Sustainable Energy-Efficient Wireless Applications Using Light

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ABSTRACT

As we step further into the 21st century, the demand for sustainable energy-efficient technology grows higher. The important area of electric lighting, currently dominated by decades-old incandescent and fluorescent sources, is being taken over by white light emitting diodes, which are solid state devices with much greater energy savings. Replacement of current inefficient lighting by these LEDs will result in reduction of global carbon dioxide emissions, a major cause of global warming, among other things. WLEDs hold the potential, in the field of photonics, to be as transformational as the transistor was in electronics. This core device has the potential to revolutionize how we use light, including not only for illumination, but also for communications, sensing, navigation, imaging, and many more applications. In this tutorial we highlight some of the potentials.

INTRODUCTION

As the third-generation mobile communication system is deployed, manufacturers and the scientific community are increasingly turning their research interests toward future wireless communication systems. It is commonly agreed that the fourth generation (4G) and beyond systems will not be based on a single access technique; rather, these systems will encompass a number of different complementary access technologies. Future systems will not only connect users and their personal equipment, but access to independent (standalone) equipment will also be provided. Ultimately, one would expect that everyone and everything will be wirelessly connected. This vision places short-range communications in a position of preponderance, as one could argue that most of the wireless links in future networks will be established over relatively short distances. In addition, a significant part of these links will be characterized by high data throughputs. Probably the largest portion of practical applications of short-range communications take the form of wireless local, personal, and body area networks (WLAN, WPAN, and WBAN), covering ranges from a few tens of meters down to sub-meter communications.

Lighting is a major source of electric energy consumption. It is estimated that one third of the global consumption of electricity is spent on lighting purposes; as such, development of more efficient lighting sources is important. This acknowledgment of concerns about significant consumption has generated significant activity toward the development of solid state sources to replace incandescent and fluorescent lights. Fluorescent lamps contain environmental pollutants; thus, their elimination will remove a significant source of environmental pollution; more specifically, their replacement with highly efficient light emitting diodes (LEDs) generating *white light* will reduce energy consumption. It is fortunate that white LEDs are already commercially available. White LEDs (WLEDs) require roughly 20 times less power than conventional light sources, even five times less power than fluorescent bulbs, which consume less energy. An entire rural village can be lit with less energy than that used by a single conventional 100 W light bulb. Switching to solid state lighting would reduce global electricity use by 50 percent and reduce power consumption by 760 GW in the United States alone over a 20-year period. To get a clear picture of the positive impact the use of WLEDs will have, we provide several concrete estimates. If all existing bulbs were replaced by WLED sources, within 10 years we would have the following benefits: energy savings of 1.9×10^{20} joules, US$1.83 trillion financial savings, 10.68 gigatons reduction of carbon dioxide emissions, and 962 million barrels less consumption of crude oil.

The field of photonics starts with the efficient generation of light. The generation of efficient yet highly controllable light can indeed be accomplished using LEDs. Using a WLED instead of conventional lighting means the size, cost, and energy consumption will decrease considerably, since optical devices are smaller and simpler than electrical devices. WLEDs are semiconductor devices. About 10 years ago, researchers came to the realization that WLED devices, in addition to being very fit for lighting the surrounding space, could also be used for wireless communications purposes. The advantages of such technology applications are many. It belongs to the *green technologies* category when used for lighting purposes, becoming even more environmentally friendly when it supports communication functionality compared to radio frequency (RF) alternatives. Also, LEDs and photodetectors tend to be considerably cheaper than their RF counterparts. Optical wireless allows easy bandwidth reuse and improves security, since light is confined within the room it illuminates. It does not generate RF contamination, nor is it impacted by RF interference. Thus, replacing RF devices with devices using white light for communications (at least for indoor environments) will reduce interference in the RF bands. It should be pointed out that while the consumer market and product developers will benefit, the technology can make a major breakthrough in cases where RF radiation is of great concern, as is the case in hospitals, schools, airplanes, and mines. RF interference has caused accidental triggering of explosions when using remote detonator devices. Federal regulation places 1 W as the maximum acceptable RF power within mines using remotely triggered detonators. Also, baby monitoring RF signals have interfered with landing instructions of planes approaching airport runways. By replacing the conventional lights with WLED and using them for both data transmissions and lighting, large amounts of energy can be saved.

The first use of optical wireless communications using visible light was as far back as 1880, when Alexander Graham Bell developed a prototype that used a sunbeam reflected on a small mirror to transfer voice, as shown in Fig. 1.

Widespread commercial use of free space optical (FSO) communication systems appeared before their RF counterparts became prevalent in the market. These made use of infrared (IR) and were for indoor use, and appeared in a number of applications (e.g., remote control units, communication ports between devices). In those early years, only IR LEDs were available at a low cost. In 1993 the Infrared Data Association (IrDA) was formed to provide low-cost interoperable worldwide infrared technology and a forum for the development of IR FSO standards. The IrDA protocol was developed, becoming an industry standard. Also, the IEEE 802.11 standard provided specifications for an infrared physical layer; however, those may not be applicable today. In terms of modulation and detection, use of intensity modulation (IM) and direct detection (DD) can provide a low-cost FSO communication system, considerably lower cost than the RF counterparts.

While FSO can achieve very high bit rates when there is an unobstructed line of sight (LOS) between transmitter and receiver, transmission rate is reduced considerably when an LOS does not exist. In many cases, ensuring that a LOS exists is a major challenge, and usually requires use of relatively complex and expensive technology. Of course, interference from ambient light has a negative effect and can be dealt with by using robust signal formats and/or optical filters.

The optical wireless communications area of research did not receive much attention for several years, except in some military applications for the security it offers. Yet the largest number of wireless devices ever sold, TV remote controls, use wireless infrared light in order to function. The number of researchers and research contributions addressing optical wireless communications is nowhere close to the number of researchers working on, and the volume of contributions generated dealing with, RF wireless communication technologies.

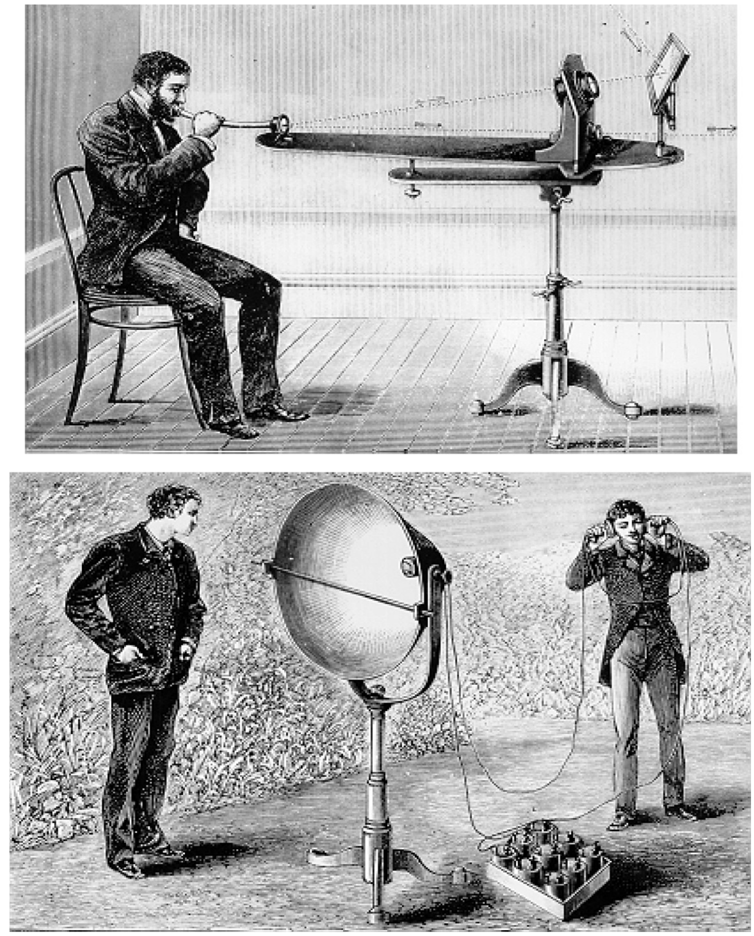

Figure 1. *Bell's Photo-phone developed in 1880, U.S. Patent #235199.*

Small research teams have contributed to the fundamentals of the optical wireless communications field for many years [1–20]. The advantages of using optical radiation over RF include:

- Virtually unlimited bandwidth with over 540 THz for wavelengths in the range [200–1550 nm]. This band is unregulated and available for immediate utilization.
- Use of baseband digital technology.
- A small receiver (photo-detector) area provides spatial diversity that eliminates multipath fading in intensity modulation with direct detection links. Multipath fading degrades the performance of an unprotected RF link.
- Light is absorbed by dark surfaces, diffusely reflected by light-colored objects, and directionally reflected from shiny surfaces. It does not penetrate opaque objects. This provides spatial confinement that prevents interference between adjacent cells operating in environments separated by opaque dividers.
- Spatial confinement of optical signals allows for secure data exchange without the fear of an external intruder listening in. This provides physical-layer security, which is the safest type.

UV imaging based on state-of-the-art semiconductor UV sensors such as avalanche photo-detectors is an emerging field for commercial aircraft landing in foggy and hazy environments, and detection of atmospheric threats for environmental health.

- There is no electromagnetic interference with other devices, making it very suitable for environments employing interference sensitive devices, such as hospitals, airports and factories, power plants, military and national security buildings.

A very recent paper [19] addresses concepts of recently implemented optical wireless transmission systems for broadband indoor applications based on infrared radiation as well as visible light. An overview of solutions and achieved performances is also presented.

Optical wireless technologies utilize optical carriers to convey information through optical wireless channels from one site to another. These channels distinguish themselves from their RF counterparts. These can occupy several orders of magnitude larger and unlicensed optical spectrum in either infrared (IR), visible light (VL), or ultraviolet (UV) wavelength range, and thus offer huge potentials in high transmission rate with enhanced data security. These are also immune to electromagnetic interference (EMI), ideal for civilian applications in sensitive environments such as hospitals and aircraft, as well as tactical applications that demand anti-jamming. The very short wavelength of an optical carrier allows for a miniaturized transceiver to emit high-density optical signals at low power and may lead to high resolution in imaging as well.

The needs for high-resolution imaging range from biomedical applications to personal and military applications. UV imaging based on state-of-the-art semiconductor UV sensors such as avalanche photodetectors (APDs) is an emerging field for commercial aircraft landing in foggy and hazy environments, and detection of atmospheric threats for environmental health. When UV spectrum is used for communications, negligible solar radiation and atmospheric scattering helps to build a high-quality non-LOS link [16]. It is particularly important for outdoor communications system operation without restrictive transmitter/receiver pointing. The feature is also attractive in unattended ground sensor networks for robust connectivity of sensor nodes. These areas have continually intrigued defense and associated R&D activities in the defense industry.

Research contributions targeting the use of visible LEDs produced for communications purposes can be traced to as early as 1998–1999. However, compared to other areas of wireless communications, the reported research work is considerably limited. The very early contributions addressed narrowband low-bit-rate systems and applications [13, 14]. Contributions addressing broadband visible light communications using WLED started appearing in 2001 [15] and continued in the following years with contributions made by researchers from Keio University, Yokohama, Japan. In November 2003 the Visible Light Communications Consortium (VLCC) was established in Japan, having among its membership major Japanese industrial organizations. Toshiba, NEC, KDDI, Panasonic, Sony, Toyota, Sumitomo, Mitsubishi, NTT DoCoMo, Casio, and Sharp are among those. Also, Samsung of South Korea has joined the consortium. The VLCC was established among these major companies to develop, plan, research, and standardize Japan's own VLC systems. Its goal is to develop, test, investigate, plan, and standardize ubiquitous high-speed biologically friendly VLC LED systems.

Later, the Wireless World Research Form (WWRF) initiated some activity on this subject. While a few more contributions appeared between 2000 and 2006 by other researchers, the research area has started showing some noticeable activity since 2007 when an invited paper by the author [11] appeared in *Scientific American* that was translated into multiple languages. It is only in 2008 that the United States and Europe initiated and funded major research projects focusing on this technology. The European Union heavily funded the *hOME Gigabit Access* (OMEGA) project, seeking to develop global standards for home networking, including the use of optical wireless using infrared and VLC technology. This was established as a part of European Union's EU- Framework Programme 7 (P7)R&D program. Major industrial members are France Telecom, Thomson, IHP Microelectronics, ComNets (RWTH), and Siemens. Finally, the IEEE issued a Call for Contributions on IEEE 802.15.7 VLC in 2009 and held the first meeting.

Ubiquitous solid state lighting by WLEDs is gaining popularity in both residential and commercial buildings because of high energy efficiency, long sustainability, and low production and maintenance cost. The U.S. Department of Energy is encouraging large-scale applications of LED technologies. White LEDs can be pulsed at hundreds of megahertz, making it possible to transmit data at high speed without noticeable effect on lighting output. Thus, LEDs can be used as transmitters to embed signals to communicate with a variety of electronic devices, such as computers, printers, mobile phones, PDAs, TVs, and other electronics. This efficient communication infrastructure could enable low-cost ubiquitous communication and wireless networking [11]. In addition to these cost savings, the optical spectrum is unlicensed and several orders of magnitude larger than the crowded RF spectrum, and thus has huge potential for low-cost interference-free and high-data-rate communications. Within the optical band, VL has more relaxed exposure limits enforced by safety regulations than IR and UV, allowing high transmitted signal power and thus improved signal quality. Intel, Boeing, and Samsung and professional organizations such as IEEE are now paying particular attention to standardization and realization of VL communication (VLC) technology in the near future. Moreover, gaps and challenges exist in joint design and optimization of communications and illumination protocols. These add-on capabilities would significantly enhance the utility of the lighting system and would allow costs to be spread over a wider level of utility. Ubiquitous communications with lighting will help large-scale energy savings and stimulate the LED lighting and communications industry as well as economic growth in this new area. There is no doubt that this *energy-efficient* technology is capable of answering the problems and technical challenges mentioned earlier. At the same time, there is a great deal of original research needed in order to bring this technology to the level of its full potential.

In the next section we focus on system-level issues for optical wireless networks in general. The discussion is then continued with a focus specifically on visible or WLED LANs. Finally, we provide some conclusions in the final section.

System Level Issues and Optical Wireless Networks

The ultimate goal is to provide ubiquitous connectivity, integrating seamlessly operations in the most common scenarios, ranging from fixed and low-mobility indoor environments at one extreme to high-mobility cellular systems at the other. Surprisingly, perhaps the largest installed base of short-range wireless communications links are optical rather than RF, however. Indeed, *point-and-shoot* links corresponding to the IrDA standard are installed in 100 million devices a year, mainly digital cameras and telephones. It is argued that optical wireless communications has a part to play in the wider 4G vision [18]. Indoor wireless connectivity is always appealing to consumers because of the convenience it provides. One conventional wireless access system is today's Wi-Fi. In the past few years we have witnessed a rapid growth in technologies producing low-cost communications devices, using the RF license-free bands, industrial, scientific, and medical (ISM, 2.4–2.4835 GHz) and unlicensed national information infrastructure (UNII, 5.15–5.25 and 5.35–5.825 GHz). As the technology advances, the service capability of such devices will strengthen. However, uncontrolled deployment of devices using the same spectrum allocation can generate interference beyond the level systems can afford, thus leading to service quality deterioration. The IEEE 802.15.2 working group was formed to address this growing problem; however, without controlling the number of devices operating within certain areas, the problem cannot be solved unless more bandwidth becomes available. The 57–64 GHz band has been added to license-free bands; however, design of communication systems at these extremely high frequencies is very challenging. It will take several years before products of reasonable cost and satisfactory performance in terms of power consumption are introduced in the market. Also, adding bandwidth does not address the problem at its root. In summary, these systems and other similar RF wireless schemes suffer from shortfalls, like interference, not providing quality of service (QoS), and, most important, lack of security.

What is needed is a broadband, interference-free or at least interference-resistant technology, allowing easy frequency reuse made available to the customer at an affordable cost. Considering the rapidly growing wireless consumer devices sector, it is evident that the need for such technology is quite urgent. Visible light and IR light exhibit very similar qualitative behavior because of the closeness of their wavelengths; however, in terms of indoor communications, only IR has been used. The reason is that until recently, it was not possible to manufacture highly efficient WLEDs.

Hence, a good candidate for wireless home networking is optical wireless. The concept of indoor optical communications has been an active area of research since the early 1980s [1–20]. Most of the research in this area is based on IR, or the *RED wavelength* in sunlight, as a communication carrier, and nearly all results from these efforts are applicable to any part of the light frequency spectrum. IR is what brings warmth to our lives. It is harmless, as we have lived with it for thousands of years. Use of conventional lasers for optical indoor communications has not been feasible as yet because of the lack of mass volume availability of these light sources. Now, instead of laser, LEDs can be used as communications transmitters connected to the electric grid, receiving high-bit-rate signals via installed indoor powerlines.

In general, within large open environments where individual users require 100 Mb/s or more, optical wireless is a more sensible solution because of its limited cell size. Today's RF LANs cannot realistically support more than one or perhaps two high-capacity users per cell. With cell sizes of ~100 m that could accommodate tens of users, this is highly wasteful. Multiple high-capacity users could only be serviced by deploying a similar number of systems, all within the same locale. This would create a situation where the multiple cells almost completely overlap, which then raises concerns regarding interference, carrier reuse, and so on. In contrast, optical wireless could deliver the necessary capacity to each user through multiple user-sized cells, and because of the intrinsically abrupt boundary of these cells, interference would be negligible and carrier reuse would not be an issue. Indeed, optical wireless is a future-proof solution since additional capacity far beyond the capabilities of radio could be delivered to users as their needs increase with time. Readers familiar with RF cellular technology know the capacity growth in RF cellular has always been logarithmic, even after introduction of the RF multiple-input multiple-output (MIMO) concept, as RF interference limits the MIMO system gain over single-input single-output system gain. This is shown in Fig. 2 demonstrating the evolution of cellular systems. However, with light it is easy to form *engineered pipes* using cheap lenses and so on, and there are no multipath fading issues as with non-LOS RF links. Hence, achieving linear capacity growth is straightforward. This is accomplished through spatial separation of small cells.

Anyone who has used a remote control to change the TV channel has seen IR in action. The technology is also used in laptop computers and palm-type devices for wireless communication over short distances. But these links work best when the transmitter is pointed at the receiver, something that would not be practical when linking an entire office or offering network access in a public place such as an airport or a restaurant. One way around the problem is to bounce wide IR beams off the ceiling, scattering the reflections around the room. This so-called *diffuse* configuration allows receivers to be point-

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The author and his team have been researching a system that sends pencil-thin infrared beams bouncing around a room, connecting computers to one another and to a central transmitter and receiver that is wired to a larger network. This is based on a concept called multi-beam transmitter and fly-eye receiver.

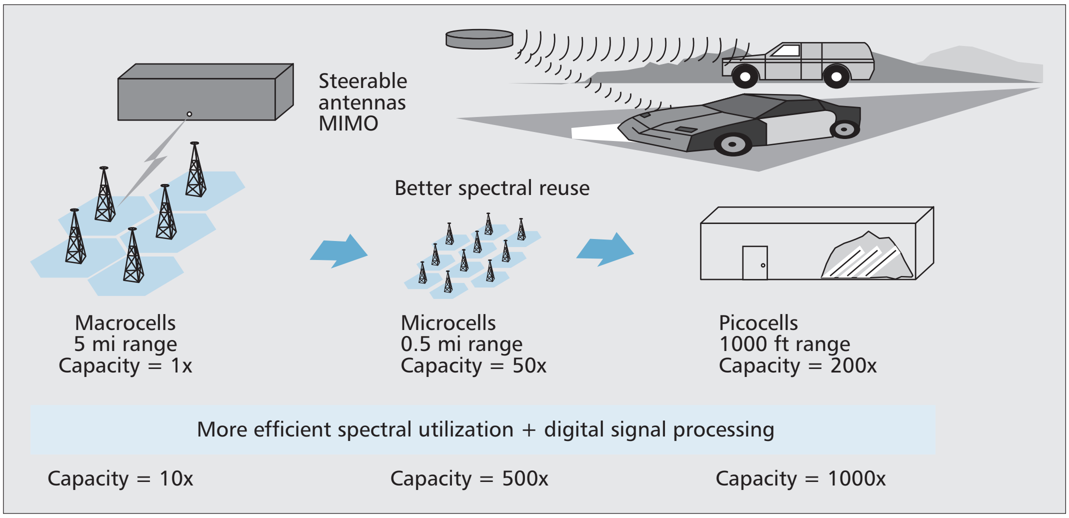

Figure 2. *Logarithmic capacity growth in RF wireless due to interference.*

ed in any direction. While some networking products already use this approach, the scattered beams create something similar to an echo, causing data loss and limiting the network's speed.

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- Implementation of multibranch angle diversity using non-imaging elements requires a separate optical concentrator for each receiving element, which may be excessively bulky and costly. Yun and Kavehrad proposed the *fly-eye receiver* [2], which consists of a single imaging optical concentrator (e.g., a lens) that forms an image of the received light on a collection of photodetectors, thereby separating signals that arrive from different directions. In this article we refer to this design as an *imaging angle-diversity receiver*, or simply an *imaging receiver*. Implementation of an angle-diversity receiver using imaging optics offers two advantages over a non-imaging implementation. First, all the photodetectors share a common concentrator, reducing size and cost. Second, all the photodetectors can be laid out in a single planar array, facilitating the use of a large number of receiving elements or pixels.
- In non-LOS wireless optical links, [2] also proposed the *spot-diffusing transmitter*, which utilizes multiple narrow beams pointed in different directions, as a replacement for the conventional diffuse transmitter, which utilizes a single broad beam aimed at an extended reflecting surface. In this article we refer to the spot-diffusing transmitter as a *multibeam* or *quasi-diffuse transmitter*. While the diffuse transmitter provides considerable immunity against beam blockage near the receiver, it yields a high path loss. The quasi-diffuse transmitter is expected to reduce path loss compared to the diffuse transmitter, because the narrow beams experience little path loss traveling from the transmitter to the illuminated reflective surfaces.

In other words, the author and his team have solved the long echo problem by using a photolithographic filter to produce thin beams that create a large grid as they reflect around the room. This is a really cheap and easy way of producing these multiple beams. Having the pencil beams allows one to send the signals very fast, and not relying on just one of them allows one to move around, and one can do this entirely at low power levels. With another holographic receive filter, light rays are collected from different directions, and with a clever way of combining the collected energies, quality of signal reception is enhanced. This technology could transmit multiple gigabits per second, or several hundred times as much data as a cable modem, with very few transmission errors.

Providing enough bandwidth for activities like videoconferencing is one area where infrared has an advantage; the radio spectrum is tightly regulated so only certain frequencies can be used for data transmissions. Manufacturers can push into higher frequencies in search of free space, but at the same time, the components needed become more expensive. Infrared has no such problems, because its frequencies, which are just below visible light on the electromagnetic spectrum, are unregulated. Also, because IR transmissions do not penetrate walls, there is no chance of interference or overlap in neighboring rooms. That also can be a security advantage; RF networks open the possibility of eavesdropping, perhaps by someone sitting in the parking lot with a laptop and an antenna. However, the inability of IR to pass through walls and other objects used to be a disadvantage in deployment. This has been a reason that optical wireless communication did not penetrate the WiFi market. However, with the advances in powerline transmissions, this situation has altered now. The indoor powerlines can also be used for data transfer. A low-cost powerline modem replaces the wireless router and connects the home to Internet delivery medium of choice. LEDs

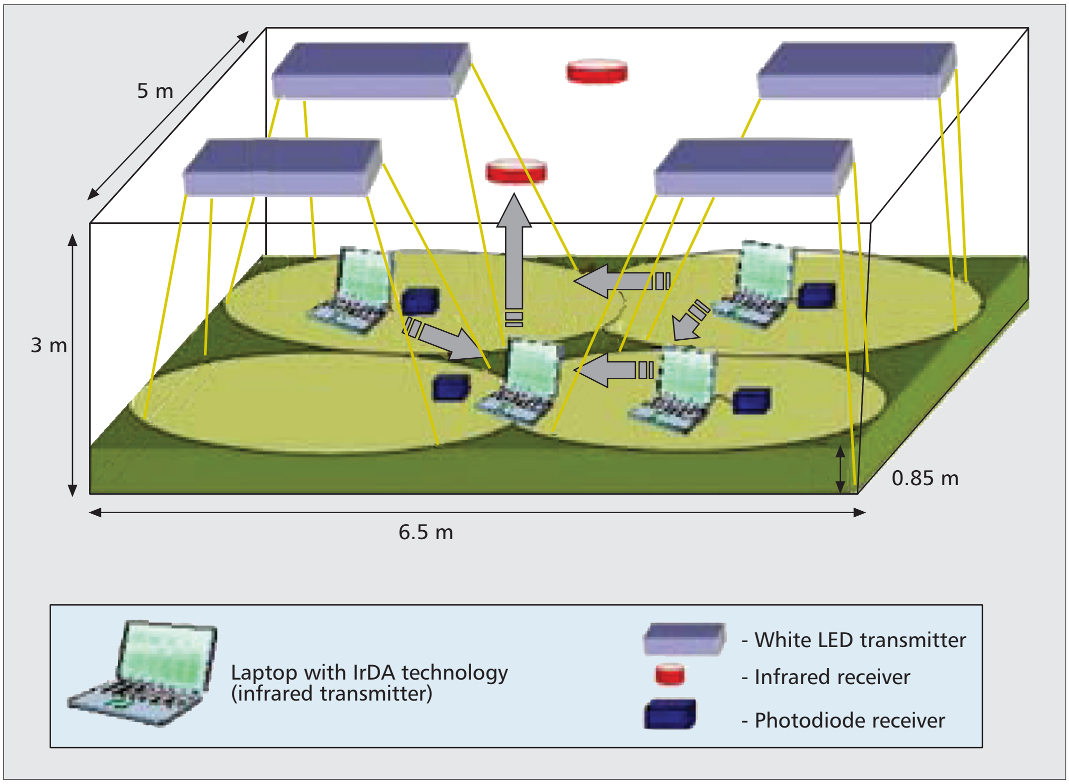

Figure 3. *Visible light communications using white LED for downlink and IR for uplink.*

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installed in each room broadcast the broadband data.

For high-speed wireless home networking, delivering voice/video/data (triple play), optical wireless is indeed a good choice [12] now. A relatively expensive laser source cannot be considered for such applications. A well-known low-cost alternative is to employ an LED. The latter used to be just a dim and dowdy indicator light. Now these have become bright enough to make an iguana squint [21]. LED emission has a much wider spectral line width (30–70 nm) compared to laser diode (1–5 nm) and an optical filter with a larger bandwidth has to be used at the receiver to limit the background noise. This results in less rejection of ambient light and a subsequent reduction in the received signal quality. Next section will discuss white LEDs.

Energy-Efficient White-LED Communications

In response to ever increasing energy demands and subsequent costs, a tremendous emphasis is being placed on saving energy using solid state lighting devices in the form of LEDs [22]. Specifically, a need exists for pure white-light LED's as a more efficient replacement for conventional lighting sources.

White LEDs are considered strong candidates for the future of lighting technology [22]. The reason is that LEDs offer very favorable characteristics such as high brightness, very low power consumption, and high lifetime expectancy. Therefore, it is predicted that in the near future, low-cost, efficient, and miniature WLEDs will replace incandescent and fluorescent lamps. Researchers pledge that by 2012, these devices will reach 7 W and 1000 lumens. This is brighter than a 60 W bulb, yet draws a current provided by four D-size batteries.

As LEDs increasingly displace incandescent lighting over the next few years, general applications of VLC technology are expected to include wireless Internet access, vehicle-to-vehicle communications, broadcast from LED signage, machine-to-machine communications, and so on.

The VLC technology also has potential in a number of specialized application areas including the following:

- Hospitals and healthcare: enabling mobility and data communications in hospitals
- Hazardous environments: enabling data communications in environments where RF is potentially dangerous (such as oil and gas, petrochemicals, and mining)
- Commercial aviation: enabling wireless data communications such as in flight entertainment and personal communications
- Corporate and organizational security: enabling the use of wireless networks in applications where WiFi presents a security risk
- WiFi spectrum relief: providing additional bandwidth in environments where unlicensed communication bands are congested
- Green computing: greater energy efficiency
- Defense and military applications: enabling high-data-rate wireless communications within military vehicles and aircraft
- Underwater communications: between divers and/or remote operated vehicles.

The author's team and others have shown that a white-LED system for lighting and high data-rate indoor wireless communications, coupled with broadband over low-voltage power-line grids, can offer transmission capacities that by far exceed DSL or cable and are more secure than RF.

Moreover, LEDs can be used as a wireless communications transmitter. This is not possible for any other kind of lamps in broadband transmissions. This functionality of LEDs as a transmitter is based on a fast response time and modulation of visible light for wireless communications. Figure 3 shows a very general realization of a visible light communication system using white LEDs. This system is a wireless optical indoor system that uses visible light as a communications carrier.

There are several advantages to using WLEDs for communications over the alternative wireless approaches for indoor communications:

- Installation is easier than most other wireless systems.
- WLED radiation is not subject to spectrum licensing regulations because it does not cause any electromagnetic interference, whereas there are always concerns in using Wi-Fi or any other RF communications systems in terms of interference from or to other wireless communication systems.
- Different users in different rooms and buildings do not interfere with one another because LED signal rays do not go through walls; hence, a huge band can be reused many times over in a small area. On the other hand, in WiFi systems it is possible that different transmitted access point signals interfere and cause degraded performance.
- The shadowing effect is so much less compared to directed methods, as LED light fixtures are distributed throughout a room.
- LEDs are less expensive than laser sources used in IR.
- The receiver obtains at least one strong line-of-sight signal as the transmitters are on the ceiling. This is not the case in most IR transmission situations.

Hence, one can use the same white LEDs not only for lighting the homes but also as light sources for wireless in-house communications. Using this new and developing technology along with powerline communications can create a revolution in the area of consumer networking because of its efficiency and affordability. Powerlines make up the largest metallic infrastructure in the world. There are power outlets at every corner of a home or office building, making it an all-encompassing network. No new wiring is required to communicate anything from low rate data to audio and video. In addition, with advanced light fixture discovery and binding mechanisms that are abstracted from the user, a powerline communications (PLC)-enabled lighting control network can be established without needing to remember a single number or risking accidentally turning off ones neighbor's light. Powerline networks use a bus topology, which provides a high level of reconfiguration capability and the ability to control more than one device from a single controller. This controller could manage all the lights in a room or even all the lights in the home. Additionally, the bus topology enables multiple controllers to control a single lighting fixture. This way, a lighting fixture in one room can be controlled from other rooms (i.e., turn off all the house lights from the bedroom). Such a topology also enable the controller to keep track of all the devices on the network and to serve as a backbone for expandability and *plug and play* installations where any new light can immediately become part of the network. The PLC has been folded into the SMART-GRID concept. Dynamic bit rate adjustment can be made possible with the use of adaptive filtering and/or varying the light intensity. Therefore, in future, one may turn on the lights for indoor low-cost lighting and one can receive broadband via the same through WLED light, modulated by broadband data. We are entering a new era of *always on* connectivity. The expectation from consumers for not only ubiquitous but also seamless data, voice, and video services presents a significant challenge for today's telecommunications systems.

The utilization of white LEDs for communication purposes needs more work to resolve such issues as uplink design (LEDs emitting visible light cannot be employed on the uplink), the effect of natural background daylight coming through windows, and so on. The best illumination of a room with respect to both lighting and communications has to be researched through simulations and experiments. Specific signaling schemes have to be designed that will be compatible with these two purposes of such light sources. The uplink could use an infrared light beam or even RF to make a connection between the user terminal and the ceiling mount where the lighting LEDs reside. Low-cost integrated LED/IR light source modules help to solve this issue. For detectors, low-cost PIN diodes or APDs can be used.

Recently, Siemens scientists working with the Heinrich Hertz Institute reported a VLC system using WLED technology to transmit data at 500 Mb/s rate over 5 m [19]. Also, recently our group [20] reported an IR laser link transmitting data at a rate 1 Gb/s over a 7 m directed/non-LOS optical path. The latter was reported in the MIT Technology report in January 2010.

Meanwhile, indoor optical wireless communications through lighting LEDs is continued to be investigated. The author's team and others have shown that a WLED system for lighting and high-data-rate indoor wireless communications, coupled with broadband over low-voltage power-line grids, can offer transmission capacities that by far exceed DSL or cable and are more secure than RF. This is to make home and office wireless Internet hookups faster, more reliable, and more secure by using pulses of light. The Penn State team released a paper [12] stating that WLEDs, wired to a broadband-over-powerline system, can make accessing the public network very easy. Internet signals would come to one's home through twisted pair, cable or fiber as proven commercial technologies today. Then, overhead light is modulated — pulsed in an encoded fashion — so that receivers in a laptop, PC, or other device can translate the signal to web pages, email, or chat sessions. Because light cannot go through walls, unlike the radio frequency signals used by WiFi, the method is less susceptible to intruders.

CONCLUSIONS

In this tutorial we provide an overview on energy-efficient wireless applications using light. We discussed applications of optical wireless communications systems using ultraviolet, visible light, and infrared parts of the unregulated light spectrum. Use of white LEDs not only for lighting the homes but also as means for wireless in-house communications was detailed. Using this new and developing technology along with powerlines communications can create a revolution in the area of consumer networking because of its efficiency and affordability.

After a brief description of several techniques for optical wireless indoor and outdoor systems for transmission, navigation and imaging, it has been determined that full-duplex indoors optical wireless transmission is feasible. Indoor lighting and downlink transmission can be achieved through the installation of an appropriate number of LEDs in the room. Communications coverage footprint follows the illumination pattern of LEDs; hence, by spotlighting, high-bit-rate islands (hotspots) can be created. A portable terminal will have a visible light photodiode and a near IR LED as well to enable full-duplex operation anywhere within the room. As such, the design of this optical wireless network is plausible and advantageous to the average home user and even small LANs as the cost is cheap, yet provides full-duplex communication and lighting. All these techniques incorporate small parts of our designs, and with success of applications and high-intensity LEDs, optical wireless technology is finally becoming a real complement for RF technologies in order to reduce RF interference. By incorporating these techniques, we are setting a new standard for reliable indoor optical wireless networking. There will no longer be a need for separate lighting and communication equipment as well as interference creating RF restrictions. With this technique consumers will have a network at a very low cost and with very little hardware and configuration. Briefly speaking, visible light communications is the best system, from ecological and human health perspectives, and can use the established retro-systems including the lighting facility as well as powerlines. This system is also free from the current radio regulations.

In terms of economic opportunities, we need to develop components that are optimized for the proposed applications rather than using available commercial off-the-shelf (COTS) units which, for the most part, are not optimum. This is a great way to bring back manufacturing and revive the economy.

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REFERENCES

[1] F. Gfeller and U. Bapst, "Wireless In-House Data Communication via Diffuse Infrared Radiation," *Proc. IEEE*, vol. 67, no. 11, Nov. 1979, pp. 1474–86.

[2] G. Yun and M. Kavehrad, "Spot Diffusing and Fly-Eye Receivers for Indoor Infrared Wireless Communications," *Proc. IEEE Int'l. Conf. Selected Topics Wireless Commun.*, Vancouver, Canada, June 1992, pp. 262–65.

[3] M. Kahn and J. R. Barry, "Wireless Infrared Communications," *Proc. IEEE*, vol. 85, no. 2, 1997, pp. 265–98.

[4] J. Carruthers and J. Kahn, "Angle Diversity for Non-Directed Wireless Infrared Communications," *IEEE Trans. Commun.*, vol. 48, no. 6, June 2000, pp. 960–69.

[5] S. Jivkova and M. Kavehrad, "Multi-Spot Diffusing Configuration for Wireless Infrared Access," *IEEE Trans. Commun.*, vol. 48, no. 6, June 2000, pp. 970–78.

[6] S. Jivkova and M. Kavehrad, "Receiver Designs and Channel Characterization for Multi-Spot High Bit Rate Wireless Infrared Communications," *IEEE Trans. Commun.*, vol. 49, no. 12, Dec. 2001, pp. 2145–53.

[7] Y. Alqudah and M. Kavehrad, "MIMO Characterization of Indoor Wireless Optical Link Using a Diffuse-Transmission Configuration," *IEEE Trans. Commun.*, vol. 51, no. 9, Sept. 2003, pp. 1554–60.

[8] E. Simova, M. Tai, and M. Kavehrad, "Indoor Wireless Infrared Link with a Holographic Multiple-Spot Diffuser," in *Applications of Photonic Technology*, vol. 2, Plenum Press, 1996, pp. 223–28.

[9] M. Pakravan, M. Kavehrad, and H. Hashemi, "Indoor Wireless Infrared Channel Characterization by Measurements," *IEEE Trans. Vehic. Tech.*, vol. 50, no. 4, July 2001, pp. 1053–73.

[10] J. Kahn *et al.*, "Imaging Diversity Receivers for High-Speed Infrared Wireless Communication," *IEEE Commun. Mag.*, vol. 36, no. 12, Dec. 1998, pp. 88–94.

[11] M. Kavehrad, "Broadband Room Service by Light," *Sci. Amer.*, July 2007, pp. 82–87.

[12] M. Kavehrad and P. Amirshahi, "Hybrid MV-LV Power Lines and White Light Emitting Diodes for Triple-Play Broadband Access Communications," *IEC Comprehensive Report on Achieving the Triple Play: Technologies and Business Models for Success*, Jan. 2006, pp. 167–78.

[13] G. Pang *et al.* "Visible Light Communication for Audio Systems," *IEEE Trans. Consumer Elect.*, vol. 45, no. 4, Nov. 1999, pp. 1112–18.

[14] Y. Tanaka, S. Haruyama, and M. Nakagawa, "Wireless Optical Transmission with the White Colored LED for the Wireless Home Links," *Proc. IEEE PIMRC*, London, UK, 2000, pp. 1325–29.

[15] Y. Tanaka *et al.*, "Indoor Visible Communication Utilizing Plural White LEDs as Lighting," *Proc. IEEE PIMRC*, 2001, pp. F81–F85.

[16] Z. Xu and B. Sadler, "Ultraviolet Communications: Potential and State-of-the-Art," *IEEE Commun. Mag.*, vol. 46, no. 5, May 2008, pp. 67–73.

[17] S. Hranilovic, *Wireless Optical Communications Systems*, Springer, 2005.

[18] D. O'Brien and M. Katz, "Short-Range Optical Wireless Communications," *Wireless World Research Forum*, Oslo, Norway, Apr. 2004.

[19] K.-D. Langer and J. Vucic , "Optical Wireless Indoor Networks: Recent Implementation Efforts," *Proc. ECOC*, Torino, Italy, Sept. 2010.

[20] M. Kavehrad and J. Fadlullah, "Wideband Optical Propagation Measurement System for Characterization of Indoor Optical Wireless Channels," *Proc. SPIE*, vol. 7620, San Francisco, CA, Jan. 2010.

[21] G. Zorpette, "Let There Be Light," *IEEE Spectrum*, Sept. 2002, pp. 70–74.

[22] U.S. Dept. of Energy, "Solid-State Lighting Portfolio — Energy Savings Potential of Solid-State Lighting in General Illumination Applications," 2008; http://www1.eere.energy.gov/buildings/ssl/.

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