

Integration of Indoor Visible Light and Power Line Communication Systems

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Abstract—With the recent successful standardization of broadband power line communication (PLC) (IEEE 1901, ITU-T G.9960/61) and visible light communication (VLC) (IEEE 802.15.7), there is an excellent opportunity to consider their integration. In particular, there is inherent benefit to leveraging existing power line infrastructure to provide connectivity while exploiting energy-efficient LED illumination systems for wireless downlink. The ubiquity of LED lighting together with power line networks leads us to conclude that VLC will be a strong complementary wireless technology to indoor PLC much in the way that Wi-Fi currently supports broadband Ethernet connections. This paper will survey some aspects of both PLC and VLC and present new proposals for their integration.

I. INTRODUCTION

Current wireless communication systems are constrained by a shortage of spectrum and interference. A largely unexplored wireless access medium uses visible light which is modulated outside the human perceptual range as the physical carrier for information [1], [2]. Typical light-emitting diode (LED) lighting fixtures are being widely deployed due to their energy efficiency, small size and long lifetimes compared to incandescent and fluorescent illumination sources. Indeed, in several jurisdictions less efficient incandescents are being outlawed. However, an often neglected feature of LED illumination devices is that they possess a significant modulation bandwidth of up to 100's of MHz and their emissions are unregulated world wide. These exciting complementary communication aspects to LED lighting have generated considerable research and industrial interest culminating in the recent development of the IEEE 802.15.7 standard for visible light communications [3], [4].

On the other hand, power line communication (PLC) has been used some time in applications such as automation, control and monitoring [5]. Much like indoor illumination systems, power line networks were not designed with communication purposes in mind. Thus, the designer is faced with the difficulties of a medium not designed in principle to manage high frequency signals and already occupied by low frequency electric signals. Recent development in data modulation and transmission techniques has enabled high speed communications in this hostile medium. Techniques like multicarrier modulation including orthogonal frequency-division multiplexing (OFDM) are used to overcome the intrinsic multipath and noise inside power line systems [6].

The ubiquity of power line transmission and indoor power outlets point to the potential of using PLC as a networking backbone for smart home networking. Monitoring devices, computers, and multimedia devices can be seamlessly interconnected by existing power lines. Coupled with the need to power LED lighting systems, PLC presents an attractive solution as a backbone network for an indoor VLC system, much like the role Ethernet plays towards Wi-Fi. A VLC modem in an LED illumination fixture can receive data from the very power line that provides its power through a PLC modem and then act as the optical transmitter to cover the indoor area wirelessly. While the main use of VLC is for broadband downlink, i.e., from LED lighting to devices, we argue that this is well matched to Internet and multimedia data traffic, which is mostly in the downlink direction. For bi-directional communication, VLC would be paired with a lower rate uplink using RF or infrared [7]. We also mention an exciting additional application of VLC, which is localization. This is due to the unique feature of VLC networks that the emitted signal from a ceiling mounted light is highly localized beneath the fixture.

In this paper, we first review the current state of both broadband PLC and VLC systems. We then propose a number of new directions for the integration of PLC and VLC networks, which are inspired by modern wireless radio frequency (RF) communication techniques. In this regard, our work greatly extends previous contributions that consider some of the potential benefits of combining PLC and VLC, cf. [8], [9], [10], [11], [12]. We hope that this paper raises awareness and inspires interest in the PLC and VLC research communities for this promising combination of communication technologies.

II. BROADBAND POWER LINE COMMUNICATION

Even though 3G wireless cellular telephone networks and Wi-Fi are widely used for delivering broadband, PLC is a competitive solution especially for indoor networking.

The early use of PLC has mostly been limited to narrowband and low data-rate PLC systems, providing voice communication, supervisory control and data acquisition, and remote meter reading services [5]. In the 1990s, research and industry attention shifted towards broadband PLC. Both access and indoor communication scenarios were at the centre of

attention, with the latter proving to be the perhaps commercially more successful application scenario. Broadband PLC solutions commonly operate in the frequency band starting at about 2 MHz and ranging up to about 30 MHz or optionally beyond. Nominal data rates are usually above 100 Mbps. Recently, in 2009 and 2010, a number of existing broadband PLC specifications have been consolidated into two standards ratified by two standards developing organizations, namely IEEE 1901 [13] and ITU-T G.9960/61 [14], cf. also [15], [16].

The indoor PLC network usually has a tree structure, where lines branch off a breaker box towards the different building units and rooms. One derivation box usually connects all the power outlets in a room, cf. e.g. [17, Fig. 3]. This renders the links to different outlets being connected at a common point, which is alike the mobiles of a wireless communication system being connected to an access point or base station. PLC modems would be located at the outlets and communicate to each other and/or to a gateway modem located near the breaker box.

The PLC channel is generally a quite hostile communication medium. It is characterized by time, frequency, and location-dependent access impedances, frequency and time-varying channel transfer functions, and possibly high attenuation for the frequencies used for broadband PLC [6, Ch. 2]. At the same time, PLC is also affected by various noise types, in particular colored background, narrowband, and periodic and aperiodic impulsive noise [18]. To deal with the difficult transmission environment, multicarrier modulation has emerged as the dominant modulation technique, especially for broadband PLC. In particular, variants of OFDM have been adopted in the IEEE 1901 and ITU-T G.9960 standards. This includes various forms of adaptation of modulation and coding to cope with the frequency and time-selective behavior of the channel. For sufficient resilience to noise, powerful forward error correction and upper layer protocols are applied [19]. For further details we refer to [20], [6].

III. VISIBLE LIGHT COMMUNICATIONS

Having briefly revisited key facts about broadband PLC, we now move on to introduce the basics of VLC. Aiming at a mostly PLC-educated audience, we find it convenient to go into some more detail to make the integration of visible light and power line communication discussed in Section IV clearer.

A. Background

Optical wireless (OW) systems send information by varying the instantaneous intensity (i.e. power) of the optical source in time. Data are not sent in the underlying phase or amplitude of the optical carrier but rather only in its power. As a result, only non-negative signals can be sent from the transmitter. The total emitted power from the optical source is restricted by international eye and skin safety standards. At the receiver, a photodiode integrates the envelope of the received field and outputs an electrical current in near proportion to the optical power impinging on it.

A vast majority of OW systems operate in the infrared (IR) region. Such links can send data at rates of many Gbps over ranges of several kilometres. These systems are often referred to as free-space optics systems (FSO) and are currently commercially available from several vendors. In comparison, although the underlying devices are similar, VLC is a far less explored.

The key advantage of VLC is that transmitters are widely deployed due to their symbiotic relationship with indoor energy efficient lighting. Thus, VLC enabled lights could be easily and widely deployed in existing and new construction. In contrast to RF networks, the bandwidth available to optical emissions is nearly unlimited and can be used license-free worldwide. This is a major consideration given the ubiquity and widespread potential of VLC. Light is easily confined to a room by opaque boundaries increasing security of VLC emissions and virtually eliminating interference between VLC emitters in different locations. In addition, visible light emissions are intrinsically safe and cause no electromagnetic interference making VLC well suited to hospital, industrial and aerospace applications. Visible light is also much more eye-safe than infrared links due to the inherent blink reflex. As a result, safety regulations permit far larger emitted optical powers at visible wavelength range over IR. Unlike RF front-ends and receive chains, all signals in the VLC transmitter and receiver are at baseband and up/down conversion is done in the inexpensive optoelectronic components yielding a simpler, lower power transceiver.

Despite the inherent advantages, VLC systems also have numerous challenges. Due to the directionality of the emitted light, broadcast emissions can be difficult. Indeed, the confinement of optical energies to opaque boundaries can hamper mobility and accessibility. For example, a VLC receiver placed in your pocket will not receive any data! A key impairment for VLC receivers is if large ambient light is also collected which can induce short noise in the receiver. In addition, VLC emissions are limited not only by eye-safety standards but also the ability of users to dim the lights.

B. VLC System Components

1) *Transmitters:* The enabling technology for VLC emitters are white light illumination LEDs. The most common, and inexpensive, white illumination device is a blue LED which excites a yellow phosphor coating on the package. The phosphor is required to generate a more pleasing output colour temperature. This technique leverages existing knowledge in the formulation of good phosphor coatings, is robust and inexpensive to produce.

If the blue LED is modulated, as in a VLC system, the slow relaxation time of the phosphor coating will essentially lowpass filter all output emissions. As a result, in phosphorescent LEDs the modulation bandwidth is on the order of about 3 MHz. A simple technique to improve the bandwidth of the transmitter is to simply apply a blue filter at the receiver. In this way, the slowly varying wavelengths added by the phosphor are effectively removed leaving only the blue emission.

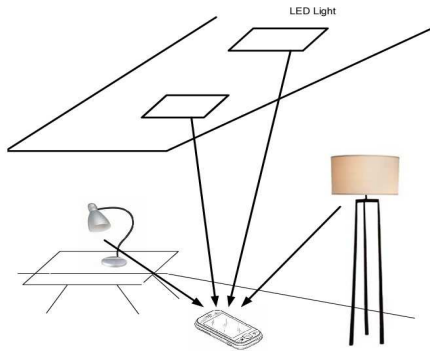


Figure 1: Configurations of indoor visible light communication system.

This blue filtering approach has been shown to improve the bandwidth on the order of 10-20 MHz [21], [22] at the expense of a loss of some signal power. Another method to improve the transmitter bandwidth is through pre-compensation. By employing pre-compensation techniques at the transmitter's side, higher modulation bandwidths for phosphor-based LED are achieved [23], [24]. In [23], a link that uses 16 LEDs which are modulated using a resonant pre-compensation technique is described, yielding an overall transmitter bandwidth of 25 MHz. Using this technique, a 40-Mb/s On-Off keying Non-Return-to-Zero (OOK-NRZ) link which operates at low error rates is achieved.

More complex and expensive LED architectures are also available for illumination applications. One example is the red-green-blue (RGB) LED which contains three LED dice which are jointly packaged. This device omits the need for a phosphor and is able to have high modulation bandwidths in excess of 100 MHz. In addition, the colour of the output light can be modified according to the user demand. More advanced resonant cavity LEDs (RCLEDs) also hold much promise for illumination and employ a Bragg reflector in the device to enhance the emitted light, offering high efficiency and high bandwidth in light communication systems.

2) *Channel*: Similar to infrared links, indoor VLC links can be classified into line-of-sight (LOS) and non-line-of-sight (NLOS) links [25]. Figure 1 presents some configurations for indoor VLC links. LED emitters could be housed in a variety of illumination devices which are ceiling or desk mounted.

In LOS links, the VLC Channel exhibits high signal-to-noise ratios (SNRs) due to international regulations that maintain a minimum illuminance of 400 lux for all office workspace. Experimental measurements of VLC channels have noted SNRs in excess of 30 dB [2] and often approaching 60 dB [26]. Thus, indoor VLC channels are well modeled as bandwidth limited and often with high SNRs. NLOS VLC links exist due to diffuse reflections from surfaces in the room. Such links suffer from limited bandwidth due to multipath dispersion and a loss in received signal power [25] [27]. Notice, however, that indoor optical wireless links do not suffer from multipath

fading since the receiver photodiode is tens of thousands of square wavelengths in size providing an inherent degree of spatial diversity. Since NLOS links have far lower received signal power and lower bandwidths due to diffuse reflections, LOS VLC links are considered the most attractive for short range communications.

3) *Receivers*: The photoreceivers in the VLC link, as shown in Figure 1, can be housed in a portable device such as a smart phone. Such devices currently include a wide variety of optical sensors which can be leveraged or expanded to take advantage of VLC. For example, ambient light sensors on the device are typically implemented with simple photodiodes which could be employed to detect the changing optical intensity. Inexpensive communication photodiodes exist which can support data rates in excess of 1 Gbps.

Another possibility for a receiver is the use of the imaging array on the phone. These devices typically have many million receive elements, excellent optics and frame rates on the order of 30 fps. Indeed, the images on smart phone can be considered as broadband receivers. Such devices, although limited in signalling rate, are able to detect large amounts of spatial information. Thus, they are ideally suited to multiple-input/multiple-output (MIMO) VLC architectures.

C. Technology Development

The use of white LED illumination devices for indoor communications was first proposed by Komine et al. [2], [28]. However, enthusiasm for this research topic has spread worldwide with active research groups in the USA (e.g., Penn State U, Boston U, Rensselaer Poly, Georgia Tech.), Europe (e.g., Oxford, Northumbria, Edinburgh, Fraunhofer Heinrich-Hertz Inst.) and Asia (e.g., Keio U., Tsinghua U.). In addition, large research projects in VLC have been launched including the Visible Light Communications Consortium (Japan), Omega Project (2008, EU), Smart Lighting Engineering Research Center (2008, USA), Center on Optical Wireless Applications (2011, USA) and Canadian Research in VLC (2012).

Visible light data transmission exceeding 100 Mbps has been demonstrated using a phosphorescent white-light LED [29]. Visible light links operating at transmission rates up to 200 Mbps over typical room, using optical filtering and on-off-keying as well as discrete multi-tone modulation combined with off-line processing has also been shown in [30]. Utilizing RGB LEDs, a data rate of 780 Mbps is achieved at 2.5 m distance using a multicarrier (discrete-multitone (DMT)) modulation scheme [31]. Multi-gigabit-per-second data rates over short distances using arrays of LEDs in a multiple-input multiple-output (MIMO) fashion has also been shown in [32].

In 2011, the IEEE ratified 802.15.7, a wireless PAN standard for VLC [3]. The standardization activities were led by Samsung (Korea) and Intel (USA). Data rates in the standard range from 11 kbps to 96 Mbps using on-off keying (OOK), variable pulse-position modulation (V-PPM) and colour-shift keying (CSK). However, many other advanced modulation methods have been proposed. The most promising scheme is orthogonal frequency-division multiplexing (OFDM or DMT)

due to the multiple paths effects for indoor environment. OFDM is investigated in [29] [23] [26] [33] [9] [34]. Other proposed potential modulation schemes include inverted pulse position modulation (I-PPM) [35] and pulse width modulation with changing modulation depth [36].

IV. PROPOSALS FOR PLC-VLC INTEGRATION

With the newly established standards for both PLC and VLC [13], [14], [3], there is a strong motivation to explore the integration of the VLC and PLC technologies. The resulting PLC-VLC system is an efficient and economical way to fulfill the need of broadband access for indoor users. The LED lighting system then functions as a wireless broadcaster for data fed from power line communication and enables the deployment of a broadband distribution downlink with very little extra cost. This section presents some proposals for the integration of PLC and VLC communication infrastructures. Although others have considered or mentioned this topic, [8], [9], [10], [11], [12], here we up the discussion in light of the new standards as well as adding new perspectives from modern RF wireless communication techniques.

Notice that both PLC and VLC technologies provide the potential for gigabit communications at a lower cost and with higher security compared with Wi-Fi. Of course, the PLC-VLC system is ideally suited to broadband downlink, there is no fundamental reason why an optical uplink could not also be implemented, perhaps in the IR. However, due to the largely asymmetric pattern toward downlink traffic and benefits of interference mitigation, it is expected that PLC-VLC for downlink coupled with a lower rate RF link for uplink is the most likely near-term implementation.

Our vision is one of mobile devices that are able to wirelessly receive data from overhead illumination devices that are interconnected via the existing power network. When all LED lamps are connected via PLC, the PLC infrastructure could be operated as a local backbone network that allows coordination among VLC transmitters within a room or building. The coordination among VLC transmitters would enable virtual MIMO systems much like the downlink in cellular systems.

A number of techniques successfully developed in wireless cellular networks can possibly benefit PLC-VLC systems. Here we propose some system models and directions primarily focused on cooperation in PLC-VLC systems. Generally speaking, there are two ways of cooperation in wireless networks: (i) via a MIMO or virtual MIMO model for cooperative transmission over otherwise interfering links and (ii) using relays.

A. Proposal 1: MIMO Techniques in PLC-VLC

Indoor VLC is inherently a multi-transmitter medium. Each lighting fixture is composed of many individual LEDs while a room will have many lighting fixture interconnected by PLC. User mobility is likely to be slow so that the channel can be viewed as quasi-static. Since VLC employs direct detection receivers, the overall MIMO channel matrices differ greatly from their RF counterparts [32].

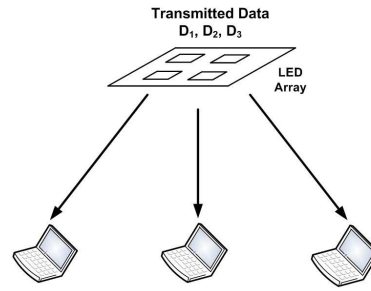


Figure 2: Illustration of a broadcast-channel model for a PLC-VLC system.

1) *Broadcast Channel*: Consider a VLC broadcast network where each light fixture represents a separate transmitter, as illustrated in Figure 2. Thus, each LED light fixture can be thought of as an access point. Borrowing concepts from multi-user MIMO broadcast in cellular networks, each LED light fixture represents a single antenna in the PLC-VLC system. Channel state information (CSI) can be made available at the transmitter by using an RF uplink which feeds back the receiver's estimates of the channel found using downlink training data. Application of dirty paper coding at the transmitter can then be used to achieve interference cancellation permitting each receiver to perform independent decoding.

2) *Cooperative MIMO in Indoor PLC-VLC*: In cellular downlink systems, the same frequency bands are re-used in different cells. Users near cell boundary areas of cellular networks are severely affected by the intercell interference since the received signal strength from different cells is nearly identical. To solve this problem, network coordination amongst base stations is employed. Antennas at different nearby base stations act as a virtual or distributed MIMO system and coordinate with each other in an interference-aware way. This coordination requires the exchange of information through backhaul links between the base stations. The outputs of different antennas are chosen in a way that minimize the intercell interference thus increasing the total channel capacity even if the receiver has a single antenna. In other words, the receiver is able to receive useful information from all nearby base stations.

In the context of PLC-VLC integration, consider adapting this concept with PLC acting as a local backbone network for different VLC transmitters. Similar network coordination can be achieved in the future indoor PLC-VLC system, where each lighting fixture is an optical base station and its emission area is the cell coverage area, as seen in Figure 3. At the interface between two lamps, their coverage area overlaps leading to optical intercell interference. With the support of the underlying PLC backbone network, coordinated transmission can be accomplished so increasing spectral efficiency and quality-of-service (QoS) of indoor network services.

The practical challenges of this approach mirror those in cellular downlink systems, namely imperfect synchronization among LED lamps and network latency resulting from the

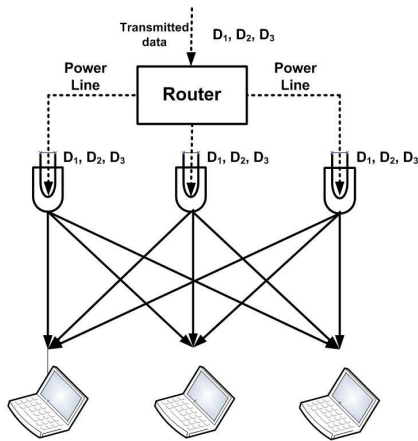


Figure 3: Illustration of a cooperative MIMO model for a PLC-VLC system.

distribution of channel estimates across the LED lamps. In this PLC-VLC system, PLC acts as the backbone network and so the latency requirements for the PLC network need to be further explored.

B. Proposal 2: Relaying Techniques for PLC-VLC

The finalization of standards for PLC and VLC is an essential step towards the wide spread of the PLC and VLC technology. The IEEE 802.15.7 [4] defined the MAC and PHY for a VLC personal area network (VPAN). In this standard, three modulation schemes, on-off keying (OOK), variable pulse-position modulation (VPPM) and color shift keying (CSK) are considered. While its counterparts for broadband power line communication, IEEE 1901 [13] and ITU-T G.9960 [14], defined FFT-OFDM-based and Wavelet-OFDM-based PHYs.

The conventional integration of PLC and VLC would apply a fully-fledged PLC receiver linked to a fully-fledged VLC transmitter at the application layer. Here we propose an alternative form of integration, again inspired by cooperative transmission techniques, namely the employment of relays. In a cellular network, both throughput and range extension can be enhanced with the use of relay. A PLC-VLC system can be considered as a relay-assisted two-hop communication system without direct link between the source and the destination. LED lamps act as relays while the transmission in the power line can be regarded as the first hop. At the signal transmission level, there are two methods for the combination of PLC and VLC imported from the cellular network, one is decode-and-forward (DF), the other is amplify-and-forward (AF). In the former, the PLC signal brought to the LED array could be demodulated and decoded and then re-encoded and re-modulated for the VLC transmission. In the latter, the analogue PLC signal plus the noise component will be directly amplified and then retransmitted by the VLC transmitter. Figure 4 illustrates the PLC-VLC link with the DF/AF-based signal combination. Even though there are papers comparing DF with

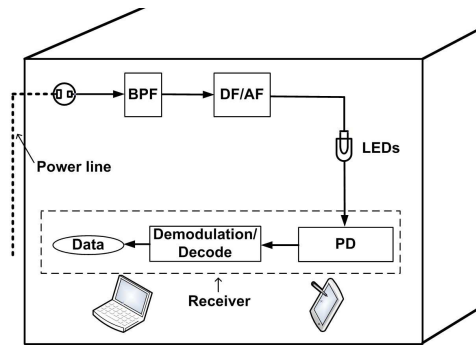


Figure 4: Illustration of the PLC-VLC link with DF/AF-based signal combination (BPF: bandpass filter, PD: photodiode).

AF [37], [38], the unique set of channel conditions of PLC and VLC requires a revisit to this topic to investigate the suitability of DF and AF for PLC-VLC.

Modern broadband PLC systems are primarily based on multicarrier modulation, like OFDM. Since this modulation has also been proposed for high data-rate VLC systems, we suggest multicarrier-based AF implementations. Modulation bandwidth, the proper multicarrier format for VLC, LED nonlinearity, filtering of low frequency noise on the power line, and the implementation of the PLC-VLC coupling unit should be considered. For the DF approach, interesting aspects include the calculation of achievable network data rates and the proper formats of VLC for combination with a multicarrier PLC system, so that the overall PLC-VLC link throughput is maximized.

V. CONCLUSION

Both VLC and PLC are opportunistic communication channels which piggyback on primary roles of illumination and power delivery. With the recent ratification of broadband PLC and VLC standards, the integration of these two techniques for indoor wireless networks has begun to attract the attention of the research community. This paper has provided a brief introduction to these channels and has discussed several proposals for integrating them. We have looked at the opportunities for integrated power line and visible light communication, borrowing concepts from modern RF wireless communications. In particular, and for the first time, cooperative transmission concepts that exploit the joint use of PLC and VLC have been introduced. We hope that this paper spurs further discussion and research on this exciting union of communications technologies.

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