equipped to be the bridge that can bring this digital access across the last few feet to where we live and work. ■