High-Speed Visible Light Communication Systems

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ABSTRACT

This article presents recent achievements and trends in high-speed indoor visible light communication (VLC) research. We address potential applications and future visions for the VLC technology, where transport of information is "piggybacked" on the original lighting function of LED-based lamps. To mature this technology and transfer it into practice, our recent research is focused on real-time implementation and trials. For the first time, a bidirectional real-time VLC prototype achieving data rates of up to 500 Mb/s is presented. This system paves the way for future real world applications. Finally, we discuss the remaining technical challenges as well as the research outlook in the field of high-speed VLC systems.

INTRODUCTION

OPTICAL WIRELESS COMMUNICATION

When using the term optical wireless communication (OWC), we consider a free-space optical link, where the transmitter and receiver are not necessarily aligned to each other. OWC in general addresses quite different applications, starting from chip-to-chip interconnects and ending in intra-satellite data links.

OWC links can be realized with quite different optical sources and detectors. For low data rates, such as "optical telegraph," traditional light bulbs, liquid crystal displays (LCDs), or plasma display panels (PDPs) can be used. As a receiver, we can use low-cost digital cameras, as currently they feature in practically every mobile device. However, not only the serial read-in and read-out of images, but their processing as well limit achievable transmission speed. High-speed displays and digital cameras provide frame rates of hundreds and thousands of frames per second, respectively; thus, only data rates of a few kilobits per second can be achieved [1].

The new LED-based luminaires will be omnipresent a few years from now. Besides their original lighting function, their light can be modulated at high speed. In this way, we can realize significantly higher data rates over moderate distances, which is the focus of this article. For higher speed (>10 Gb/s) or longer distances, laser diodes, as typically applied in outdoor free space optical (FSO) communications, appear to be the better choice. In both cases, PIN or more sensitive avalanche photodiodes (APDs) are used as receivers.

VISIBLE LIGHT COMMUNICATION

Visible light communication (VLC) comprises OWC links in which visible light sources are applied. Hereby, the main task and challenge is the development of luminaires with an add-on function (i.e., data transmission), which has no negative influence on their illumination functionality. This dual role can best be fulfilled by LEDs, and over the past few years research groups have been able to demonstrate that high data rates up to the gigabit per second range are possible with such devices [2, 3].

The main driver behind high-speed VLC is the rapidly growing presence of LEDs in practically every signaling or illumination entity. By as early as 2018, the majority of new energy-efficient lighting installations are expected to be LED-based [4]. As current-driven semiconductor diodes, LEDs provide a respectable modulation potential. This aspect increases the attractiveness of VLC and offers benefits such as:

- Huge bandwidth in the visible part of the "optical" electro-magnetic spectrum
- Absence of electro-magnetic interference (EMI) with existing radio systems
- The intuitive option to create and isolate communication cells with very high privacy by either directing the light to the working area or using any opaque material

A further important driver for VLC systems comes from the flood of wireless applications. According to the Federal Communications Commission (FCC), a "spectrum deficit" (i.e., lack of usable radio frequencies for new wireless applications) was already expected for this year (2013) due to exponential growth in demand for wireless transmission capacity [5]. While the response of radio technology is a further increase in spatial reuse (e.g., by using more antennas and smaller cells), optical frequencies remain unregulated

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worldwide. Creating a small personal optical cell is a fairly intuitive and easy task; even rice paper is enough to isolate the light beams!

This article is organized as follows. First, we address future visions and the main VLC applications. Then we describe high-speed VLC system aspects and review the main laboratory achievements. Our newly developed real-time high-speed bidirectional VLC system is presented afterward. A short system evaluation is made in the following, where future technical aspects are also touched on. Before the conclusions, aspects of rollout and standardization are discussed.

Future Visions and Main Applications

A few years ago, the following dense wireless communications scenario was foreseen far into the future: Several people sit comfortably in an indoor environment and watch different HD video content on their portable devices by sharing a high-speed Internet connection. This scenario applies, for instance, to private homes and offices as well as in-flight and in-railway environments.

One viable solution for this scenario is individual data transmission via illumination using VLC (Fig. 1). Such a dense high-speed access solution is often referred to as *optical WiFi*. The first step toward this vision was a real-life demonstration of the European FP7 project OMEGA in 2011, where the user was able to download several HD-video streams in parallel (http://youtu.be/AqdAR-FZd_78; more details later).

One advantage of the VLC concept is that illumination-devised LEDs can be extended for data transfer with only minor effort. Through the use of visible light, the user gains very intuitive control over sharing data with others. As soon as an object (like a hand) gets between the light source and the receiver, data transfer is impaired. This can equally be seen as a positive feature as far as communication security is concerned. VLC is not intended to replace WLAN, PowerLAN, or mobile networks. Rather, it is suited as an additional high-speed data layer in a heterogeneous network environment, providing an alternative wireless data link where radio transmission is not desired, not possible, or not sufficient.

Evidently, VLC applications based on LED lighting are more attractive in environments where the lights are always switched on, for instance, in industrial settings, public transport or medical areas. On the other hand, simple integration of an infrared LED chip into future LED luminaires will allow for continuous data flows even if the lights are switched off. Deployment is rather easy as data can be provided from a local aggregation point to the luminaires via existing infrastructure like power cables. VLC applications will also be related to IT-security (e.g., in the financial sector with its high security and confidentiality requirements) to protect private information against jamming and tapping. Furthermore, VLC is predestined for use in EMI-sensitive environments like operating theatres or aircraft cabins, and also in places where radio transmission is problematic such as industrial production sites or exhibition halls.

Figure 1. *An artist's vision of a future "optical wi-fi" real-life application.*

Although one mostly thinks here about bidirectional data links, there are a multitude of broadcasting applications for VLC, starting with simple messaging using street or traffic lights or advertising displays, continuing with augmented reality applications in museum exhibitions, and ending with HD video streaming to a display monitor.

Moreover, VLC presents a unique feature in short-range underwater transmission where light sources in the blue-green spectral window are convenient. The reach is, of course, limited by the clarity and attenuation of the water, but the lack of alternatives for high-speed wireless underwater communication underscores the potential of VLC for resource exploration and yield as well as for data exchange between divers or between robots and submarine docking stations.

Last but not least, a further interesting research and development topic is the application of VLC for indoor navigation and localization, in particular in large labyrinthine buildings like hospitals, railway stations, or shopping malls. While GPS signals are often not available indoors and radio fails due to rich multipath propagation, artificial lighting is omnipresent in such areas. Obtaining indoor location information by means of light sources may be an attractive solution. A spatial resolution of a few centimeters can potentially be achieved by using multiple lamps transmitting individual beacon signals in combination with imaging optics (e.g., a smartphone camera).

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High-Speed VLC Links

Channel Characteristics

VLC can be applied in various scenarios. One important parameter for high data rates is the availability of a line-of-sight (LOS) optical link, where the transmitter is directed to the receiver (Fig. 2a), while non-directed LOS transmission or diffused lighting is likely to limit the achievable data rates (Figs. 2b and 2c). Thus, the capacity of the VLC channel depends strongly on the availability of the LOS path. As the lighting scenario may vary, a dynamic rate adaption appears necessary, as already proposed in [6–8], in order to achieve a robust VLC link.

LED Characteristics

Over the past few years, growing insights have been gained into the efficient implementation of VLC data transmission using LEDs initially

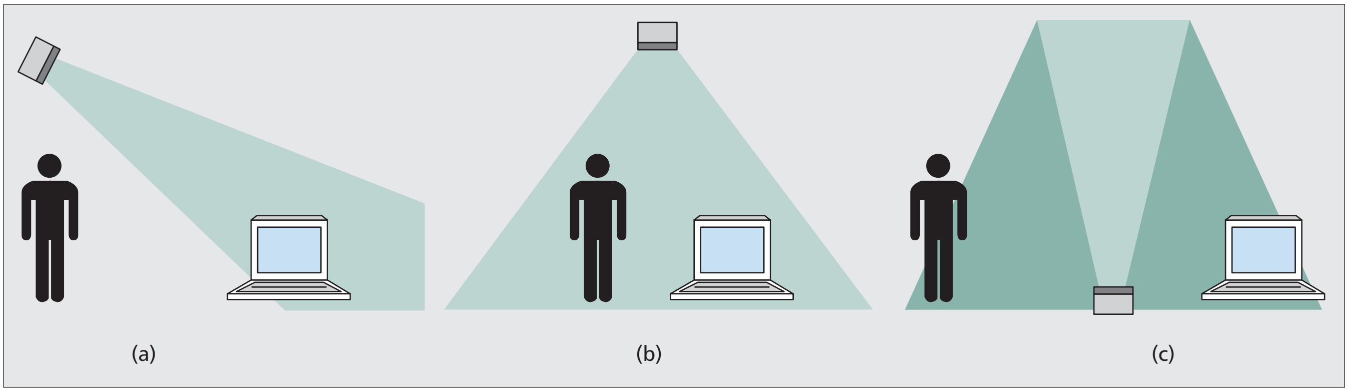

Figure 2. *a) Directed LOS configuration; b) non-directed LOS configuration; c) diffused light configuration.*

developed for illumination purposes. In general, there are two main types of white-light LEDs commonly used for lighting: phosphorescent and multi-color (RGB). The phosphorescent type consists of a blue LED chip plus a yellow phosphor layer. The multi-color type, in contrast, consists of three (or in some cases four) individual chips, mostly red, green and blue (hence RGB). While the phosphorescent type allows for cost-efficient installations, mainly because of its simpler driver design, it provides only narrow modulation bandwidth, given the slow response time of the phosphorescent material. However, we were able to demonstrate that the bandwidth can be enhanced by an order of magnitude of about 20 MHz by suppressing the phosphorescent portion of the optical spectrum with the aid of a blue filter at the receiver end [6]. In contrast, white-light RGB-type LEDs enable three individual color channels, each providing approximately 15 MHz bandwidth. By using three drivers in parallel, wavelength-division multiplexing (WDM) can be realized. However, the advantage of an increased aggregate data rate is achieved at the expense of higher costs.

VLC Achievements

A couple of research groups have demonstrated that although illumination LEDs are not intended for data transmission, they do offer significant potential for high-speed communications. Starting with phosphorescent LEDs and simple on-off keying (OOK) modulation, which enable 100–230 Mb/s data rates [9], transmission speeds have been increased continuously by applying more spectrally efficient modulation formats. In particular, orthogonal frequency-division multiplexing (OFDM) alias discrete multitone transmission (DMT[1]) in several variants have been studied and evaluated over the years. Using a phosphorescent LED in an LOS configuration, data rates up to 1 Gb/s have been achieved in the laboratory by means of offline-processed experiments [2], and even rates of up to 1.5 Gb/s when using RGB-LEDs in a single-color transmission mode [3, 10]. Work on optimization of LED modulation is still in progress, for example, on parameters such as power efficiency.

In contrast to LOS scenarios, non-directed LOS or diffuse configurations call for adaptive transmission schemes due to their specific channel properties, for instance, the common appearance of spectral notches [11]. The idea of dynamic data rate adaptive OFDM was proposed and developed almost at the same time by another research group and by us independently in [7, 8]. We have continued working on implementation of such sophisticated adaptive systems and have shown that data rates up to the gigabit per second range, based on DMT modulation with bit and power loading for throughput maximization beyond conventional 3 dB bandwidth limitations, are feasible.

A real boost of the throughput can be achieved with RGB-LEDs using WDM. The principle is shown in Fig. 3. DMT via WDM channels and VLC was studied in detail in [3] using a commercially available high-power white-light RGB-LED as the optical source and WDM pass-band filters combined with an APD as the receiver element. Compared to single-color transmission, the aggregate data rate was extended to 1.25 Gb/s at an illuminance level of 1000 lx at the receiver, a value within the range recommended by the European lighting standard (EN 12464-1 from 2003) for working environments. Based on a similar offline-processed WDM-VLC setup and a low-power RGB-LED, the authors in [10] reported an aggregate data rate of 3.4 Gb/s.

Of course, WDM is also applicable for setting up bidirectional VLC links operating in a full duplex mode. Corresponding experiments for proof of principle by means of offline processing are described, for example, in [12]. There it was shown recently that bidirectional VLC links can provide capacities of more than just a few hundred megabits per second.

Real-Time 500 Mb/s Bidirectional VLC Link

System Design

Besides the high-speed offline-processed laboratory achievements, the maturity of VLC technology for all potential applications has to be proven with real-time systems. This is an aspect on which we have recently focused. The very first high-speed VLC real-time demonstration was presented in February 2011 at ORANGE laboratory facilities by the consortium of the EU project OMEGA (www.ict-omega.eu). This system provided a 100 Mb/s net data rate. OFDM-based modulation and demodulation, forward error correction, synchronization, and a specifically developed medium

[1] The DMT technique is known from digital subscriber line (DSL); in radio systems it is known as OFDM. DMT can be realized using OFDM where a real-valued waveform is obtained using a so-called mirror function [6, 8].

access control (MAC) were implemented on field programmable gate arrays (FPGAs). In an area of about 10 m^2, equipped with 16 LED lamps distributed on the ceiling, four HD video streams were broadcast simultaneously to different laptops located in the service area [9].

In order to advance VLC technology toward future commercial applications, more recently we developed the first bidirectional real-time high-speed rate-adaptive VLC system. It operates in half-duplex mode based on time-division duplex (TDD). The idea is presented schematically in Fig. 4. Data transmission is based on a rate-adaptive OFDM modulation and demodulation scheme. The transceivers are equipped with tailored VLC transmitter and receiver modules. As the VLC channel is based on intensity modulation and direct detection, a real-valued positive waveform is needed. Here, DC-biased DMT is applied to obtain a unipolar (positive valued) time domain signal at the transmitter, while any potentially remaining negative signal amplitudes are clipped at the expense of an increased error rate. Possible bit errors are handled by integrated forward error correction (FEC). The VLC transmitter is primarily composed of a newly developed LED current driver and an off-the-shelf high-power visible-light LED. The VLC receiver comprises a transimpedance amplifier (TIA) and a commercially available high-speed Si-PIN-photodiode. These new modules have significantly increased the modulation bandwidth of our optical link up to 180 MHz.

These transceiver modules can operate without active cooling and are easily usable. Meanwhile, a second generation of such modules with a reduced form factor (Fig. 5) has emerged. Each transceiver is equipped with an external power supply and 1000BASE-T Ethernet interfaces using standard RJ45 connectors (further details will be published elsewhere).

Experimental Results and Discussion

One particular advantage of our real-time VLC system is the use of bidirectional rate-adaptive OFDM transmission enabling a variable throughput with controlled error rate, depending on the quality of the optical communication channel. At a typical working distance of 2 m between the ceiling and the tabletop, and in a circular spot covering a typical working area of roughly 60 cm in diameter, the system enables a data rate of 200 Mb/s per user. By using the same transceiver combined with narrow-beam optics, we improved the system performance, achieving a data rate of 100 Mb/s over 20 m distances. As shown on the left of Fig. 6, the most important parameter is the light intensity at the receiver, leading to nearly proportional adaptation of the data rate. Thanks to the dynamic rate control, by reducing the distance or using a more directional beam, the data rate can steadily be increased until the 500 Mb/s peak data rate is reached (Fig. 6, right).

Our bidirectional VLC experiments demonstrate for the first time that the dense optical WiFi communication scenario, still considered visionary earlier, can now be realized in a reasonable indoor setup using commercially available hardware. We exemplarily used red LED sources, as shown on the right of Fig. 5, for better visualization of the bidirectional data transmission. In fact, any other high-power LED could be used as the light source regardless of its color. In the near future, we expect that more powerful OFDM chips will be available. As our VLC components already provide the necessary analog bandwidth, there is a significant potential for further increased data rates.

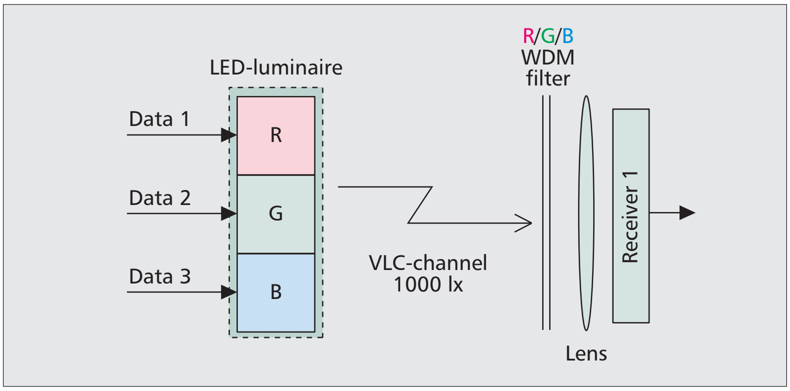

Figure 3. *The WDM principle for VLC showing in-parallel transmission of three (RGB) channels and reception of one channel via color filtering.*

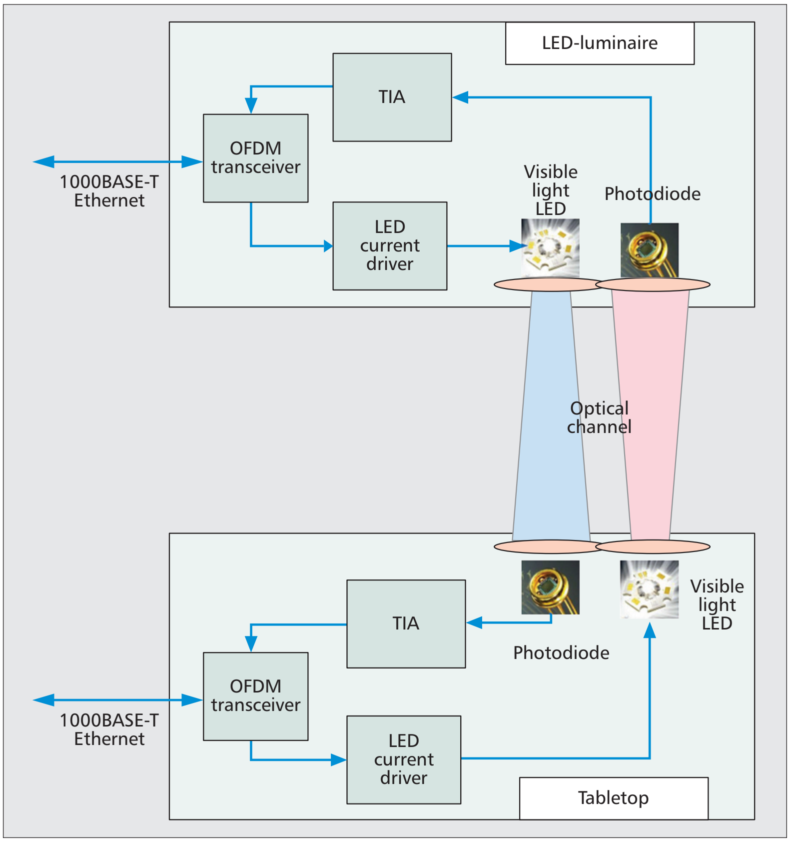

Figure 4. *The overall scheme of a bidirectional real-time LOS VLC link.*

Technical Outlook

VLC has high potential if the "piggyback" effect on the lighting function of white-light LEDs is used. Similar to LED lamps, low-cost mass fabrication is an essential prerequisite for ubiquitous acceptance of VLC, as are minimal power consumption, improved robustness, and higher data

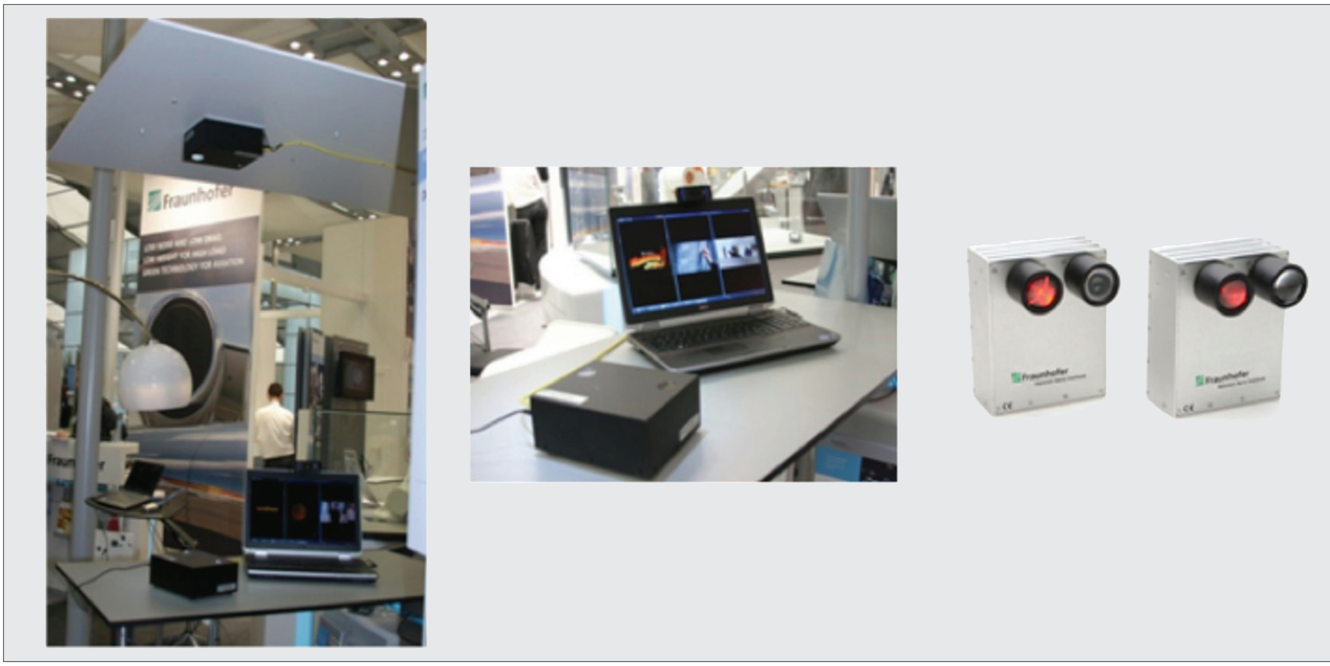

Figure 5. *Left: First generation real-time point-to-point 500 Mb/s VLC system as shown at a commercial exhibition. Middle: Zoom-in of the desk part. Note that this setup includes an infrared uplink, while visible light could be used as well. Right: Second generation of the bidirectional transceivers with a reduced footprint of 87 mm × 114 mm × 42 mm without lenses.*

rates. Our experiments have conclusively demonstrated that there are no real technical showstoppers.

Deployment costs will be dominated by three contributions. First, the LED needs a bias-T for high-speed modulation. Second, we need a powerful analog LED driver and a low-noise amplifier after the photodiode. Both require careful impedance matching. Third, a baseband chip is needed based on adaptive OFDM providing an interface to the network infrastructure (e.g., via the power line). All these aspects are already realizable today with commercial components, so mass production appears feasible. Moreover, low-cost mass production calls for monolithic system integration as the form factor can be further reduced in this way. Despite the add-on of communication to lighting, the developed system is quite energy efficient. Power consumption is only moderately increased by 30 percent compared to the original lighting function in our real-time VLC system due to the optimized LED driver design. As the choice of color temperature is relatively unimportant for communication, the system can also operate with tunable light color.

As discussed in the previous section, there is some potential for higher link capacity in both the optical subsystem and the baseband. In the latter case, development depends strongly on the availability of adaptive OFDM chips with an extended baseband bandwidth. Depending on the optical link setup, the choice of suitable optical lenses can significantly increase the attainable link margin. Until now, adaptive transmission has been realized using DMT with bit and power loading on individual subcarriers. For enhanced robustness, advanced waveforms with reduced clipping probability, such as blockwise pulse amplitude modulation (PAM) with frequency domain equalization [13] may be promising because the non-directed LOS channel is essentially flat, apart from the low-pass character of the optical transmitters and receivers. Single-carrier transmission combined with frequency domain equalization and modifications thereof [14], and extended to support multiple users, as in Long Term Evolution (LTE) mobile radio, also has high potential for VLC.

Higher point-to-point user data rates are certainly feasible utilizing higher bandwidth and WDM, as described earlier. Moreover, there is significant potential for spatial multiplexing using pixelated transmitters and receivers, possibly reaching 10 Gb/s and beyond. On the other hand, hundreds of megabits per second may be enough for a single user nowadays. Thus, it might be wiser to exploit the spatial multiplexing potential to achieve higher aggregate data rates for multiple users in a homogeneously lit large coverage area. Note that optical bandwidth is more easily shared than radio. Using, for example, selective light beams, data can be directed to one user without complex signal processing. Optical space-division multiplexing can also enable high-speed access for each individual user by spatially reusing the modulation bandwidth. While optical beam-forming has often been demonstrated in the scientific literature [15, references therein], further research is needed to integrate this new technology autonomously into optical access points and terminals.

Rollout and Standardization

From our point of view, optical wireless will increasingly complement radio in the future. Hybrid technologies, involving the use of unified wireless data protocols and link management, will accordingly play a significant role.

An important aspect of rollout in the poten-

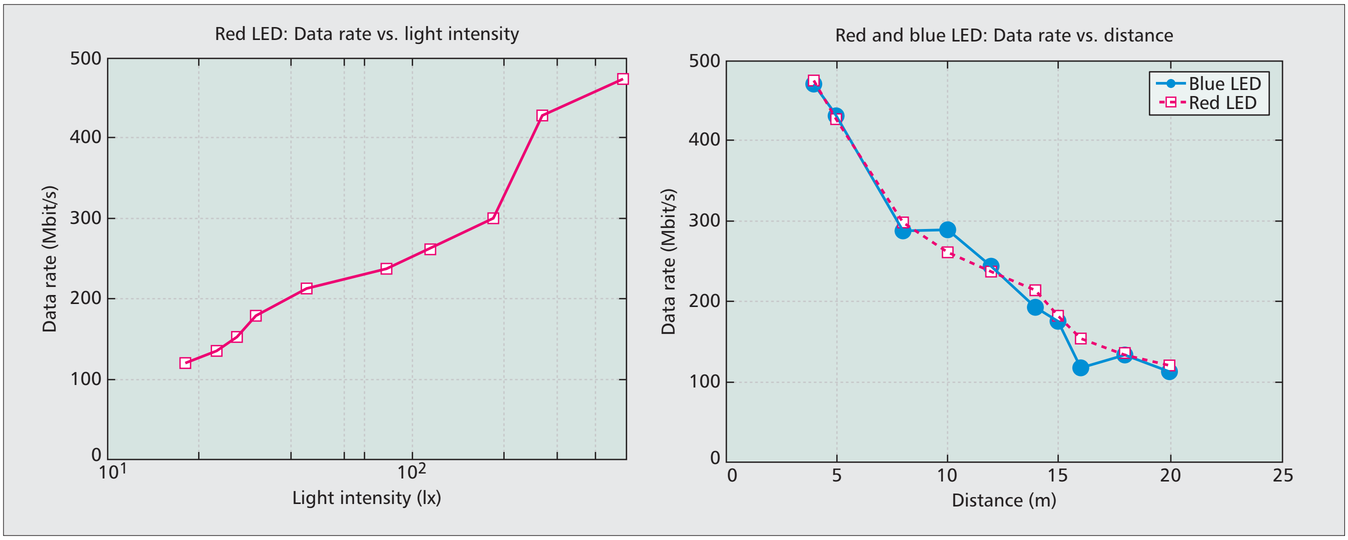

Figure 6. *Measurement results for the real-time VLC system. Left: Achieved data rates for the red LED-based transmitter depending on the light intensity measured using a standard photometer at the receiver entity. Right: Measured data rates over varying transmission distances demonstrating the practically color-independent bidirectional data transmission.*

tial application scenarios is a low-cost network behind VLC. For existing indoor environments, it is intuitive to use the power lines to the room lighting as a network infrastructure, in order to accelerate deployment and reduce costs. For extending the already existing power line communications (PLC) technology with VLC, amplify-and-forward or decode-and-forward strategies are of interest. On the other hand, for new installations, plastic optical fibers (POF) are considered promising, as they provide improved data security. VLC could be combined with an optical backhaul, paving the way for future all-optical wireless solutions.

A dedicated standardization roadmap is essential for the future availability of VLC in a large number of portable devices. Standardization activities so far emanate from the Infrared Data Association (IrDA) interest group and from the IEEE. Whereas IrDA provides mainly specifications for wireless infrared protocols, the IEEE published a first OWC standard, IEEE 802.15.7-2011, using VLC in September 2011. The recent extension of the International Telecommunication Union (ITU) g.hn standard (ITU-T Recommendation G.9960, 2011) foreseeing an optical channel is equally of importance. Research and development is already coordinated on several platforms: the Visible Light Communications Consortium (since 2003, http://www.vlcc.net), the Li-Fi (Light-Fidelity) Consortium (launched 2011, www.lificonsortium.org) and the COST action OPTICWISE (since 2011, http://opticwise.uop.gr).

After short-range IrDA links were replaced by Bluetooth, optical wireless became a niche market, and substantial acceptance has not yet been reached in the industry. We believe that the mass market opportunities for VLC will be drastically increased when the lighting industry agrees on the incorporation of data transmission features into common lighting. Standardization needs equally to move forward from point-to-point link design issues to address multipoint-to-multipoint functionality. Finally, energy efficiency aspects will certainly play a major role, in particular for the implementation of VLC in mobile devices.

Conclusions

In this article we have recapitulated recent developments in the area of high-speed visible-light communication. These systems exploit the natural opportunity of piggybacking data transmission over new LED-based luminaires. Our focus was on demonstrating the maturity of this technology for a number of dense high-speed wireless communication scenarios envisioned mainly in indoor settings such as aircraft cabins, operating theatres, trade fair halls, or private homes.

We have summarized recent experimental work demonstrating that VLC has high potential for high-speed communications in these scenarios. Even today, the simplest on-off keying modulation enables more than 100 Mb/s, while transmission speed can be further increased beyond 1 Gb/s by using more spectrally efficient adaptive wideband modulation techniques and wavelength-division multiplexing.

A bidirectional real-time visible light communications prototype, supporting data rate adaption according to the lighting conditions and operating at speeds of up to 500 Mb/s, has been presented for the first time. It combines both lighting and fast wireless data communications under very realistic conditions and is entirely based on commercially available low-cost hardware.

Future research and development will be directed toward further system optimization, hybrid integration with other wired and wireless technologies, and the use of space-division multiple access for operating multiple optical wireless links in parallel. An increasingly important aspect is an internationally harmonized view on standardization in order to create the ecosystem needed for the rollout of this technology in the future.

Future research and development will be directed toward further system optimization, hybrid integration with other wired and wireless technologies and the use of space-division multiple access for operating multiple optical wireless links in parallel.

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BIOGRAPHIES

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