U.S. DEPARTMENT OF ENERGY

PNNL-19204

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Technology Forecast:

Using Solid-State Lighting for Wireless Communications

PM Aker

February 2010

Pacific Northwest
NATIONAL LABORATORY

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(U) Summary

(U) Colored and white-light LED (light-emitting diode) devices, commonly called solid-state lighting (SSL), are now considered excellent candidates for signage and overhead lighting applications. An interesting characteristic of a LED is that its output intensity can be modulated. This characteristic shows that SSLs could be used for wireless optical communications. This dual functionality has led many people to propose that SSLs could be used for a variety of new applications; ranging from short-range (<1 m) personal area networking (Scenario 1 in this report), through medium-range (<5 m), two-way, high-speed wireless internet connectivity using overhead SSLs (Scenario 3), to longer range (<100 m) one-way information broadcasting (Scenario 2).

(U) The proposal to use overhead SSLs for two-way, high-speed wireless internet connectivity is probably the most intriguing, but this application is unlikely to be commercialized because eye-safety restrictions will limit achievable communication rates to levels well below that currently provided by WiFi. It is interesting to note that eye-safety considerations also have prevented commercialization of high-speed overhead/diffuse wireless infrared communications.

(U) The proposal to use SSLs for short-range, high-speed personal area networking, specifically communication between two mobile devices such as cell phones or laptop computers, is in the process of being commercialized. We coined the term P2P VLC (person-to-person visible-light communications) to describe this technology, and we are highly confident that the technology will be adopted. Samsung has already demonstrated a prototype 320-Mbps version in their laboratory and has introduced the concept at a number of trade shows. The Institute of Electrical & Electronics Engineers, Inc. (IEEE) 802.15 WPAN (wireless personal area network) committee has had a Task Group 7 formulate a set of industry standards that are expected to be voted upon in early spring 2010. Once these standards are accepted, we expect mobile device manufacturers will make this technology available to the general public within a two-year time frame. There is excellent potential for this technology to achieve gigabytes per second (Gbps) data rates, meaning that large amounts of information can be exchanged during a simple "bump" between two devices. This extremely fast data-transfer feature may have an impact on national security, because the communications made at these transfer rates will be extremely difficult to intercept.

(U) The technologies for using SSLs for long-range, one-way broadcast communications is not as well developed as those for P2P VLC, but their development continues, primarily by the people participating in the IEEE 802.15 Task Group 7. At this time, the most promising short-term application for SSLs is associated with infrastructure needs (both indoor and outdoor) to broadcast to mobile receivers, primarily for situational awareness and information updating purposes. We expect that this technology, which we call long-range VLC, will be commercialized in parallel with P2P VLC because future mobile receivers will be able to be used for both short- and long-range applications.

(U) Another promising application for long-range VLC is in the area of intelligent transportation systems (ITS). Information broadcast from LED-based traffic lights to automobiles has been demonstrated in the laboratories of both Samsung and Intel, and strategies for implementing vehicle-to-vehicle communication for crash avoidance purposes are being considered. The time frame for the commercialization of these technologies is uncertain, however, because it will rely on national mandates

being passed to require state, provincial, and local governments to install ITS systems and collaboration between VLC device makers and automobile companies.

(U) This technology forecast is organized as follows:

- (U) In Chapter 1, we first present background information to help readers become familiar with parameters important to visible lighting design, which ultimately drives white-light SSL architecture and cost. We then present a brief history of visible LED development and discuss the financial and technical issues that are currently driving white-light SSL acceptance and the commercial market.
- (U) In Chapter 2, we present three scenario studies that outline how SSLs can be used for short-, medium- and long-range wireless optical communications strategies. The current state of the art of these technologies is presented, future evolution of the technologies is discussed, and technical parameters that will dictate the success of commercialization efforts are given.
- (U) In Chapter 3, we then follow with a technology forecast analysis for short-range P2P VLC and long-range VLC for situational awareness and ITS, and provide signposts that can be used to indicate how well the technologies are progressing.
- (U) In Chapter 4, we present an analysis of the commercial adoption of P2P VLC because it is the technology in which we have the most confidence.
- (U) In Chapter 5, we provide a short description of research activities underway in the area of LED modulation bandwidth enhancement; because this area will have the largest affect on information exchange data rates. The research activities section does not discuss ongoing efforts related to parameters that affect LED efficiency, white light color characteristics, lifetimes, and production costs, because these issues are not relevant to communications performance, rather they are more important to overhead white-light SSL commercialization and product adoption. We discuss only "inorganic" LEDs in this report and do not consider organic LEDs (OLEDs) because OLEDs have modulation response times in the msec or more range; therefore, they are not suited for wireless optical communications purposes.
- (U) In Chapter 6, we present the conclusions we drew from our analysis.

(U) Acronyms and Abbreviations

ADR	angular diversity receiver
Al aluminum	
As arsenic	
BER	bit error rates
CCM	color-coded modulation
CFL	compact fluorescent lamp
CMC	color multiplex coding
CRI	color-rendering index
DBR	distributed Bragg reflector
DMT	discrete multi-tone
DOE	U.S. Department of Energy
DSRC	dedicated short-range communications
FEC	forward error correction
FOV	field of view
Ga gallium	
Gbps	gigabytes per second
HBL	high-brightness LED
HID	high-intensity-discharge
IEEE	Institute of Electrical & Electronics Engineers, Inc.
In indium	
ISI	inter-symbol interference
ITS	intelligent transportation systems
LBS	location-based service
LED	light-emitting diode
lm lumen	
lm/W	lumens per watt
M-PAM	M-ary phase amplitude modulation
N nitride	
NFC	near-field communications
OFDM	orthogonal frequency division multiplexing
OLED	organic LED
OOK	on-off keying
P2P VLC	peer-to-peer visible-light communications
POF	plastic optical fiber
PWM	pulse width modulation

QAM	quadrature amplitude modulation
RCLED	resonant-cavity LED
RGB	red, green, blue
SI	International System of Units
SIG	special interest group
SSL	solid-state lighting
Tlm	terralumen
TTL	tagging and tracking and locating
UHB	ultra-high brightness
UV ultraviolet	
VCSEL	vertical cavity surface emitting laser
VLC	visible light communications
VLCC	Visible Light Communications Consortium
VL-ISC	visible light image sensing communications
WAVE	wireless access in vehicular environments
WDM	wavelength division multiplexing
WPAN	wireless personal area network
YAG	yttrium aluminum garnet

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Tables

1.0 (U) Background

(U) Solid-state lighting based on LEDs is a technology that is being rapidly adopted worldwide. Power efficiency and device lifetime are the primary drivers for this rapid evolution. In the past few years, low-power applications (i.e., portable device backlighting and auto signal lighting) have driven the commercial LED market. However, this situation this is changing rapidly as replacement SSLs for home and office task lighting are now available. While these replacement SSLs currently are expensive, improvements in the LED manufacturing process are expected to drive prices down. Expansion into the general lighting sector has started and is expected to grow significantly in the next few years as a result of the introduction of ultra-bright, white-light LEDs.

1.1 (U) Parameters Important to Visible Lighting and Performance

(U) In this section, we present parameters that describe visible lighting and lighting performance. White-light sources are typically categorized according to their luminous flux, which is a quantitative expression of the brilliance of a source that emits light with wavelengths between 390 and 770 nm. This quantity is measured in terms of the power emitted per unit solid angle from an isotropic radiator. The standard unit of luminous flux is the lumen (lm). Reduced to base units in the International System of Units (SI), 1 lm is equivalent to 1 candela steradian (cd · sr). This unit is the same as 1.46 milliwatt (1.46×10^{-3} W) of radiant power at a wavelength of 555 nm, which lies in the middle of the visible spectrum. For people who are not knowledgeable about optics, a lumen is best described by considering the output of standard 40-, 75-, and 100-W incandescent light bulbs. Bulbs with these watt ratings have lumen ratings of 500, 1200 and 1700 lm, respectively.

(U) Only visible light is useful for illumination, and some wavelengths are perceived as brighter than others. Taking this into account, luminous efficacy is defined as the ratio of the useful power emitted (in the 390- to 770-nm range) to the total electric power input, and is expressed as lumens per watt (lm/W). The maximum efficacy possible is 683 lm/W. Luminous efficiency is luminous efficacy divided by this maximum and is expressed as a number between 0 and 1, or as a percentage. Incandescent bulbs have luminous efficacies around 15 lm/W and efficiencies that range between 1.1 and 2.4%. Compact fluorescent bulbs have efficacies around 100 lm/W and efficiencies that range between 8.8 and 10.5% (Source: Wikipedia 2010, p. 21).

(U) When it comes to general lighting, illuminance (or illumination) is the parameter that designers consider. Illuminance is a measure of the amount of light falling on a surface and is quantified in lux (which equals 1 lumen per square meter), or footcandles (which equals 1 lumen per square foot). In the interior workplace or home, general illuminance levels range are typically specified to be between 200 and 800 lux, and task illuminance levels between 500 and 1200 lux or more. Outdoor illumination levels range from 1000 to 100,000 lux or more.

(U) Good lighting depends on more than just illuminance levels. The direction, distribution, color temperature, and color-rendering index of the source all contribute to effective lighting (and visibility). The task reflectance and contrast also contribute significantly. The determination of target illuminance levels is generally considered to be a starting point in effective lighting design.

1.2 (U) Brief History of LED Development

(U) LEDs are not new. In 1961, Baird and Pittman discovered that GaAs emitted infrared radiation when an electric current was applied. They applied for a patent for the device, and because there was considerable competition in this area, they did not make their results public (Biard and Pittman 1961). The first practical visible-spectrum (red) LED was developed in 1962 by Holonyak and Bevacques (1962). Within a decade after this development and as a result of research primarily conducted by Craford, yellow LEDs became available, and the brightness of red and red-orange LEDs was improved by a factor of 10 (Perry 1995). In 1976, Pearsall invented new semiconductor materials specifically adapted to optical fiber transmission wavelengths, thus leading to the first high-brightness, high-efficiency LEDs for optical fiber telecommunications (Pearsall et al. 1976).

(U) The first commercial visible-light LED products, which were introduced in 1968, were replacements for incandescent indicators, and seven-segment displays. The initial performance of these LEDs was poor (around 1 millilumen at 20 mA), and the only color available was deep red. Steady progress in efficiency made LEDs viewable in bright ambient light, and the color range was extended to orange, yellow, and yellow/green. Between 1970 and 2000, the luminous flux from packaged LED devices doubled roughly every two years as observed and projected by Roland Haitz. The so-called "Haitz's Law" is similar to Moore's law for transistor integration. This growth rate is shown in below in Figure 1.1.

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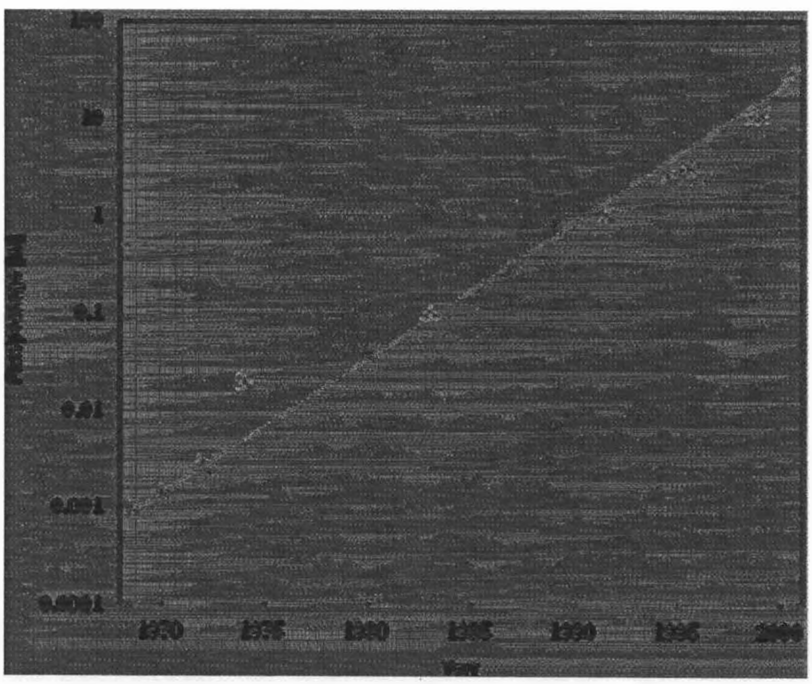

Figure 1.1. (U) Roland Haitz's Observations/Projections Showing the Approximate Doubling in LED Light Flux Every Two Years (Wikipedia 2009)

(U) Originally LEDs were limited to small-signal applications because their luminous flux was low. This situation changed in the mid 1980s when it was realized that improved efficiencies would open the market up to automotive applications. By 1990, GaAlAs efficacies reached 10 lm/W, thus exceeding those of equivalent red-filtered incandescent bulbs. More important, however, was the introduction of GaAlInP devices, which were capable of putting out yellow and green light with efficacies only slightly smaller than seen for the GaAlAs diodes.

(U) In 1993, a huge breakthrough was realized in LED technology, specifically the introduction of the efficient blue InGaN material. This advancement allowed high luminous flux to be achieved in the blue-to-green (430-to-530 nm) region, and as shown in Figure 1.2, with efficiencies surpassing those seen for GaAlInP.

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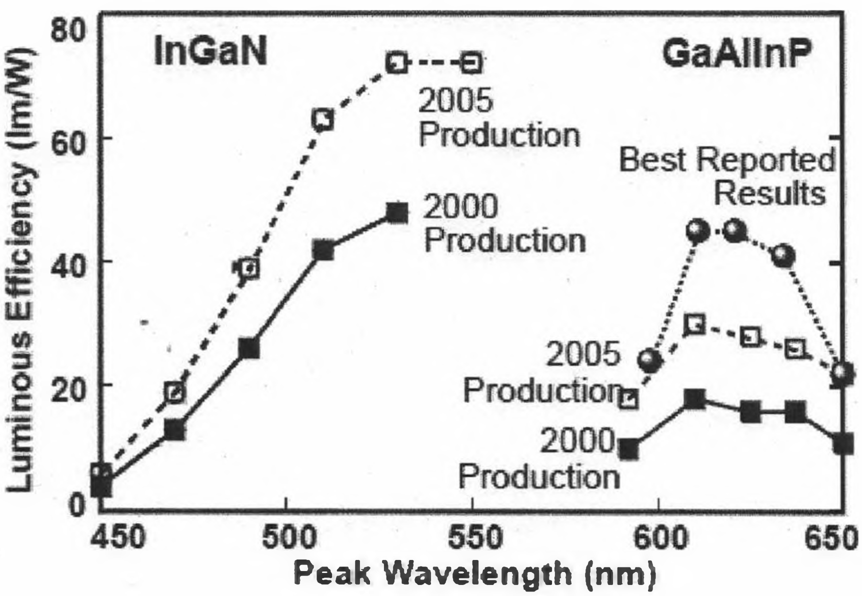

Figure 1.2. (U) LED Efficiency at a Junction Temperature of 85C° as a Function of Wavelength. Figure and results reported for 2005 are estimates presented by Haitz et al. (1999); see http://lighting.sandia.gov/ligh tingdocs/hpsnl_long.pdf .)

1.3 (U) White-Light LEDs

(U) The introduction of the blue LED opened the SSL market to white-light applications. Penetration into this particular market sector has been slow, however, because of technical problems related to white LED efficiency, lifetime, and, most important, production cost. This will be discussed in more detail below. As shown in Table 1.1, current applications, which span cell-phone keypads and backlighting, signs, and decorative lighting, still are dominated by "conventional" single-color LED devices. High-brightness LEDs (HBLs), which became commercially available in 1995, are only now starting to garner a larger share of the market, principally because of lower production costs. In 2008, HBL sales for lighting applications were $5.1 billion, with a volume of over 50 billion units.

Table 1.1. (U) Current LED Capabilities and Market Share

	Conventional LED	High Brightness LED	Ultra-High Brightness White LED
2008 Market Share	83%	15%	2%
Specifications:			
Electrical Power	< 200 mW	Up to 1 W	Up to 5 W
Luminous Efficacy	20 lm/W	> 30 lm/W	> 50 lm/W
Luminous Flux	1–3 lm	5–30 lm	> 100 lm
Packaging	Epoxy housing	Custom	Custom
Markets	Cell-phone keypad Cell-phone backlight Signs Decorative lights	Screen backlight Dashboard backlight Large Displays Task Lighting	Car headlamps High-end applications General Illumination
Cost (> 10000 units)	\$0.1–0.2/part	\$0.8–2.0/part	\$3.00 for 100 lm LED

(U) Applications for LEDs have followed their rising power and declining cost. Figure 1.3 shows the luminous fluxes required for different applications and recent times-to-market for mass production. Data from Table 1.1 and Figure 1.3 are from Perkins (2009).

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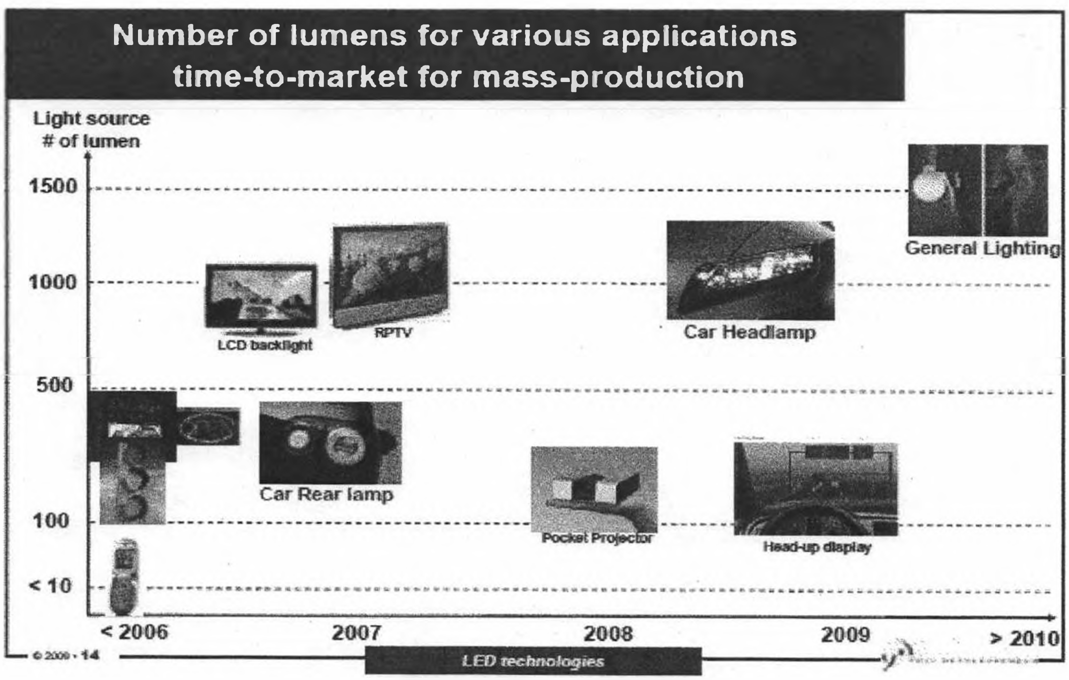

Figure 1.3. (U) Luminous Flux Required for Selected LED Applications and a Timetable for Becoming Commercially Available (Perkins 2009)

(U) White-light SSLs for general lighting are expected to be the next major application. The business case relates to the global lighting fixtures market, which is expected to reach \$94 billion in 2010; recent concerns over global warming; and a renewed attention on energy efficiency. Lighting is the second largest end-use of energy in buildings; in 2008, it accounted for about 22 percent of the total electricity generated in the United States and 342 million metric tons of CO_2 emissions (EIA 2009). Currently, incandescent lighting accounts for about 42 percent of the energy consumption (321 TWh/yr in 2001); fluorescent lighting accounts for about 41 percent; and high-intensity-discharge (HID) lighting accounts for about 17 percent. As we noted before, the luminous efficiencies of incandescent and fluorescent light are ~2 and 10 percent, respectively, which is not very impressive. Current white-light LEDs have luminous efficiencies ranging between 10 and 17 percent, and the efficiencies of this light source are expected to increase significantly in the next few years. Clearly a transition to SSL general lighting represents not only significant global energy savings, it also helps reduce greenhouse gas emissions. This leads one to wonder why white-light SSLs have not already achieved significant market penetration. The reason is twofold—cost and color—with cost being the primary hindrance.

(U) The pricing of lighting is typically compared on an initial price per kilolumen (klm) basis. A 60-W incandescent costs $0.30 per klm, a 13-W compact fluorescent lamp (CFL) costs $2 per klm, and a fluorescent lamp and ballast system costs $4 per klm. In contrast, the U.S. Department of Energy's (DOE) 2008 cost estimate for integrated LED lamps (luminares) was $170 per klm. This cost is 560 times the cost of an incandescent and 85 times the cost of a CFL (DOE 2009a). As Figure 1.4 shows, the most of the luminare cost is the LED package itself, with thermal management components and the power supply, running second and third, respectively.

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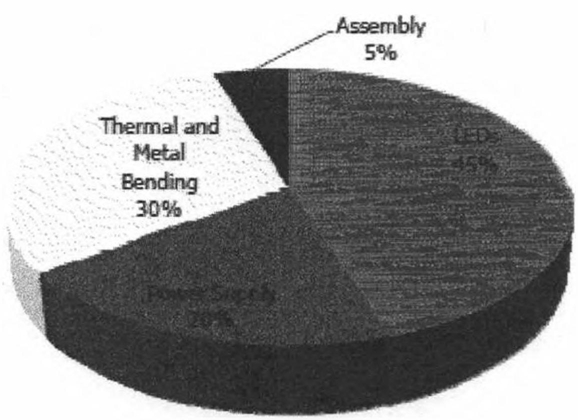

Figure 1.4. (U) Approximate Cost Breakdown for LED Luminare (Pickard 2009)

(U) The greatest potential for cost reduction is in reducing the costs of the LED package; however, the cost of the remaining components still need to decrease to make the SSL price competitive with incandescent and CLF lighting. After conducting several workshops with a variety of LED manufacturers, the DOE SSL manufacturing roadmap predicts that the LED package cost decrease by 87 percent within 6 years (see Figure 1.5).

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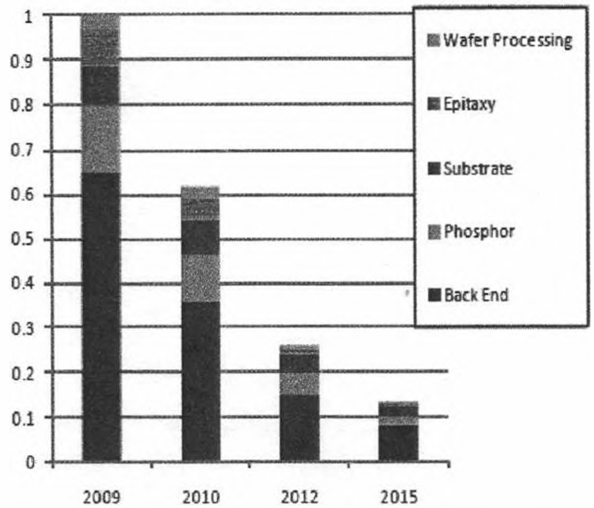

Figure 1.5. (U) LED Package Manufacturing Cost Breakdown and Projected Cost Tracks for Individual Processing Steps (DOE 2009b, p. 9)

(U) Power supply cost reductions are expected to come from higher-volume manufacturing that will come when an industry standard has been defined. Negotiations to define the standard currently are underway. Higher-efficiency LED SSLs, which is a current fundamental research focus, will reduce costs associated with thermal-management components, and reduce the number of LEDs needed to achieve the require illuminance level, which in itself is a further cost saving.

(U) Based on an analysis of these other parameters, DOE has predicted future LED and LED luminare efficacy and price out to 2015 (see Table 1.2). As can be seen, the initial luminare lighting cost in 2015 is expected to be around $28/klm. This is not as cheap as initial fluorescent lighting cost, which ranges from $2 to $4/klm, but the increase in lighting efficacy, to 188 lm/W, will more than compensate for the CFL efficacy, which currently is 100 lm/W. Note that here we compare cold white-light LEDs, which have a color rendering index (CRI) value between 70 and 80, with CFLs because the latter also have a low CRI.

Table 1.2. (U) DOE LED Package and Luminare Metrics Roadmap (DOE 2009b, p. 21)

Parameter	Unit	2009	2010	2012	2015
LED Efficacy (2800–3500K, >=85 CRI)	lm/W	83	97	114	138
LED Price (2800–3500K; 350 mA)	$/klm	46	25	11	4
LED Efficacy (4100–6500K, 70-80 CRI)	lm/W	132	147	164	188
LED Price (4100–6500K; 350 mA)	$/klm	25	13	6	2
OEM Lamp Price	$/klm	130	101	61	28

1.4 (U) White-Light SSLs for General Lighting Roadmap

(U) Given the savings in operating cost because of the increased efficiency, we expect white-light SSLs to start to dominate the general lighting market by 2015, and perhaps a year or two earlier because of the rapid progress currently being made in fundamental LED material science. However, there a caveat to this predication that relates to the quality of the light output by the luminares. The reason most people have resisted (and will continue to resist) using CFLs is that the color is unappealing. CFLs give off a blue hue that is called cold white light. On the other hand, incandescent lights give off a yellow hue that is called warm white light. For LEDs to gain better acceptance than CFLs, they will have to be able to produce warm white light with a hue that matches that of an incandescent light.

(U) As we mentioned earlier, good lighting depends on more than just illuminance levels. The direction, distribution, color temperature, and color of the source all contribute to effective lighting (and visibility). The visible mix rendered by the colors in light is called the CRI. A CRI number of 100, the color of pleasing Edison incandescence, is the gold standard for color. A CRI below 90 is noticeably unappealing to the eye. CFLs have CRI numbers in the 70s range, and for physical chemistry reasons, improvements currently are not possible.

(U) There are two primary ways of producing high-intensity white light using LEDs. One is to use individual LEDs that emit red, green, and blue light, which are the three primary colors, and then mix all the colors to produce white light. This approach is called multicolor LED, or RGB LED. The other method to produce white light is to use a phosphor material to convert monochromatic light from a blue or ultraviolet (UV) LED to broad-spectrum white light, much the way a fluorescent light bulb works. This approach is called dichromatic LED or phosphor-based LED.

(U) Several key factors that play among these two approaches include color stability, color rendering capability, and luminous efficacy. Often higher efficiency will mean lower color rendering, resulting in a trade-off that must be accepted between the luminous efficiency and color rendering. For example, dichromatic white LEDs that have the highest luminous efficacy (~130 lm/W) will have the lowest CRI (70 to 80). Conversely, although multi-color white LEDs have excellent color rendering capability (a CRI of 100 is possible), they often have poor luminous efficiency, primarily because the green LED used in this device currently has low efficacy. It is anticipated that this deficiency will improve with further research efforts.

(U) Because RGB LED luminares require sophisticated electronic and optical subsystems to control the blending and diffusion of different colors, this approach has rarely been used to mass produce white-light SSLs. Nevertheless this method is particularly interesting to "smart" lighting design engineers because of the flexibility of mixing different colors. In principle, this mechanism also has higher quantum efficiency in producing white light when compared with the dichromatic blue LED/phosphor approach. Therefore, with improvements in green LED efficiency, these devices may achieve much more market penetration in the future. The DOE SSL program estimates that if improvements in green LED efficiency can be made, an RGB luminare could have an efficacy of 198 lm/W. It also is interesting to note that if general lighting SSLs are going to be used for visual light communications (Scenario 3 in Section 2), the RGB devices offer higher data rate potential as a result of the ability to do color coded modulation (which is a variant of wavelength division multiplexing).

(U) In the phosphor-converting blue LED approach, an LED emits blue light generally at about 460 nm, and some of this light is down-converted to longer wavelengths by a phosphor coating, typically a Ce^{3+}:YAG (yttrium aluminum garnet) compound, which broadband emits between 500 and 700 nm. This produces white light with a low CRI. Some manufacturers have successfully increased the CRI by adding a second phosphor, typically a europium-doped nitride or sulfide, to the package, but at a cost to package efficacy. Another approach, taken by Philips Lumileds (Luxeon product line), involves combining three cool-white, phosphor-based LEDs with one or two amber LEDs. The resulting bulb, known as the "Pharox" replacement bulb, has a CRI greater than 85.

(U) Phosphor-based LEDs have a lower efficiency than normal LEDs because of heat loss from the Stokes shift, and they also have shorter lifetimes because of phosphor degradation. However, the phosphor LED method is still the most popular technique for manufacturing high-intensity, white-light SSLs because the design and production of a light source or light fixture using a monochromatic emitter with phosphor conversion is simpler and cheaper than the complex red, green, blud (RGB) system. Research on improving phosphor conversion efficiencies and lifetimes is underway. The DOE SSL program estimates that, with improvements in these areas (and others related to blue LED efficiency and light-extraction improvements), a phosphor-based LED luminaire could have an overall efficacy of 147 lm/W.

(U) Cree LED Lighting Solutions, Inc. has just reported (Cree 2009) new R&D results for an ultra-high brightness (UHB) white LED. The UHB LED produced 197 lumens of light output and achieved 186 lm/W efficacy at a correlated color temperature of 4577 K. The tests were conducted under standard LED test conditions at a drive current of 350mA at room temperature. The CRI was not measured, and the device contained a chip measuring 1.4×1.4 mm (i.e., 2 mm^2). The chip size is important when trying to compare results, because a larger chip at the same current has lower current density (i.e., this is what gives the device enhanced performance). It is important to emphasize that this is a laboratory result and that this level of performance is not yet available in Cree's production LEDs. However, history shows that the scale-up of new research and development results into production can occur in a remarkably short time.

1.5 (U) LED Manufacturers and LED Materials Supplies

(U) The major LED players are GE Lumination (joint effort between General Electric and Nichia with headquarters in Valley View, Ohio), Cree LED Lighting Solutions, Inc. (headquarters in Durham, North Carolina), Philips Lumileds (headquarters in San Jose, California), and Siemens-Osram (headquarters in Regensberg, Germany). All of these companies have dedicated technology centers, located primarily in the United States, Germany, and Japan, and manufacturing facilities located in the United States, Singapore, China, and Malaysia. While these four companies dominate the market there are still a large number of minor players (Maxim 2010).

(U) All of the major LED players have phosphor-production and research facilities; however, because new intellectual property developed in this area is rich for patenting, several independent phosphor producers exist. These include Mitsubishi, TG, Tridonic, Intematix, Sarnoff, Seoul Semiconductors, and Dowa.

(U) The main "ingredients" for LED chips are gallium (Ga), arsenic (As), indium (In), aluminum (Al), and nitride (N). There is a question about whether the planet has enough gallium to light the world with GaN-based LEDs. Sandia National Laboratories has studied this issue in detail and has concluded that there is enough gallium to support this application (SNL 2004). Assuming a worldwide need for 8 terralumen (Tlm) of new lighting (i.e., LED-based lighting would be phased in over time, as opposed to instantaneous conversion) each year, LED luminous efficacies of 150 lm/W, GaN wafers as the production substrate (this is a worst case scenario), and 50% efficiency use of mined gallium, 50 tons of gallium would be needed annually.

(U) The U.S. Geological Survey (USGS) reported in 2008 that worldwide gallium production was 184 metric tons, refinery capacity was 167 tons, and the recycling capacity was 78 tons (USGS 2009). The non-LED electronics industry currently uses about 100 tons of gallium annually, so there is a more than an adequate supply of gallium to light the world with LEDs.

(U) Gallium is found and extracted as a trace component in bauxite and, to a small extent, from sphalerite. The amount extracted from coal, diaspore, and germanite, which also contain gallium, is negligible. The USGS estimates that world gallium reserves exceed 1 million metric tons, based on 50 ppm by weight concentration in known reserves of bauxite and zinc ores. Reserves in the United States are estimated at 15,000 tons. It is interesting that the United States currently imports all of its gallium from foreign sources, with 17 percent coming from China, 17 percent from the Ukraine, 16 percent from Germany, 14 percent from Canada and 36 percent from other countries.

1.6 (U) White-Light SSLs for General Lighting – Geographic Differences

(U) The adoption of white-light SSLs for general lighting will most likely follow the phase-out of incandescent lighting that has been called for by a number of national and local governments. In some jurisdictions, this has been done, or is being done, by legislation, while in other jurisdictions, voluntary measures have been used. Given the current high introduction price of white-light SSLs, it would seem that the highest rates of adoption will be in areas where legislation has passed. It should come as no surprise that this has occurred mainly in economically advantaged nations.

(U) Brazil and Venezuela started to phase out incandescent lights in 2005, and other nations are planning scheduled phase outs.

- Australia, Ireland and Switzerland in 2009
- The European Union in general between 2009 and 2012
- The Philippines by 2010
- Argentina, Italy, Russia, and the United Kingdom by 2011
- Canada and Japan by 2012
- The United States by 2014.

(U) Russia has announced that phase-out plans will begin in 2011 and end by 2014, and China has plans to phase out by 2017. India has not legislated incandescent light phase outs but has plans to replace 400 million incandescents with CFLs by the year 2012.

2.0 (U)Scenario Studies

(U) Colored and white-light LED devices have been widely adopted in niche markets that include indoor task and specialty lighting, outdoor architectural lighting, full-color displays (signage), traffic lights, and automobile (or boat) signaling. As a result of improvements in semiconductor materials science, new classes of high-brightness LEDs (HBLs) are beginning to penetrate the lighting sector. These devices offer higher power efficiency, longer lifetime, higher tolerance to moisture and vibration, lower heat generation, and smaller size when compared with conventional lighting sources. As a result, SSLs are now considered excellent candidates for general lighting applications in the future.

(U) An interesting intrinsic characteristic of a LED is that its output intensity can be modulated, which is a characteristic that can be used for wireless optical communications. This dual functionality led several academic and industrial groups to propose using dedicated device-based LEDs or general SSL fixtures as wireless routers for information transport. Figure 2.1 conceptualizes several different networking scenarios based on this approach. Some people have speculated that data rates in the Gbps range and transmission distances on the order of hundreds of meters might be achievable using this technology. Much excitement was generated by the possibilities of this new application, which is now known as visible light communications (VLC).

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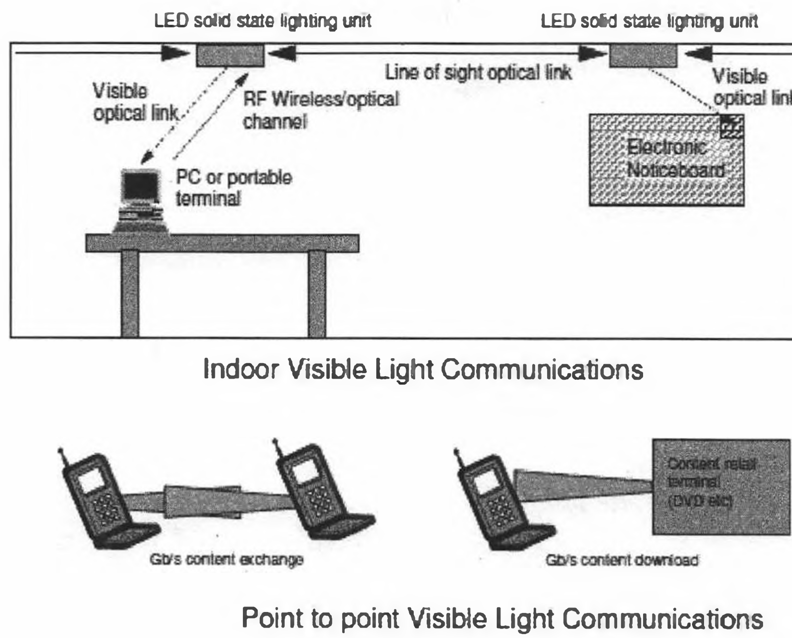

Figure 2.1. (U) Concepts for Future Wireless Optical Networking Platforms (O'Brien et al. 2006)

(U) The data rate and ranging expectations for VLC have been scaled back considerably since the late 1990s and early 2000s. This scaling back of expectations has resulted from experimental observations of prototype systems built using commercially available LEDs or SSL devices, more robust approaches to theoretical modeling of different physical configurations, and practical considerations regarding implementing the technology in real world situations (i.e., eye safety limits on optical intensity levels, intermittent link loss due to moving objects, and shadowing).

(U) Despite these practical constraints, several industrial groups and a number of government agencies (local and foreign) have decided to move forward with developing new products/protocols that feature VLC technology. Two forerunning applications, the first that should have wide market adoption within the next 2 to 5 years and the second that should enter the commercial market within 5 years are 1) the use of "short-range" (i.e., < 20 cm range) VLC for peer-to-peer (P2P) information exchange, and 2) the use of "long-range" (i.e., up to 300 m) VLC for situational awareness (i.e., intelligent traffic systems) or advertisement/tagging applications. Industry dedication to near-term global introduction of these two VLC technologies is evidenced by the fact that two special interest groups (SIGs) have been formed to develop standards for these new communications systems. These SIGs are the Visible Light Communications Consortium (VLCC) (http://www.vlcc.net/e/index.htm l) and the IEEE 802.15 Working Group for WPAN – Task Group 7 (http://www.ieee802.or g/15). Details about these groups can be found in Appendices A and B. Below we will outline the current state of these technologies, discuss what advances will need to be made for global adoption, and predict new applications that are expected in the mid- and long-term time frames.

(U) A third VLC application that is being considered is using overhead white SSLs for indoor wireless local area networking. Current research in this area is confined primarily to the academic community, and rapid strides in increasing achievable data rates have been made in just the last 2 years. From a purely technical perspective, it would appear that this could be an emerging technology that could be introduced in 4 to 8 years. However, comparison with progress made in wireless infrared communications and consideration of eye-safety issues indicate that it is unlikely that this technology will be adopted.

2.1 (U)Scenario 1 – Short-Range VLC for Wireless P2P Information Exchange

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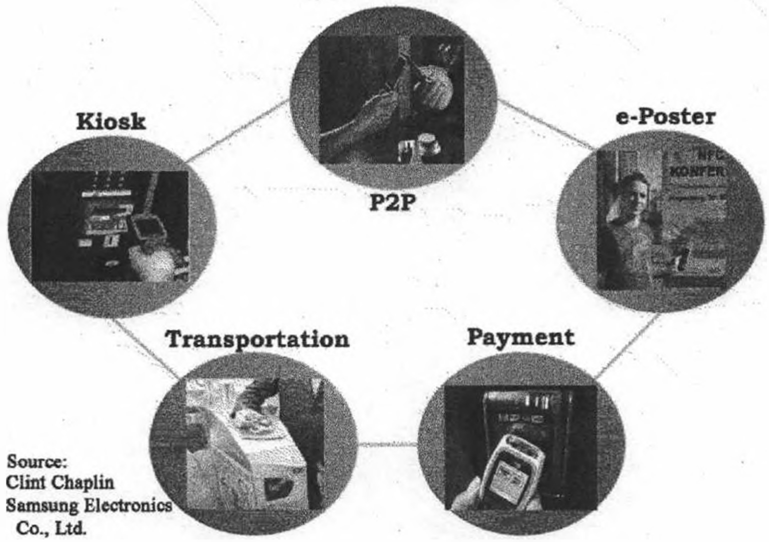

Figure 2.2. (U) Applications Envisioned for Short Range PDP Information Exchange (Chaplin 2008)

(U) Wireless short-range (generally considered less than 5 meters) communications has undergone tremendous evolution in the last decade. Figure 2.2 illustrates concepts currently being proposed for short-range P2P VLC. If VLC is to be used for this application, it must be able to deliver services comparable with that offered by line of sight infrared (commonly referred to as IrDA), Bluetooth, WiFi, and near-field communications (NFC). Table 2.1 summarizes the current state of the art of these four technologies, as well as performance information recently reported by Samsung for VLC (Chaplin 2008). As can be seen, the current capabilities of short-range VLC are competitive with IrDA, NFC, and Bluetooth. This comparison demonstrates why industry has already decided to introduce this new technology to the general market, and we expect to see devices in stores within 2 years.

Table 2.1. (U) Existing Wireless Communications Technologies

Name	Source	Bit Rate	Range
IrDA	Infrared, ~ 850 nm	2.4–16 Mbps, 1 Gbps coming	< 1 m
Bluetooth	RF, 2.4 GHz	1–3 Mbps	10 m
WiFi	RF, 2.4 and 5 GHz	5–144 Mbps	15–90 m indoors, 30–300 m outdoors
NFC	Magnetic field induction, 13.56 MHz	106–848 kbps	10 cm
VLC	Visible LED 380–780 nm	4 or 10 Mbps (IEEE, VLCC), 320 Mbps (Samsung)	< 10 m < 1 m

(U) Samsung has recently reported that it demonstrated 320 Mbps VLC between two PDAs in the laboratory (see Figure 2.3). If this configuration can be transitioned to realistic environments, then it can be anticipated that short-range VLC will overwhelm WiFi.

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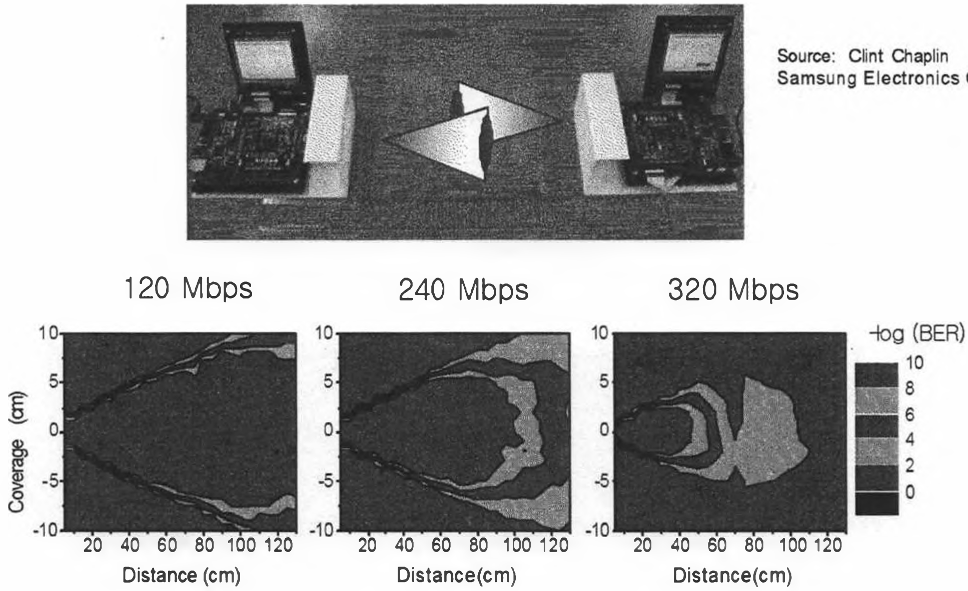

Source: Clint Chaplin
Samsung Electronics Co., Ltd.

Figure 2.3. (U) Samsung Laboratory Demonstration of VLC Between Two PDAs (Chaplin 2008)

(U) Current short-range VLC applications that device manufacturers are envisioning include 1) mobile-to-mobile device content sharing and data transfer (i.e., sharing pictures between cell phones or data between laptops) and 2) fixed-device-to-mobile-device file transfer (i.e., video streaming, and m-commerce). The advantages that VLC offers over the other technologies, at least according to what the VLC community is saying, include freedom from current radio frequency band regulation, suitability for operating in RF-sensitive environments, low power demand, intuitive alignment, and subsequent visible evidence of security—IR and RF cannot be detected by the human eye; therefore, users cannot be certain where their information transfer vectors are pointed). The VLC community has been especially aggressive at touting that the latter feature makes VLC ideal for interception-sensitive situation. Their mantra has been, "What you see is what you send." As we will discuss below, this is not necessarily true.

(U) International standards for short-range VLC P2P communications currently are being developed by the IEEE 802.15 WPAN Task Group 7, which includes members from the VLCC (i.e., Japan), Korea, the United States, and the European Union. (It is interesting that members from China, Russia, and Australia have not participated in this particular group, even though they have participated in other groups formed under IEEE 802.15 WPAN.) There appear to be minor technical issues that currently are being resolved, but looking at the considerable progress this group has made since it was officially formed in January 2009, we expect a formal standards document to be voted on early in 2010.

(U) With regard to the technical issues, the first one pertains to deciding whether to advance the technology using a single "white" light color band (i.e., 380 to 780 nm), or to enable data transmission using three (i.e., RGB) or seven (i.e., blue, blue-green, green, yellow, red-orange, red, and far-red) color bands. The argument for adopting the single band scheme is design simplicity, cost reduction (a single common transceiver will not require narrow band filters on the receive side), and the ability to transition the short range P2P VLC standards to future overhead SSL VLC systems (this assumes that general lighting SSLs will be based on blue LED/yellow phosphor technology). The arguments for adopting a multiple color band strategy include the enhancement in data rate that would come from color code modulation (i.e., a modulation technique somewhat like wavelength division multiplexing [WDM] except that information is transmitted as the intensity ratio among RGB and not the individual RGB absolute value that WDM uses) and enhancement in signal-to-noise ratio (and hence ranging or data rate) that comes from using color filters on the receive side to reject interfering ambient white light. The arguments against using a multiple color band scheme are primarily increased cost (more components in each transceiver), reduced reliability because different color LEDs chips have different aging behaviors (a proposal to solve this problem has been submitted by Joachim Walewski of Siemens/Osram), and increased electronics complexity because the wavelength dependence of the silicon receiver response will cause separate channels to have different signal-to-noise ratios. Despite these disadvantages, the most recent proposal that the IEEE 802.15 WPAN Task Group 7 has put forward indicates that a consensus has developed for using a three-color RGB transmission technology, primarily because faster data rates can be achieved.

(U) A second issue regarding VLC technology standards adoption concerns the modulation format. Normally, we would not expect this to be a problem, and it would simply be a matter of choosing between the on-off keying (OOK; note that this is the only way a LED can be modulated because the device is not amenable to wavelength modulation) formats developed for RF or IrDA. However, it was recognized early on that if the standards developed for short-range VLC were going to be applicable to long-range VLC from signboards or traffic lights (Scenario 2) or overhead general lighting SSLs (Scenario 3), then a modulation scheme would have to ensure that the DC content of an OOK VLC transmission was held constant to keep the LED light source illumination level stable (i.e., to prevent "flickering" that would result from different data patterns or data frame headers and footers). It also was recognized early on that the modulation format must be able to accommodate an SSL dimming control scheme. With regard to the latter requirement, no standard has been formally adopted but it appears that a pulse width modulation (PWM) scheme has wider acceptance than a forward current reduction scheme.

(U) Based on the latest consensus proposal put forward, it appears that IEEE 802.15 WG7 will move forward with adopting a DC balancing "line code" approach for LED modulation. Several candidates have been proposed, including Manchester, 4B6B, 8B10B, and 4, 8, and 16 color-coded modulation (CCM). Table 2.2 outlines the specific modulation schemes, data rates, and forward-error-correction formats proposed for what is called the PHY II feature that has been developed for short-range (i.e., up to 3 m), high-rate VLC.

(U) It is interesting to note that the IEEE 802.15 TG7 emphasis on developing VLC communications standards will be compatible with general lighting requirements. This suggests that some members on this committee clearly expect that overhead general lighting SSLs will be used for wireless networking in the future (Scenario 3 in this report). This is interesting given that the most active members on this committee are industry-based scientists from Samsung Electronics, Intel, Siemens, France Telecom, Panasonic, Toshiba, Sharp, and NEC. The committee members from academia are from Oxford University, California State University of Sacramento, Fraunhofer Institute for Telecommunications, and the Electronic and Telecommunications Research Institute (Korea).

Table 2.2. (U) Data Rates and Modulation Schemes for PHY II and CCM VLC (P802.15 2009)

	Optical Rate	Modulation	Line Coding	Forward Error Correction (FEC)	Data Rate
PHY II	6 MHz	VPM	4B6B	4/5	3.2 Mbps
	12 MHz	VPM	4B6B	4/5	6.4 Mbps
	24 MHz	OOK	8B10B	1/2	9.6 Mbps
	60 MHz	OOK	8B10B	1/2	24.0 Mbps
	60 MHz	OOK	8B10B	4/5	38.4 Mbps
	120 MHz	OOK	8B10B	4/5	76.8 Mbps
	120 MHz	OOK	8B10B	1	96.0 Mbps
CCM	12 MHz	4 CCM		1/2	12.0 Mbps
	12 MHz	8 CCM		1/2	18.0 Mbps
	24 MHz	4 CCM		1/2	24.0 Mbps
	24 MHz	8 CCM		1/2	36.0 Mbps
	24 MHz	16 CCM		1/2	48.0 Mbps
	24 MHz	8 CCM		1	72.0 Mbps
	24 MHz	16 CCM		1	96.0 Mbps

(U) Probably the most pressing limitation of current short-range VLC technology is the data-rate limitation imposed by a specific LED response (although this is obviated somewhat by using color coded modulation). Samsung has currently reported a data rate of 320 Mbps using a custom red, resonant-cavity LED (RCLED). Current green and red RCLEDs from Nichia are apparently capable of transmitting ~ 250 Mbps. We expect these rates to increase to perhaps 500 Mbps in near future with further improvement to RCLED devices currently being developed for plastic optical fiber (POF) applications. We suspect that short-range VLC Gbps rates be possible in the future. Walter et al. (2009) just reported fabricating a tilted-charge AlGaAs (1 μm) LED having a –3 dB response at 7 GHz. If this approach can be transitioned to InGaN or AlGaInP devices, then Gbps communications will be possible, and the adoption rate of short range P2P VLC will be very fast. This research will be discussed in more detail in Section 6.

(U) From a security perspective, wireless P2P VLC *ad hoc* networks are no different from any other wireless network. As illustrated in Figure 2.4, they are vulnerable to passive eavesdropping attacks and potentially even active tampering because physical access to a wire is not required to participate in communications. Because the LED light transmitting the information has a fairly large angular divergence, light scattered off, or sent past, a receiving device can be easily intercepted with a telescope-type receiver. Interpretation of the intercepted signal will be fairly easy with the VPM and OOK modulation schemes listed in Table 2.2. CCM signals might be a bit more difficult to interpret if interception is done by looking at scattered light because scattering off different materials is wavelength dependent. But this effect could probably be mitigated using post collection signal processing.

(U) The IEEE 802.15 WG7 has considered the issue of security, not from an optical perspective but from an encryption perspective. They acknowledge that an *ad hoc* VLC network has constraints that severely limit the choice of cryptographic algorithms and protocols, and it looks like the cryptographic mechanism they favor, including in the standards document, is based on symmetric-key cryptography that uses keys provided by higher-layer processes.

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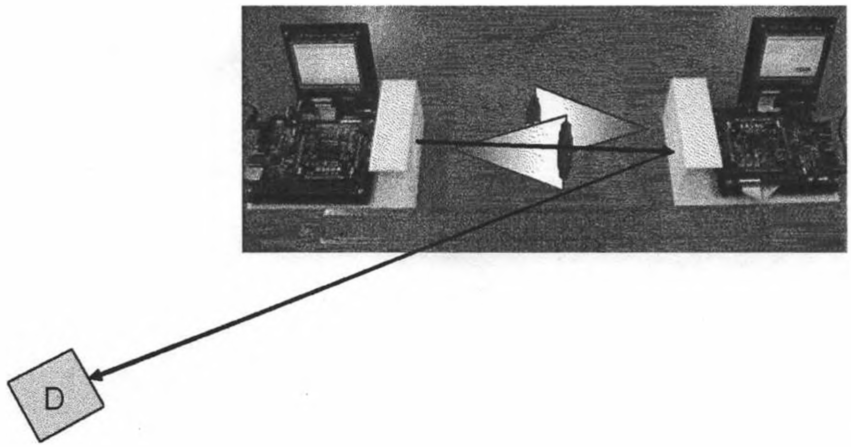

Figure 2.4. (U) Light Scattered Off a Receiving Device can be Easily Intercepted with Any Number of Telescope/Receiver Type Systems. Interception will necessarily be short range; however, because the light levels sent from various devices will be low because compliance with eye-safety standards will be necessary.

2.2 (U) Scenario 2: Long Range VLC for Situational Awareness and Intelligent Transportation Systems (ITS)

2.2.1 (U) First Generation One-Way Broadcast

(U) The root of this concept is to use SSLs associated with infrastructure (both indoor and outdoor lighting) for broadband information broadcasting. The first-generation systems being planned today are for one-way, fixed-broadcast to mobile receive. Broadcast ranges and the data rates are anticipated to be in the tens of meters and from 6.25 to 400 kbps, respectively. Because flickering light sources are not wanted, the IEEE 908.15 WG7 has suggested adopting a DC balanced coding mechanism. Table 2.3 lists the data rates, line coding, and modulation schemes for what they define as the PHY-1 layer of standardized VLC.

Table 2.3. (U) Data Rates and Modulation Schemes for PHY-1 VLC (P802.15 2009)

Optical Rate	Modulation	Line Coding	FEC	Data Rate
200 kHz	OOK	Manchester	1/16	6.25 kbps
200 kHz	OOK	Manchester	1/8	12.55 kbps
200 kHz	OOK	Manchester	1/4	25.00 kbps
200 kHz	OOK	Manchester	1/2	50.00 kbps
200 kHz	OOK	Manchester	1	100.00 kbps
600 kHz	VPM	4B6B	1/2	200.00 kbps
600 kHz	VPM	4B6B	1	400.00 kbps

(U) Applications that are currently being discussed include indoor navigation and individualized information exchange. Figure 2.5 outlines the concept behind indoor navigation. A map is downloaded at the building entrance, and selected LED lights located within a building are given unique modulation frequencies that serve to identify them. The mobile device "reads" the LED identification, and tells the user where they are in the building.

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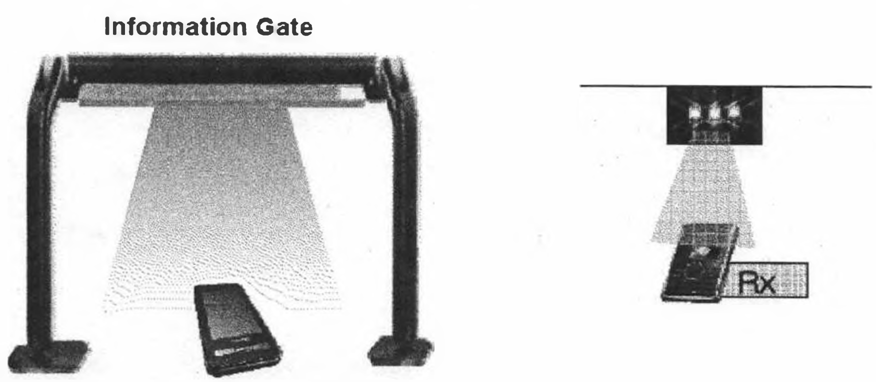

Figure 2.5. (U) Concept for VLC-Based Indoor Navigation (Bae et al. 2008)

(U) Samsung, which is second in mobile phone sales, is promoting this application rather heavily. Cell phones are already equipped with GPS, but GPS technology does not work well indoors. The next generation cell phone is expected to be able to provide not only GPS but also location-based service (LBS). Current LBS technologies include IR, RF and RFID, and UWB, but significant adjustments in infrastructure would need to be implemented to use these technologies, which also are generally quite power hungry. The VLC-based solution requires less power, and it also is simpler to install because it only requires replacing existing light bulbs with LED bulbs that have been preprogrammed to modulate at a specific frequency. The VLC-based solution also offers enhanced sales and marketing applications, because with simple programming changes at the entry ports, consumers can be informed of daily specials at specific restaurants or of sales at certain stores.

(U) Once VLC mobile phones or PDAs have medium-to-widespread acceptance by the general public, which we expect to occur within the next 2 years, indoor VLC navigation, and information broadcasting will most likely be rapidly embraced by large shopping malls, business complexes, big-box retailers, etc. We expect this technology to be introduced first in Asia because new mobile device technology acceptance is strongest there. We expect that this new technology will be adopted quite rapidly in the European Union and in North and South America.

(U) Another application being considered for first-generation, long-range VLC is related to individualized information exchange. This application is especially suited for environments that are sensitive to noise or RF. As depicted in Figure 2.6, overhead LED lights can broadcast site-specific information, such as details about displays at a museum, or medical records in hospitals, although the latter would require the LED to be connected in some way to a local area network.

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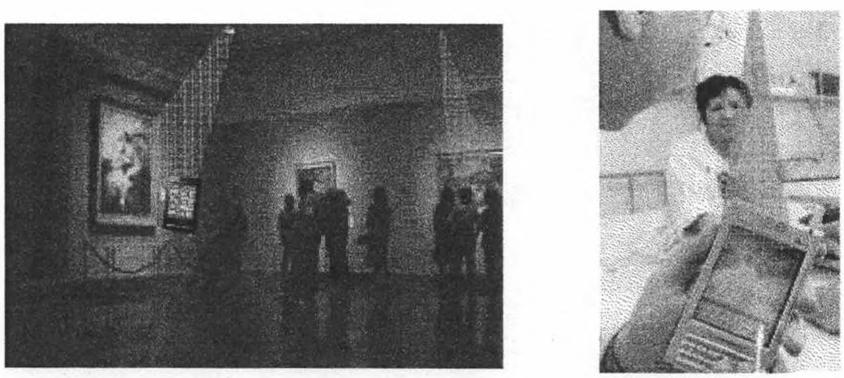

Figure 2.6. (U) Other Applications Anticipated for First-Generation Long-Range VLC (Bae et al. 2008)

(U) Long-range VLC in one-way broadcast mode is, by its very nature, vulnerable to interception. Alternatively, this communication technology enables "anonymous" message spreading in that the entryway portal could be outfitted with a second, uniquely colored LED (UV, for example) that can be programmed to send a message different from that designed to be sent to the general public. A mobile receiver outfitted with a specific optical filter and receiver would be capable of gathering this hidden message.

2.2.2 (U) Second-Generation, Long-Range VLC – Tagging and Tracking and Locating Applications

(U) There are two second-generation long-range VLC technologies that are being considered. The first technology is related to tagging and tracking and locating (TTL), and the second to intelligent transportation systems (ITS).

(U) The TTL application, as initially proposed by optical engineers at NEC and Casio, combines image sensing (using large-pixel-count, complementary metal-oxide-semiconductor cameras) with LED tags (i.e., LEDs preprogrammed to modulate at a specific frequency) to provide location information. This concept is illustrated in Figure 2.7.

(U) It appears that NEC's rationale for advancing this concept is that it can be used for package/item tracking in large warehouses, as conceptualized in Figure 2.8. The 5-cm resolution afforded by this technique (acquired using a 640 × 480 2400-fps camera) is somewhat better than the 15-cm resolution offered by RFID tagging technology.

(U) It is difficult to see how this technology will achieve widespread market acceptance because of its cost. Passive RFID tags now cost less than $0.06 per tag, and the readers cost between $20 and $5000 per unit, depending upon the ranging requirements. The LED tag, however, must contain not only the LED chip and optics but also a power source, making the cost probably at least 10 to 20 times more than the cost of a passive RFID tag. Also, the 2400-fps camera is currently a one-of-a-kind laboratory instrument.

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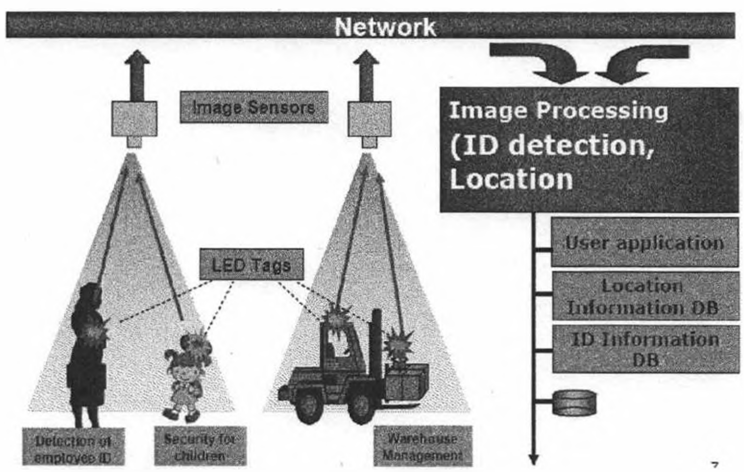

Figure 2.7. (U) Concept Behind Using LED Tags with Image Sensing to Provide Location Information (Suzuki 2008)

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Application for Warehouse Management

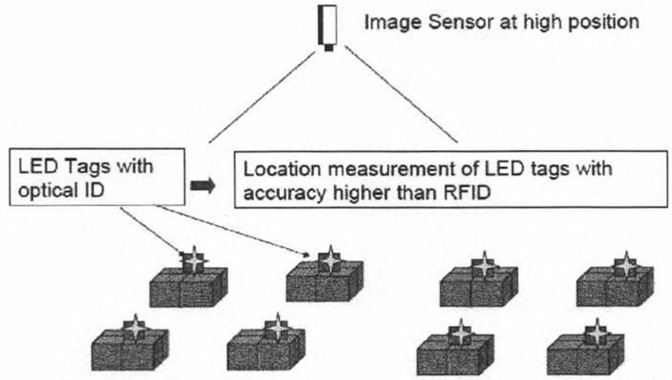

Figure 2.8. (U) Conceptualization of LED Tags for Warehouse Management (Suzuki 2008)

(U) While combining imaging sensing with VLC, which is known as visible light image sensing communications (VL-ISC) will probably not be feasible in the warehouse-management sector, it may play a role other TTL applications, provided that the scenario can accept that the subject is knowingly tagged. Another use for VL-ISC may be in ITS. However, we do not expect this application to realized in the near future because the data rate and modulation standards for long-range VLC that the IEEE 802.15 WG7 has proposed do not include the low rates (~ 1200 bps or less) that can be achieved currently with existing imaging equipment.

2.2.3 (U) Second-Generation, Long-Range VLC – Intelligent Transportation Systems

(U) In an ITS, information and communications technologies are combined with transport-infrastructure http://en.wikipedia.org/wiki/Vehicleinformation to manage vehicles, loads, and routes. The goal is to improve safety and reduce vehicle wear, transportation time, and fuel consumption. Interest in implementing ITS technologies is driven mostly by the need for solutions to problems caused by traffic congestion. It is further motivated by homeland security concerns because some of the proposed ITSs would be able to provide roadway surveillance.

(U) Applications associated with ITS are quite varied and include basic management functions, such as car navigation, electronic toll collection, dynamic traffic signal control, container management systems, variable message signs, automatic license plate recognition, and speed cameras, to more advanced applications that integrate live data and feedback from a number of other sources, such as parking guidance and information systems, weather information, bridge deicing systems, and collision avoidance. Sensors have already been installed on highways in Japan to notify motorists that a car is stalled ahead.

(U) As envisioned by the U.S. Department of Transportation and the Intelligent Transportation Society of America, ITS will use dedicated short-range communications (DSRC) in the licensed ITS band of 5.9 GHz (5.85 to 5.925 GHz) for communication between vehicles and roadside infrastructure at distances up to 500 meters. Currently, the IEEE is crafting a draft amendment, IEEE 802.11p, to add wireless access in vehicular environments (WAVE). The amendment defines enhancements to 802.11 that require support of ITS applications.

(U) While WAVE is currently RF-based, initially it was recognized that there could be a role for VLC in ITSs because traffic lights (i.e., roadside infrastructure) and automotive signal and brake lights (and soon headlights) are LED based. Both the VLCC and members of the IEEE 802.15 WG7 have proposed new applications and, in some cases, have demonstrated preliminary proof of concepts.

(U) Intel and an academic group at Multimedia University in Cyberjaya, Malaysia, have modeled data transmission from an LED-based traffic light to a hypothetical receiver situated in the center of the front window of an automobile. Intel's result, which presumes there is no optical filter on the receiver side, indicates that data rates up to 50 kbps can be transmitted out to 100 meters (Roberts et al. 2009). The Multimedia University group (Lee et al. 2008a) modeled a dual-filter receiver, and they showed that rates up to 3 Mbps could be transmitted out to 100 meters. Both of these studies, albeit theoretical and exclude adverse weather conditions, indicate that sufficient information can be transmitted during the time an automobile approaches a traffic light to provide timely warning of adverse conditions ahead. The IEEE 802.15 WG7 has used these results to propose standards for VLC-ITS. These standards are the 25-to-400 kbps, PHY-I data rates and modulation protocols listed in Table 2.3.

(U) The first application being envisioned (primarily by ETRI, Casio and Intel) for VLC-ITS is one-way LED traffic-light-to-vehicle communication, which is depicted in Figure 2.9. Information broadcast, also known as telematics, from the light most likely will include:

- Red light interval time (audio), instructions for idle stop (future)
- Car black box (save traffic signal information), check stored data after accident
- Road rules/conditions/hazards ahead (audio)
- Location (audio).

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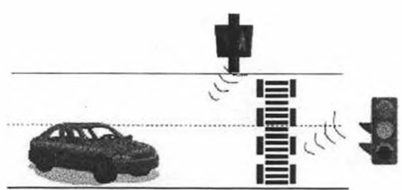

- Alarm to vehicle: stop
- Indication to vehicle: go
- Providing location information to vehicle

Figure 2.9. (U) Envisioned Information Broadcast from Installed Traffic Lights (Kang et al. 2008)

(U) At first glance, it is difficult see how the second-generation, long-range VLC from traffic lights/signs will gain much share in the ITS market. It is entering late into a sector that is already dominated by wireless 5.9-GHz RF. In addition, it has shorter ranging (100 m vs. 500 m), it requires line-of-sight transmission, and it will be ineffective in adverse weather conditions, which is when it will be needed the most. On the other hand, the cost to implement this technology in already existing roadside infrastructure is low. LED-based traffic lights and existing illuminated road signs will only need to be retrofitted with chips to modulate the source, whereas RF transmitters would have to be installed at each traffic light/sign position designated to be an information broadcast station. Given a state or federal mandate to install ITS and a choice of cost, one can be certain that local officials will chose the lowest cost alternative.

(U) Despite the current limitations that VLC has for ITS, Intel, Samsung, Casio, NEC, and Toshiba have all been very active in promoting this technology to the IEEE 802.15 WPAN committee, so it appears that these major industry leaders are prepared to move forward with a commercial introduction of ITS technology. We suspect that these companies are doing so, in part, because of the success they anticipate in providing low-cost, one-way broadcast ITS solutions and the huge market potential that a third-generation product will have.

2.2.4 (U) Third-Generation, Long-Range VLC – Intelligent Transportations Systems

(U) The third-generation product will enable VLC between vehicles for collision avoidance. This concept is illustrated in Figure 2.10, which shows an alarm signal being sent from the brake lights of a leading vehicle to a receiver located on the windshield (or front bumper) of a trailing vehicle. It is this particular application of ITS that gives VLC an advantage over existing RF communications systems. Because VLC requires line-of-sight transmission, the alarm signal will be received by a vehicle located directly behind a rapidly slowing leading vehicle. With RF technology, all vehicles located within a 500-m radius, even those travelling in the opposite direction of the lead vehicle, will receive an alarm. This could cause considerable confusion.

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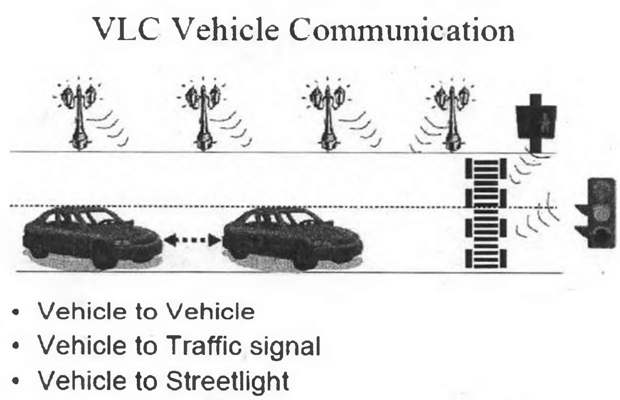

Figure 2.10. (U) Third-Generation VLC-ITS will Most Likely Involve Direct Vehicle-to-Vehicle Communications Using LED-Based Tail Lights (Kang et al. 2008)

(U) It appears then that the large companies participating in the IEEE 802.15 WG7 are looking to capitalize on two technologies for third-generation VLC ITS: telematic services and collision-warning systems. According to Forrester Research, telematic services, including voice-command e-mailing, Internet access, and customized traffic advisories, will grow from a $3 billion to an estimated $20 billion industry over the next 4 years. Likewise, automakers know that crash-avoidance systems can lure customers. J.D. Powers and Associates reports that more than two-thirds of new-car buyers specifically look for safety features, and they are willing to pay for them. Given this, we expect to see automotive VLC commercially available within the next 4 years.

2.3 (U) Scenario 3: Internet Connectivity Using Solid-State Lighting

(U) The idea of using white, overhead SSL for wireless Internet connectivity was first proposed by Nakagawa in 1999 (Nakagawa 1999). The idea received much attention, and it was not long before market forecasters and some academic groups were making grandiose claims that this technology, ultimately capable of Gbps data rates, would soon replace existing in-home wireless networking technologies. A variety of applications were proposed. As shown in Figure 2.11, "smart" overhead lighting could be used to provide Internet connectivity and streaming video anywhere in a house or office to control household appliances and energy use. In addition, communication "security" also was touted with the rational being that because light cannot penetrate walls it could not be intercepted as easily as a wireless RF signal could.

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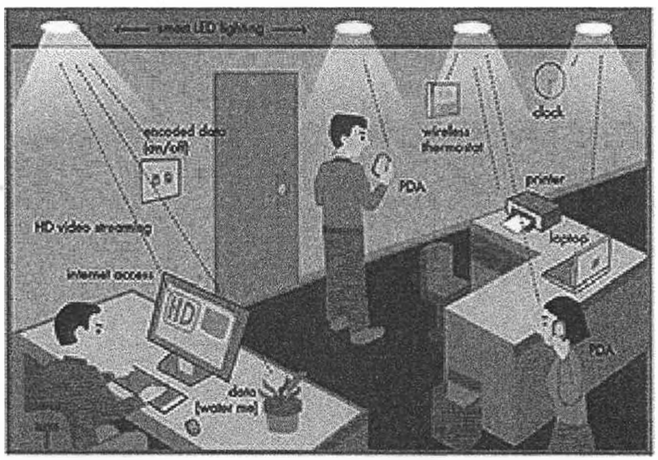

Figure 2.11. (U) Conceptualization of Tasks that "Smart" LED Lighting Could Accomplish (Little 2008)

(U) Over the years, people have scaled back their expectations about what overhead white-light SSL can provide regarding Internet connectivity. This scaling back of expectations, especially in terms of achievable data and bit error rates, has occurred because of modulation bandwidth limitations in current white-light LED sources, inter-symbol interference (ISI) because of multiple path scattering, and background light interference.

(U) As mentioned in Chapter 1.0, there are basically two sources for white-light SSLs: phosphor-coated blue (or UV) LEDs and a three-color (or more) RGB LED system. Most research on the use of white-light overhead SSLs for VLC has been done with phosphor/blue LEDs. The rationale for using this approach is that, because their production cost is lower, they will dominate the overhead lighting market.

(U) Initial research investigating the feasibility of using white-light SSLs for VLC was theoretical in nature. In 2001 Tanaka and co-workers (Tanaka et al. 2000) modeled light propagation from a single centrally located overhead fixture (composed of an idealized LED). They determined bit error rates

(BER) for different subcarrier BPSK modulation schemes (primarily 10 and 100 Mbps) using different receiver field-of-view parameters. The results basically showed that ISI resulting from multipath scattering limited the achievable bit rate to 10 Mbps (this assumes that a BER of 10^{-4} is acceptable).

(U) With this knowledge, Komine and Nakagawa (2004) presented results from a more detailed study that modeled light distribution at the desk-top level coming from four equally spaced, ceiling-mounted SSLs (OOK modulated). They determined the signal-to-noise ratio at different points in the room, and compared behavior seen for a receiver configured to track and detect directed light (i.e., line of sight) or a non-tracking receiver configure to detect reflected (i.e., diffuse) light. They showed that ISI was the dominant noise source in both the tracking and non-tracking cases and suggested that the former system was capable of detecting 100 Mbps with a BER of 10^{-6} at most places in the room. They also studied the relationship between receiver field of view (FOV) and signal-to-noise ratio and showed that while narrow FOV would reduce ISI, there would be several points within the room where the signal would drop to unacceptable levels (i.e., blind spots would exist). They showed, however, that a tracking receiver with very narrow 5° FOV receiver would be capable of detecting a 10-Gbps signal with a BER of 10^{-6}.

(U) While the Komine and Nakagawa study is interesting, it was done assuming an unlimited LED response time. There is currently no LED available, even those tailored for emission in the IR that can be modulated at these speeds. As shown in Figure 2.12, the phosphor-coated blue LEDs currently being used for white-light generation have a dual-component frequency response—a "fast" component at 12 MHz that comes from the blue LED itself and a "slow" component at ~ 2 MHz that is due to the phosphor.

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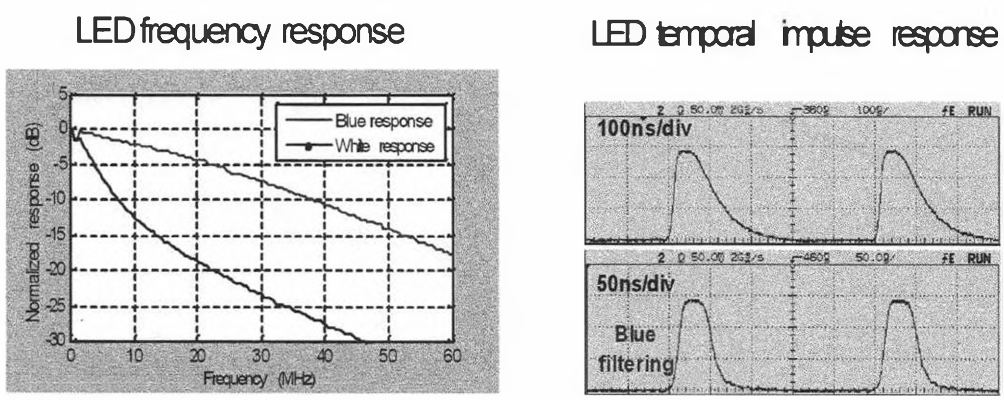

Figure 2.12. (U) White-Light, Phosphor-Coated Blue LED Modulation Bandwidths (O'Brien 2008)

(U) The inherently slow response time of white-light LEDs partially explains why some experiments done to date have been unable to achieve the high bit rates initially touted in the Komine and Nakagawa paper. The first investigations using white-light LEDs were done in 2006 and 2007 by the Haas group at the University of Bremen. In their first attempt, they used a single (24-mW optical output power) white-light LED, an optically unfiltered detector, and an orthogonal frequency division multiplexing (OFDM) modulation scheme to send data across a distance of 80 cm at a rate of 16 kbps, with a BER of 10^{-3} (Afgani et al. 2006). In their second attempt, this group used the same white-light LED and a combination of OFDM and FEC to send data across a distance of 90 cm with a BER of 10^{-5} (Elgala et al. 2007).

(U) Around about this time, Lee and co-workers measured the −3 dB bandwidths of commercially available RGB LEDs and determined that the blue LED would give the fastest performance (Lee et al. 2007). They connected seven blue LEDs in series and used simple OOK to send data over a distance of 12 cm at 10 Mbps and got a BER of 10^{-6}. Subsequently, they improved their receiver circuit and used 10 newer LEDs (with 18-MHz modulation bandwidth) and were able to achieve data rates with similar BER at 20 Mbps (Kim et al. 2006).

(U) In similar work, Aker, Harper, and Pratt (PNNL, 2007–2008 unpublished results) have used a single UHB (700-mW optical output power) blue LED to transmit data over 75 feet in air. An OOK modulation scheme that used DC-balanced Manchester coding allowed them to send data at 1 Mbps with a BER of $< 10^{-9}$.

(U) Once it was realized that the phosphor response was the bottleneck to high white-light SSL VLC rates, the experimental approaches shifted, and an optical filter was added to the receive side so that detection occurred only in the blue region of the spectrum. In 2007, a group from the Fraunhofer Institute and Siemens AG (Grubor et al. 2007b) used a single white-light phosphor LED, combined with a blue filter on a receiver spaced 1 cm away, to send 40 Mbps using simple OOK. They did not measure a specific BER; however because the eye diagram they presented was partially closed, this would indicate that the BER was not especially good. In the same paper, this group also reported the same experimental set-up was capable of transmitting at 117 Mbps when they used a discrete multi-tone (DMT) modulation scheme, and reported BER rates for individual channels ranging between 10^{-3} and 10^{-5}.

(U) Lee and co-workers subsequently reported using an array composed of 20 white-light LEDs to send data to a blue-filtered receiver located 0.75 meters away (Lee et al. 2008b). Using a DMT modulation scheme, they reported achieving a rate of 74 Mbps with a BER between 10^{-2} and 10^{-5}.

(U) Concomitant with the experimental efforts was a renewed dedication to theoretical modeling, ostensibly to determine which modulation scheme would afford the highest data transfer rate. The theoretical studies were primarily conducted by the Langer group at the Fraunhofer Institute and the O'Brien group at the University of Oxford. These studies have used the physical set-up shown in Figure 2.13. The set-up consists of a 5 m × 5 m × 3 m room and a receiver located on a virtual desk located in the middle of the room and at a height of 0.85 m. An idealized receiver, consisting of a single optical filter that passes only blue light, a concentrating lens, and a silicon detector, is used in the modeling studies. This receiver is identical to the one used in the original model used by Komine and co-workers.

This Figure is Unclassified

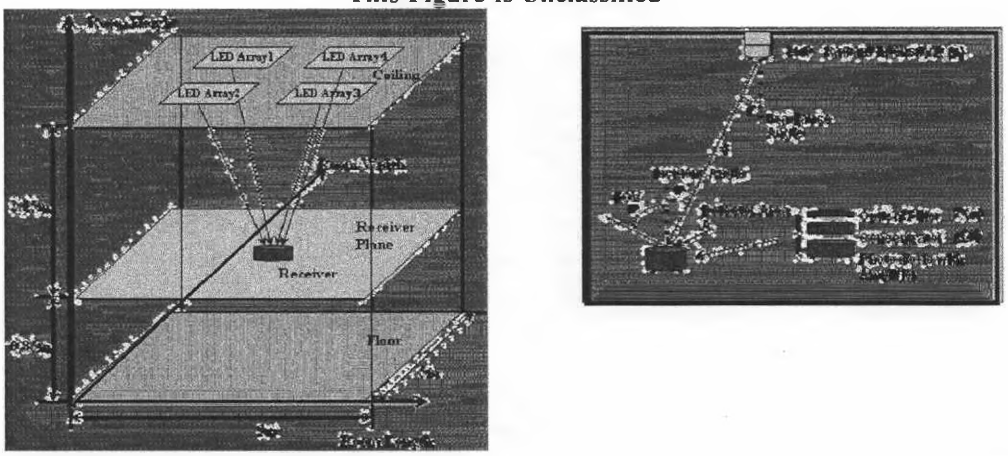

Figure 2.13. (U) Typical Physical Set-up Used for VLC Modeling Studies (O'Brien et al. 2006)

(U) In 2008, O'Brien and co-workers (Zeng et al. 2008b) used the physical set-up described in Figure 2.13, employed post-equalization (which involves combining the responses from multiple LEDs each being driven at a resonant frequency) at the receiver, and compared NRZ-OOK (1 percent depth) and Manchester modulation schemes. To get a BER of 10^{-6}, the NRZ-OOK data rate was 16 Mbps without equalization and 32 Mbps with equalization; Manchester encoding achieved an 8 Mbps transfer rate without equalization and 16 Mbps with equalization. In a later paper, this group used the same physical set-up and added pre-equalization, used NRZ-OOK modulation, and showed that data rates up to 75 Mbps could be achieved with a BER of 10^{-6} (Zeng et al. 2008a).

(U) The O'Brien group also followed up with some experiments (Minh et al. 2008). Here they projected light from an array composed of 16 white-light LEDs onto a receiver essentially identical with that used in the modeling calculations. They individually modulated (NRZ-OOK) each LED at its resonant frequency (this corresponds to pre-equalization) and adjusted the bandwidth by controlling the relative contribution of each LED (this corresponds to post-equalization). They measured BER performance as a function of data rate for two separations between the source and the receiver. A BER value of 10^{-6} at a data rate of 40 Mbps was measured when the separation was 2 meters, and a BER of 10^{-5} at a data rate of 30 Mbps was achieved when the separation was 2.5 meters. These data rates are much smaller than those predicted by theory, indicating that some penalty must be missing in the theoretical model. They did present results indicating that the BER was quite sensitive to the position of the receiver away from the source line of sight, but this cannot account for the huge discrepancy between the experimental and theoretical results. It should be noted that the position-sensitive nature of a pre- and post-equalization communications system makes it unsuitable for simple "stop and talk" communications with overhead lighting, as **both** the source and receiver equalization parameters have to be re-optimized each time the geometry between the source and the receiver changes.

(U) In 2009, the O'Brien group also presented results on a VLC system that used a hard-wired circuit (consisting of a capacitor wired in parallel with a resister) to post-equalize a blue-filtered photodetector receiver response (Minh et al. 2009). In their experiments, they directed the output of a single white-light phosphor LED (45° beam angle) onto the receiver, and using an OOK-NRZ (with a 40 percent modulation depth), measured BER vs. data rate. They measured a BER of 10^{-9} for a data rate of 100 Mbps, but this rate was achieved at ~10 cm, which is a very distance between the LED source and receiver, and the received optical power had to be very high, −10.5 dBm, which corresponds to about 0.1 mW. They did not specify whether this received power included the yellow component or corresponded only to the blue light that penetrated through the filter.

(U) Between 2007 and 2009, a group consisting of personnel from the Franhofer Institute, and Siemens AG modeled the set-up described in Figure 2.13, and compared different modulation schemes (Grubor et al. 2007a; Langer and Grubor 2007; Grubor et al. 2008; Vucic et al. 2009a; Vucic et al. 2009b). An interesting observation made in their earliest paper (Grubor et al. 2007a; Langer and Grubor 2007) is that the ISI resulting from multi-path scattering becomes a constant DC background signal when the LED modulation rate is kept below 98 MHz, and that the ISI from different line-of-sight paths that result from using overhead lights that contain LED arrays will have no impact until the modulation rate nears 200 MHz. When they compared two different modulation schemes—one being baseband M-PAM (M-ary phase amplitude modulation) and the other being a DMT with M-QAM (quadrature amplitude modulation)—they calculated that 256-PAM modulation would give a BER of 10^{-6} and a data rate of 160 Mbps and the DMT scheme would give the same BER but at a rate of 196 Mbps.

(U) In a later paper, Grubor and co-workers (Grubor et al. 2008) used essentially the same physical set-up in their model and determined achievable data rates, but this time for higher a BER, specifically 2×10^{-3}. We note here that a BER this large is unacceptable for communications purposes; nevertheless, Grubor and co-workers use it as a criterion because they assert (Vucic et al. 2009a) that, as long as the error rate is kept below this level, it can be improved to an acceptable level by using FEC. The results showed that data rates of 275 Mbps and 305 Mbps could be achieved using the 256-PAM and DMT schemes, respectively. It is worthwhile to note that, in both of these papers, Grubor and co-workers assumed that there was no limit to the LED modulation response. This assumption was made because it made the calculations, which are quite extensive, much simpler and it would lead to only a "slight" overestimation of results.

(U) Not long after they completed the theoretical studies, the Fraunhofer/Siemens AG group performed experiments to determine if their research direction was correct. In their first attempt (Vucic et al. 2009a), they used a commercially available LED luminare containing six white-light (blue/phosphor) LED chips, collimated the output, and then used a second lens to focus the light onto a receiver that consisted of a blue-filter, a second concentrating lens, and a large area Si detector. The optical components were chosen to maintain the illuminance at the receiver at 800 lux, which is what would be encountered for typical overhead illumination in an indoor environment. This optical set-up also prevents interference from multi-path scattering (i.e., it is exclusively single line-of-sight). They used NRZ-OOK modulation with an index of 0.35. They measured BER performance as a function of data rate at two link distances; 0.5 and 5 meters. A BER of 10^{-6} was achieved at a data rate of 90 Mbps for the 0.5-m span, and at a data rate of 80 Mbps for the 5-m span.

(U) In their second set of experiments (Vucic et al. 2009b), they used the same LED source and receiver, and a single lens was positioned at the output of the source to focus light onto the receiver (so again this experiment is single line-of-sight). Experiments were done using two brightness levels at the receiver, 1100 and 550 lux, which was achieved by moving the receiver further from the source. It is interesting that they give no information on the actual link distances used. They used a discrete-multitone-modulation scheme, recorded the received signals on a storage oscilloscope, and then performed offline processing to calculate the BER for each modulated subcarrier. They discarded results for several subcarrier orders that exhibited severe distortion and RF interference effects, and then used the mean to calculate a total BER. For experiments performed at 1100 lux, they calculate $BER_{tot} = 7 \times 10^{-4}$ at 231 Mbps data rate; the 550 lux calculations gave a $BER_{tot} = 8.3 \times 10^{-4}$ at 202 Mbps. Note that the quoted data rates assume 32 independent subcarrier orders, which we know is not true because they state that they did not use orders that showed severe distortion. The "true" data rates cannot be estimated because the authors provide no information on how many subcarrier orders they discarded. Given this information and the fact that signal processing was done offline, these experimental results should be viewed with some skepticism.

(U) The theoretical studies done by the O'Brien group and the Fraunhofer/Siemens AG group show that, in principle, high VLC data rates, specifically 75 Mbps (10^{-6} BER) and 305 Mbps (2×10^{-3} BER), can be achieved using either pre and post-equalization or discrete-multitone-modulation schemes, respectively. But the highest rates that both groups could measure by experiment, even using illumination geometries designed to preclude ISI from multiple path scattering, were significantly lower, being 40 Mbps (10^{-6} BER) and 231 Mbps (7×10^{-4} BER), respectively. Clearly the models are missing something. As first realized by Inan and co-workers, the blue LED optical output response is nonlinear with respect to input electrical power (Inan et al. 2009). This nonlinear response causes, for example in DMT, interference between the subcarrier orders that, in turn, causes the BER to experience an error floor. Increasing the number of subcarriers, which is usually what is done to increase the data rate, only makes the situation worse. Hence, until the blue LED nonlinear response, which is affectionately known as "efficiency droop" can be improved, VLC communications using white-light luminares that contain blue/phosphor LEDs will most likely be limited to ~16 Mbps using NRZ-OOK modulation without equalization (see O'Brien group 2008 experimental paper above).

(U) As mentioned in the Scenario-1 study, the IEEE 802.15 TG7 group expects that a three-color RGB transceiver and a CCM scheme will be capable of getting the short range (<1 m) VLC data rate up to 96 Mbps. To date, experimental or theoretical modeling results supporting that this data rate can be achieved with a reasonable BER have not been presented in the public domain. In 2008, A. Yokoi (of Samsung) presented preliminary results to the IEEE 802.15 TG7 group (Yokoi 2008). It was there that he first suggested that the IEEE consider using CCM for VLC and presented results from preliminary theoretical and experimental studies. The description of the methodology used is extremely sketchy. However, theory appears to show that a 16-color multiplex coding (CMC) scheme can achieve a BER less than 10^{-6} when the signal-to-noise ratio at the receiver is maintained above 12 dB. This was confirmed by a laboratory demonstration (link distance not given) that showed that a 16 CMC was capable of transferring data at a rate of 20 Mbps with a BER $< 10^{-6}$. Because Samsung rarely publishes their results in the open literature, progress on the potential adoption of CMC in overhead SSL VLC will probably be best determined by monitoring patents that Samsung files in the communications arena.

(U) Until the blue/phosphor LED nonlinear response (droop) problem can be solved, or until it can be demonstrated that CCM of an RGB white-light LED system can transmit data at high speeds (> 90 Mbps) with reasonable BER ($< 10^{-6}$), it is unlikely that the major telecommunications companies will push to introduce overhead SSL VLC to the public.

(U) Even if it turns out that LED modulation bandwidth issues can be overcome, there are other issues that will limit overhead SSL VLC adoption. First, the theoretical studies that have modeled light propagation show that ISI from multiple path scattering limits the data transfer rate to just below 100 Mbps in a small (5 × 5 × 3 m) room, and the transfer rate is lower in larger rooms. This rate needs to be compared with that obtained using WiFi, which is currently around 54 Mbps but is expected to evolve to 104 Mbps in the near future (i.e., the new IEEE 802.11n standard). Given comparable data rates, the VLC community will have to provide the end user further justification to convince them to switch to a new technology. Three reasons have been provided already. First, VLC uses unregulated bandwidth, which is a definite advantage. Second, VLC requires less power than WiFi, which may or may not be true. Third, VLC provides enhanced communication security (and reduced link interference) because light does not penetrate walls. The last reason is not totally valid because light passing through windows and open doorways can be intercepted easily. It should also be noted that these same reasons have been used to make the case for developing indoor IR wireless communications, but despite much effort being devoted to refining this technology and less severe modulation bandwidth limitations of both sources and detectors, indoor overhead wireless IR has not yet been commercialized, even though the concept for it has been around since the early 1990s. The simple reason for this is related to eye-safety.

(U) As the early modeling studies by Komine and Nakagawa (2004) showed, the overhead light communication data rate can, in principle, be increased to the Gbps range by narrowing the receiver field of view to 5× (i.e., basically creating a simple line-of-sight system that is immune to multiple path ISI). But this would severely impact the technology's ease of use because an operator (or an interactive tracking system) would have to continually adjust the mobile device's receiver pointing vector every time he moved. It is unlikely that users would be willing to accept this deficiency when WiFi is relatively insensitive to small variations in location.

(U) The wireless IR optical communications community has come up with a solution for this problem, specifically angular diversity receivers (ADRs) that use an array of narrow field-of-view receiving elements that are pointed in different directions and quasi-diffuse transmitters that use an array of narrow-beam emitters targeted in different directions (for a good review of both, and the current status of indoor wireless IR communications research (Green et al. 2008).

(U) In 2000, Carruthers and Kahn (Carruthers and Kahn 2000) demonstrated that a prototype system using eight narrow-beam transmitters, contained in a unit mounted on the ceiling, and nine narrow field-of-view (22°) Silicon p-i-n photodiode receivers with ~ -31 dBm sensitivity, mounted on a desk, was capable of one-way transmission at 70 Mbps over a range of 4.2 m using OOK with a BER of 10^{-9}. The individual transmitters used in the ceiling unit were Sony SLD302V narrow angle (full width half maximum (FWHM) angle was 28-degrees), 806-nm IR laser diodes that were run to give 75-mW, fully modulated average optical power.

(U) In 2005, a multi-institute group headed by O'Brien (O'Brien et al. 2005, O'Brien et al. 2006) demonstrated that a prototype integrated system consisting of a transmitter station that consisted of seven integrated 968-nm RCLED chips arranged to produce a narrow-angle (12 degrees FWHM), 1.05-mW beam, and a seven-element hexagonal pitch-arrayed receiver unit with a 15 degree FOV, was capable of transmitting data at 100 Mbps up to a distance of 50 cm. They did not measure BER but did present a very clean eye diagram of the system when the distance between the transmitter and receiver was 15 cm.

The O'Brien group noted that the data rate could be increased to the Gbps range by scaling up the number of individual transmitters and receivers in the system.

(U) Given these early results and the ease at which the integration of components can now be scaled up, one wonders why wireless IR capable of Gbps communications is not available now. The answer is eye safety. Two-way communications are required for a real system. This means that a transmitter has to be associated with the portable device, and a receiver unit has to be associated with the ceiling base station.

(U) In the Carruthers and Kahn system, they show that at a distance of 4.1 meters between the transmitter and receiver the intensity at the receiver must be at least -31.5 dBm/cm^2 = 7.08 x 10^{-4}-mW/cm^2 to get a BER of 10^{-9} for transmission at 70 Mbps. This means that the intensity at the transmitter front surface (which we assume is located 1 inch from the diode source) must be 7.08 x 10^{-4} x (401/2.54)2 = 17.54-mW/cm^2. Given that the diode radiation angle is 12-degrees and $\Omega = 2\pi[1\text{-}\cos(\theta/2))$ this means that the radiance at the transmitter output must be 17.54-mW cm^{-2}/0.0344 sr = 510-mW/cm^2/sr. This radiance is 42 times larger than the 12.1-mW/cm^2/sr acceptable emission limit (AEL) for continuous viewing that is permitted for a Class 1 806-nm product under IEC-825-1 regulations (CIE/IEC825-1, 1993).

(U) The O'Brien et al. system also does not meet eye-safety criteria. Here the multiple RCLED chip transmitter was housed in an assembly with a ½-inch diameter lens at the front face. Given a 12-degree beam angle and total output power of 1.05-mW, this corresponds to a radiance of 24-mW/cm^2/sr. This radiance is just at the limiting 25.5-mW/cm^2/sr IEC-825-1 AEL for continuous viewing at 968-nm. Note that the O'Brien system corresponds to transmission only over 15 cm. To be able to transmit out to 4 meters with a similar low BER the source radiance would have to be increased by a factor of $(400/15)^2 \sim$ 700, meaning that the system would not be eye safe.

(U) We can do a back of the envelope calculation to decide if VLC using a narrow angle multiple receiver arrays can be eye-safe. Here we assume that there is a single green LED (555-nm, 10-mm apparent source size giving an apparent source angular subtense, α, of 100-mrad) transmitter on the portable unit located 4-m away from the receiver base station. We have chosen this wavelength and size because it gives us the maximum leeway with regards to eye safety. We also assume that we have a receiver configuration with identical specifications as given by Carruthers and Kahn – i.e. to get a BER of 10^{-9} at 70 Mbps the power at the receiver needs to be -31-dBm (this assumes that the Si p-i-n response at 555 nm is the same as at 805-nm, which is not true, in reality the response at the shorter wavelength is less). Given a (individual) receiver input diameter of 19 mm, this means that the luminous intensity at the source has to be P/Ω = 7.94 x 10^{-4} mW/1.76 x 10^{-5}-sr = 45.1 mW/sr = 30,800 cd (where cd is candela). This luminous intensity is 30 times larger than the 1000 cd limit specified to make a LED based device eye-safe under all conditions by the most recent IEC 62471 (2006) standard. We note this standard is set for continuous viewing conditions – standards become stricter when pulsed systems are considered, so the limit given here corresponds to a modulation scheme with a 50% duty cycle.

(U) In addition to eye-safety constraints, another parameter that will constrain overhead SSL VLC adoption is infrastructure. To provide internet access, the overhead SSL "base station" will still need a wired connection to the network. In principle, this can be done without stringing new cable in the building by using a power line home network adaptor to drive modulation (current capacity is

~ 100 Mbps) at the SSL "base station." In practice, it is unlikely that this will be practical because the network adaptor also will modulate any other LED-based light that is in the building. This will drastically increase both multipath and multisource ISI noise and completely negate any communication security from intercept claims. The only remaining choice is to separately connect the overhead SSL "base station" to the network via hardwired coaxial or optical cable. At that point, the technology becomes moot, because if user is going to install cable; he might just as well have a 10-Gbps fiber-optic wall connection.

(U) Because of these eye-safety and infrastructure issues, we think that it is unlikely that overhead white-light SSL VLC will be commercialized.

3.0 (U) Technology Forecast Analysis

(U) We think that it is unlikely that overhead white-light SSL VLC will be commercialized because of the eye-safety and infrastructure issues identified in Scenario 3; therefore, we only consider the technologies discussed in Scenarios 1 and 2 in this chapter.

3.1 (U) Future Evolution 1: Short-Range VLC for Wireless P2P Information Exchange

(U) In the constant war between cell phone and mobile device manufacturers to provide higher resolution camera sensors in their handsets and more and more games and applications in their devices, it is not surprising to hear that Sony Ericson plans to introduce a 20 MegaPixel phone in 2012. In addition. they also claim that the device will be capable of full high-definition video recording and SCG screen resolution. will run a 1-Ghz CPU, and will be capable of browsing the web at 100 Mbps (Yomogita 2008). Given that other mobile device manufacturers have similar plans, it is not difficult to see how short-range VLC will become an integral part of mobile device technology in the near future.

(U) As already mentioned. the current ~ 10 to 96 Mbps data-rate capability of short-range VLC using "standard" LED chips is competitive with current IrDA, Bluetooth, and NFC technologies, and by using RCLEDs in the mobile devices, the achievable data rates, ~ 250 Mbps, this wireless technology will far surpass that offered by WiFi. Given these developments and the potential for short-range VLC to achieve Gpbs data rates with the introduction of "tilted charge" visible LEDs, we expect that the transition of this technology to the commercial market will be rapid.

(U) We showed in Figure 2.3 that Samsung has already demonstrated a 320-Mbps, short-range VLC in a laboratory prototype. As we show in Figure 3.1, they have also demonstrated a 4-Mbps, PC-PC visible link using prototype USB adaptors.

(U) We expect short-range P2P VLC will be introduced to the public soon after the IEEE 802.15 TG7 standardization recommendations are adopted. A preliminary vote on the standardization recommendations is expected to occur in the February/March 2010 time frame. Once the standards document has been approved. mobile device manufacturers will no doubt roll out their visions for future products. Because most cell phones and other mobile devices these days have at least one USB connection, we expect the first P2P VLC products on the market, probably by 2012, will be in the form of a USB adaptor, so that the new technology can be used with older devices.

This Figure is Unclassified

Figure 3.1. (U) Samsung Laboratory Demonstration of 4-Mbps, PC-PC Visible Light Communications (O'Brien et al. 2006)

(U) During the 2012 to 2014 time period, we expect P2P VLC technology to be integrated into mobile devices and into fixed infrastructure platforms, such as application and game download kiosks, transportation pay portals, and other electronic payment terminals. We note that the IEEE 802.15 TG7 has recommended that initial data rates for short-range VLC be kept under 96 Mbps (see Table 2.2) depending upon the specific application. Given recent progress in RCLED development, however, we expect rapid transition to at least 250 Mbps by 2015. Monitoring discussions within the IEEE 802.15 WPAN community will provide a good indication of how well short-range P2P VLC technology is following this prediction. Any movement toward higher rates will need to be discussed by the standards committee, and these discussions are published on the IEEE web site. Monitoring patent applications filed for short-range VLC applications will provide another good indication of progress, although patent applications tend to made available to the public only shortly before the technology is introduced to the general market.

(U) Progress in developing "tilted-charge" visible LEDs can be used as a harbinger for a noticeable breakthrough in this short-range P2P VLC technology and can be monitored by noting the citation index of the original Holonyak paper on this topic. If Gbps data rates can be achieved, large quantities of information will be able to be exchanged between two mobile devices with a simple "bump." This may have a big impact—in both a positive and a negative sense—on the intelligence community because large amounts of information would be able to be exchanged over extremely short time periods in environments that can be crowded and chaotic. Because the "bump" exchange requires physical contact, the amount of light that will be scattered from the devices will be reduced significantly. The reduction in intensity, combined with the ultra-high data rate will make it difficult for this type of communication to be intercepted. Agencies may want to address this issue early on.

3.2 (U) Future Evolution 2: Long-Range VLC for Situational Awareness and Intelligent Transportation Systems

(U) We expect that first-generation, long-range VLC products will be focused on providing situational awareness (i.e., indoor navigation and individualized information exchange services). Adoption of this technology will most likely go hand-in-hand with the adoption of short-range P2P VLC because the mobile devices already will be capable of receiving the one-way broadcast information from the long-range VLC platforms, and installation of information broadcasting stations will be inexpensive. We, therefore, predict that this technology will become prevalent between 2012 and 2014. Data rates for this type of communication will be relatively slow (i.e., in the 10 to 400 kbps range) because received signals will be small due to the increased range.

(U) We discussed two second-generation, long-range VLC technologies in Section 2.2.2: TTL and ITS. The market case that NEC and Casio have advanced for combining image sensing with LED tags is weak, primarily because of system cost relative to that offered by RFID technology. For that reason, we do not expect this technology to be widely applied for TTL. The market case for using long-range VLC in ITS is much stronger.

(U) Samsung and Intel are already heavily invested in RF-based ITS technology. It is logical that they will try to promote the adoption of LED-based ITS, and both companies have demonstrated information broadcast from traffic lights in their laboratories. However, it is difficult to predict the timing of introduction of this technology because it will involve collaboration and agreement not only between electronics companies, but also governments (federal, state, and local), and automobile manufacturers. It appears that automobile companies are interested in LED-based vehicle-to-vehicle, crash-avoidance systems such as the one illustrated in Figure 2.10. Schaal et al. of DaimlerChrysler AG have published a concept paper that discusses such a system (Schaal et al. 2004). It is difficult to gauge how popular this technology is with other automobile manufacturers because they have not published much on this topic in the open literature. We do know that the United States, the European Union, and Asian nations have provided government funds for research in this area, but the decision to enact laws requiring local infrastructure and automobiles to be fitted with long-range VLC-ITS will have to made within their respective congresses or parliaments.

4.0 (U) Analysis of Commercial Adoption/Implementation

(U) The scenario that has the highest confidence level is the use of short-range VLC for wireless P2P information exchange. Through their involvement on the IEEE 802.15 WPAN committee, Samsung, Intel and Siemens have been very active in driving the adoption of industry standards. In addition, they have released early results of laboratory demonstrations of the technology, no doubt to whet the appetites of gadget enthusiasts. Given the interconnections that these major players have with other major mobile communications firms such as Nokia, Sony Ericsson, Motorola, LG Electronics, Research in Motion, etc., there can be do doubt that commercial adoption of this technology will be extremely rapid.

(U) We do not anticipate that economic factors will have an impact on commercial adoption. Mobile devices are already extremely popular, and while their sales volumes have, in the past, been impacted by downturns in local economies, the decreases have generally been mild and recover quickly once there is an upturn in the economy. Mobile-device customers are constantly looking for new device features, and they will be the drivers behind improved short-range VLC data rates and information exchange applications.

(U) An interesting point regarding commercial adoption of this technology is the ease by which two devices can be lined up for information exchange. One negative aspect of wireless optical IR, and a primary reason for its rejection by consumers, is that users found it difficult to align devices because the human eye cannot detect IR. The nice thing about using visible light is that the consumer will be able to "see what they send," or at least the light that is carrying the information.

5.0 (U) Research Activities

(U) Research on white-light LEDs is primarily concerned with determining ways to make the devices 1) more energy efficient, 2) produce a "warmer" output light, 3) cheaper to produce, and 4) have longer and more consistent operating lifetimes. While solving these issues is very important to worldwide white-light SSL adoption, this research will have little impact on overhead SSL VLC communication adoption, because as we have discussed previously, it is unlikely that this technology will be commercialized. Current commercially-available LEDs and RCLEDs have sufficient capability for short-range P2P VLC and moderate-range, one-way VLC broadcast. As we discuss below, research on LED modulation bandwidth may have an impact on these two technologies.

(U) Regarding research in other areas, Dr. Mary H. Crawford of Sandia National Laboratories has recently published an excellent overview of advances that the semiconductor materials science community has made on LED performance issues. Her article details specific progress that has been made in the areas of device architecture, green-yellow gap, efficiency "droop", and enhanced light extraction (Crawford 2009). Dr. Michael Krames of Philips Lumileds has also published extensive reviews on LED chip design, phosphors, and reliability and packaging (Krames et al. 2007; Dupuis and Krames 2008).

5.1 (U) Visible LED Modulation Bandwidth

(U) LEDs modulation bandwidth is the most important factor that will affect VLC communications in all three scenarios outlined above. The IEEE 802.15 TG7 has currently set a goal of 96 Mbps for short-range P2P communications, probably based on a conservative assessment of the performance of currently available RCLEDs.

(U) A RCLED is formed by a thin quantum well active region sandwiched by two mirrors that form a Fabry-Perot (FP) cavity (i.e., it is a one-dimensional photonic crystal). The total active region thickness is an integer number of half wavelengths of the emission wavelength, and is only a few nanometers thick. The mirrors of the FP resonator can be formed from either metal or a semiconductor distributed Bragg reflector (DBR). Within such a device, the spontaneous emission from the quantum wells is confined into resonances supported by the cavity that produces a profound effect on the far-field emission pattern, and gives a significant increase in the external quantum efficiency.

(U) Current 650-nm (red) AlGaAs RCLEDs, which have been developed as a result of demands from the plastic optical fiber (POF) communications community, are routinely capable of 250-Mbps (fast Ethernet) data transfer (Lambkin et al. 2002). Green InGaN RCLEDS, which have also been developed for POF applications, also support 250-Mbps data rates (Kato et al. 2005), and recently Blume and co-workers reported fabricating a blue RCLED with a −3-dB response of 130 MHz (Blume et al. 2005).

(U) For short-range P2P VLC to become really popular, and to surpass WiFi, data rates into the Gbps range will be needed. One solution would be for mobile device manufacturers to use vertical cavity surface emitting lasers (VCSELs), but before this approach could be used, eye-safety concerns would have to be addressed. In addition, because lasing is required from these components, their fabrication is fairly complex, which adds to the final cost of the mobile device.

(U) Despite this, we suspect that visible-light LEDs may be capable of Gbps modulation in the near future. Recently, the Holonyak group reported fabricating a "tilted-charge" LED with a spontaneous recombination bandwidth of 7 GHz (Walter et al. 2009; Wu et al. 2009). This device basically consists of an n-type buried "drain" layer beneath a p-type "base" quantum well (carrier and photon) active region. The drain layer tilts and pins the charge much in the way it does in a hetero-junction bipolar light-emitting transistor, and works to select and allow only fast recombination. While this particular AlGaAs LED had a wavelength in the IR spectrum, ~ 1 μm, we do not see why this particular fabrication method cannot be used to generate a red LED or blue or green InGaN LEDs. We suggest that the client consult with the LED team at Sandia National Laboratories to elicit a more informed opinion.

(U) If visible LED modulation bandwidth can reach the GHz regime, there is no doubt that this would become the wireless communication technology of choice for short-range P2P communications. There are two reasons why we make this statement: first, the speed far exceeds that of WiFi, and second, because a person can see the visible light, establishing a communication link becomes easy. With respect to longer-range communications, it is doubtful that development of ultra-fast LEDs will have an impact on the technology adoption because of the eye–safety issue. A detector still has to receive a certain number of photons to maintain the signal-to-noise ratio, and hence the BER, at an acceptable level. When the receive time scale is shortened, the number of photons collected must be increased to maintain the signal-to-noise ratio. This means that the optical output power of the transmitter must be increased, and as stated previously, this makes the system unsafe to the eye.

6.0 (U) Conclusion

(U) In this report we have considered three scenarios that involve using SSL for a new type of wireless optical networking in the visible range of the spectrum. The applications cover short-range (<1 m) personal area networking (Scenario 1 in this report), medium-range (<5 m) two-way, high speed wireless internet connectivity using overhead SSLs (Scenario 3), and long-range (<100 m) one-way information broadcasting for situational awareness and intelligent transportation systems (Scenario 2).

(U) The idea of using overhead white-light SSLs for medium-range, two-way, high-speed wireless Internet connectivity is most intriguing because it could offer a way to monitor Internet traffic without having physical access to the network. However, it is unlikely that this technology will be commercialized because eye-safety restrictions will limit achievable communication rates. Because these rates will be well below that provided by current WiFi technology, it is unlikely that the public will be keen to adopt this form of communications.

(U) The technology to use SSL, specifically individual colored LEDs integrated in mobile devices, for short-range, high-speed personal area networking is already in the process of being commercialized. We call this technology P2P VLC (person-to-person, visible-light communications) and rate its adoption with high confidence given that it has already been shown to be capable of achieving 320-Mbps data rates with existing LED chips. This rate far surpasses that available from WiFi. We expect that mobile device manufacturers will have commercial products using this technology on the market within the next two years. In addition, there is excellent potential for this technology to ramp up to Gbps data rates, meaning that mobile device manufacturers will be able to satisfy the ever-growing public demand for faster and larger information exchange avenues in the out years.

(U) The engineering behind using SSLs for long-range, one-way broadcast communications is not as well developed as that for P2P VLC, but advancements are being made, primarily by industry. The most promising short-term application is using SSLs associated with infrastructure beacons to broadcast to mobile receivers. This technology, which we label long-range VLC, will most likely be used for situational awareness and is expected to be commercialized in parallel with P2P VLC because a mobile device receiver can accommodate both applications.

(U) Another promising application for long-range VLC is in the area of ITS. Information broadcast from LED-based traffic lights to automobiles and vehicle-to-vehicle communications for crash avoidance are two regimes into which we envision the technology transitioning. The time frame for the commercialization of this type of communication technology is uncertain, however. Acceptance will be dependent on national mandates being passed to require state, provincial, and local governments to install ITS beacons, and also on collaboration between VLC device makers and automobile companies.

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(U) Appendix A

(U) Visible Light Communications Consortium

(U) The objectives of Visible Light Communications Consortium is to research, develop, plan, standardize the communication system which is a high speed and human safe ubiquitous system using LED through the home/office lightings, traffic signals, electronic advertising board, small lamps on home appliances, etc. The visible light communication is transmitted by its intensity modulation.

The VLCC Members (as of October 2008):

- The Tokyo Electric Power Co., Inc. (http://www.tepco.co.jp)
- NEC Corporation (http://www.nec.co.jp)
- KDDI R&D Laboratories (http://www.kddi.com)
- Panasonic Electric Works Co., Ltd (http://panasonic-denko.co.jp/)
- The Nippon Signal Co., Ltd (http://www.signal.co.jp)
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- Japan Rural Information System Association Information System Research Institute (http://www.syskyo.or.jp)
- Toyoda Gosei Co., Ltd. (http://toyoda-gosei.co.jp)
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- NTT DoCoMo, Inc. (http://www.nttdocomo.co.jp)
- Casio Computer Co., Ltd. (http://www.casio.co.jp)
- Nakagawa Laboratories, Inc. (http://www.naka-lab.jp/)
- Outstanding Technology Co., Ltd. (http://www.ot-c.co.jp/)
- Fuji Television Network, Inc. (http://www.fujitv.co.jp/)
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- Nitto Denko Corporation (http://www.nitto.co.jp/)
- Sharp Corporation (http://www.sharp.co.jp/)
- Japan Coast Guard - Coast Guard Research Center (http://www.kaiho.mlit.go.jp/syo ukai/soshiki/soumu/center/index. htm)

- Comtech 2000 Corporation (http://www1.ocn.ne.jp/~comtech/)
- Rise Co., Ltd. (http://www.riseworld.co.jp/)
- Japan Traffic Management Technology Association (http://www.tmt.or.jp/)
- Toyota Central R&D Labs., Inc. (http://www.tytlabs.co.jp/)

(U) Appendix B

(U) The IEEE 802.15 Working Group for Wireless Personal Area Networks

(U) The 802.15 WPAN™ effort focuses on the development of consensus standards for personal area networks or short distance wireless networks. These WPANs address wireless networking of portable and mobile computing devices such as personal computers, personal digital assistants (PDAs), peripherals, cell phones, pagers, and consumer electronics, allowing these devices to communicate and interoperate with one another. The goal is to publish standards, recommended practices, or guides that have broad market applicability and deal effectively with the issues of coexistence and interoperability with other wired and wireless networking solutions.

(U)The IEEE 802.15 Working Group is part of the 802 Local and Metropolitan Area Network Standards Committee of the IEEE Computer Society. The IEEE-SA is an international membership organization that serves industries with a complete portfolio of standards programs. The IEEE has more than 368,225 members in approximately 150 countries. Through its members, the IEEE is a leading authority on areas ranging from aerospace, computers and telecommunications to biomedical engineering, electric power and consumer electronics.

(U)The IEEE 802.15.7 Visible Light Communication Task Group 7 is chartered to write a PHY and MAC standard for VLC.

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