PLiFi: Hybrid WiFi-VLC Networking using Power Lines

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Abstract

With advancements in solid-state lighting, Visible Light Communication (VLC) provides novel opportunities for high-speed networking. Properties such as feasibility of multi-gbps data rates, lower interference, better communication privacy, and dual use of LEDs for illumination and communication make VLC an attractive choice for indoor Internet access networking. However, three major challenges - absence of low-cost solution for LED-Internet connectivity, unavailability of uplink communication, and performance degradation due to device mobility - need to be addressed for realizing VLC's full potential as Internet access network technology. In this paper, we propose PLiFi, a hybrid WiFi-VLC network architecture through the use of Power Line Communication (PLC). PLiFi creates a high-speed interconnection between LEDs themselves and to Internet at low cost, and also seamlessly integrates WiFi and VLC networks. We show how PLiFi can address the above mentioned challenges, and can create a framework for implementing VLC CoMP hybrid WiFi-VLC MAC protocols. Our preliminary results prove that today's PLC technology provides sufficient data rates and coverage. We demonstrate that RSS variations due to mobility and SINR degradation due to co-channel interference can be alleviated using coordination between LEDs which is feasible through PLiFi design.

1. INTRODUCTION

With ever-increasing interest from both research community and industry, Visible Light Communication (VLC) is emerging as a possible solution for relieving the issue of crowded RF spectrum. Visible light provides an unlicensed spectrum of over 400 THz (from 390 THz to 800 THz) that can be used for communication. Recent advances in solid state lighting have proven that LEDs (Light Emitting Diodes) can modulate the data in a variety of ways such as On-Off Keying (OOK), Orthogonal Frequency Division Multiplexing (OFDM), Color Shift Keying (CSK) etc. to increase the spectral efficiency. This is further fueled by consistently increasing adoption of LEDs in indoor lighting applications. VLC provides many advantages over RF communication. First, due to its higher frequency, VLC signals cannot penetrate walls, significantly reducing interference even when there is a dense deployment of VLC cells. Considering its very high achievable data rates (over 1 Gbps [1], [2]), VLC can provide comparable or even higher data rates than current WiFi networks. Second, VLC enables the reuse of existing lighting infrastructure for the purpose of communication. This means that networks can be deployed with more ease and at a lower cost. Third, the inability to penetrate walls provides VLC a better security where eavesdropping is comparatively more difficult.

Even with these promising features of VLC, it is far from being used as an Internet access network technology. There are many challenges that need to be addressed before visible light networks become feasible in practice. We identify three main challenges as follows -

(1) LED to Internet Connectivity: Majority of research in VLC has been focused on the issues of LED-to-receiver (photodiode or image sensor) communication without delving into how the LEDs connect to Internet for providing Internet access network-like services. For example, in an indoor environment, connecting LEDs to the Internet gateway using Ethernet is prohibitively expensive. A low-cost solution that can provide Internet connectivity to the LEDs is essential.

(2) Uplink and Coverage: Since the receiver devices (such as smartphones, wearables etc.) cannot be equipped with a high-power LED for uplink communication, the primary application of VLC has been limited to broadcast [3, 4]. In order to build a network for Internet access in practice, it is imperative for the receiver devices to rely on existing WiFi infrastructure for uplink communication. However, in the absence of any interfacing between downlink VLC and uplink WiFi, it is not possible to provide link layer reliability in VLC. Due to smaller radius of VLC cells, it is also difficult to guarantee uninterrupted coverage. Apart from the smaller radius, visible light communication can be unavailable when there is no illumination (e.g. at night time) in the indoor space. In such scenarios, the devices should rely on existing WiFi infrastructure for downlink communication as well. Hence, it is desirable that the VLC and WiFi networks can coordinate to provide seamless, high-speed connectivity to the user devices.

(3) Device Mobility and Co-channel Interference: Compared to WiFi, the received signal strength of a VLC receiver varies substantially even within one VLC cell. This is because VLC performance reduces when either the LED and receiver photodiode are not aligned with each other or there exists interference from the other transmitter. For the mobile devices, user mobility and device orientation changes can result in frequent interruptions in VLC. The problem can be alleviated by using multiple, smaller, distributed LEDs instead of one large LED (as commonly used in illumination applications). For the problem of co-channel interference, Coordinated Multi-Point transmission (CoMP) among adja-

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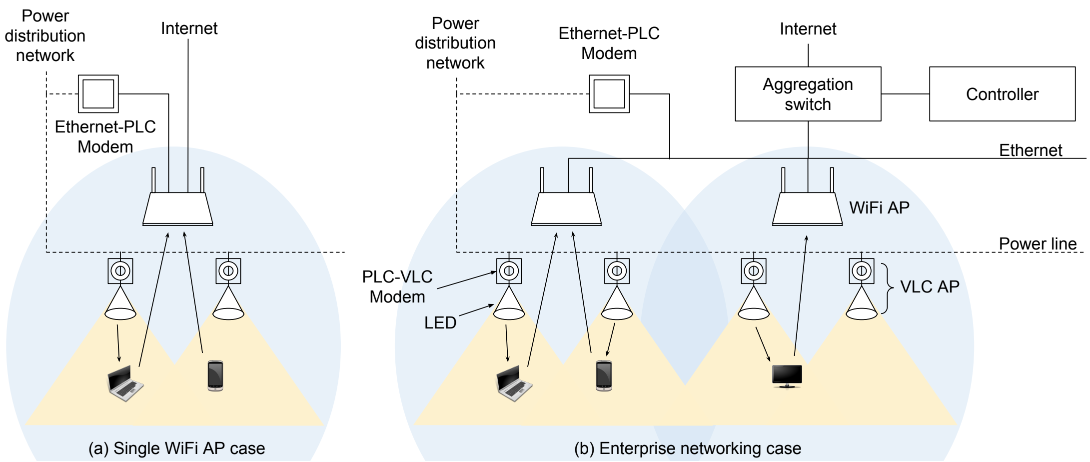

Figure 1: PLiFi **integrates WiFi and VLC networks using power line communication**

cent LEDs could improve the SINR of the receiver. However, in current state of the art, such CoMP transmission is not feasible due to the absence of any technique that can interconnect LEDs and synchronize the joint transmission.

In this paper, we propose PLiFi, a novel architecture that creates hybrid WiFi-VLC networks with the use of power line networking. PLiFi exploits the omni-present power lines for creating a wired backbone that connects the LED transmitters to each other as well as to the Internet. Additionally, PLiFi utilizes Ethernet-PLC modems to facilitate a way of direct communication between the WiFi and VLC networks. PLiFi is cost-effective since it reuses the already deployed power lines without any need of deploying additional wired backbone to interconnect LEDs. We show that the hybrid PLC-VLC-WiFi network can solve the three main challenges discussed above in a practical and cost-effective manner. We discuss the potential of PLiFi in terms of WiFi-assisted VLC MAC design, design choices in Ethernet-PLC and PLC-VLC modem as well as feasibility of VLC CoMP using power line backbone. PLiFi creates a framework for augmenting WiFi using VLC by exploiting the best of both the technologies, and developing hybrid WiFi-VLC protocols.

Our evaluation suggests that the performance of PLC using today's COTS (Commercial Off-The-Shelf) Ethernet-PLC modems is sufficient to design PLiFi. Additionally, we show how device mobility changes events can affect the RSS in VLC, and how the use of joint transmission from multiple distributed LED transmitters can relieve the co-channel interference. This substantiates the need of interconnecting LEDs which can be accomplished using PLiFi.

2. PLIFI OVERVIEW

(1) PLC Background: Power line communication utilizes the existing electrical wire network for data communication. With the introduction of HomePlug AV2 standard [5] in 2012, the popularity of PLC is increasing with over 120 million HomePlug devices worldwide by 2013 [6]. The HomePlug AV2 standard utilizes the entire available bandwidth of 1.8 to 86.13 MHz [7] and OFDM modulation (upto 4096 QAM). It also supports MIMO where any two pairs of wires from line, neutral and ground can be used for 2×2 MIMO. It employs CSMA/CA for multi-station access with similarities with IEEE 802.11 MAC. The proposed standard is shown to achieve over 1 Gbps of PHY data rate.

(2) System Architecture: Fig. 1(a) shows the PLiFi architecture in single WiFi AP scenarios such as homes, small businesses etc. Note that the central goal behind the design of PLiFi architecture is to utilize the visible light communication for augmenting existing WiFi networks through the use of power lines. As shown in Fig. 1(a), the WiFi AP connects to the power line network using an Ethernet-PLC modem. Similarly, the power line network connects to the LEDs [1] with the use of PLC-VLC modem. This results in many VLC cells within the coverage area of a WiFi cell. For the downlink transmission from the perspective of end devices, the packets received from the Internet are first forwarded to the power line network by the WiFi AP, and then to LED transmitters which deliver the packets to the end devices. On the uplink, the end-devices directly connect to the WiFi AP. Fig. 1(b) shows how the proposed WiFi-VLC access networks can be used in an enterprise scenario. In the enterprise case, more than one WiFi APs are used to provide coverage and capacity to a relatively larger area and user population. In such cases, WiFi APs are centrally managed through wireless controller. In this generalized version, the controller can be connected to the power line network to manage the WiFi APs, VLC APs and WiFi-VLC cells.

PLiFi solves the challenges described in the introduction. First, it provides a cost-effective way of connecting the LEDs to the Internet. Because the power lines are already ubiquitous, no additional cables are necessary to be deployed. The use of Ethernet-PLC modem and PLC-VLC modems incurs additional cost. We discuss in the next section how the cost of these modems can be low depending on their design. Second, because end devices use WiFi uplink and VLC downlink in PLiFi, any interruption in VLC downlink can be conveyed to the WiFi AP directly, allowing the controller (WiFi AP itself in a single AP case and dedicated controller in the enterprise case) to switch to WiFi for downlink communication. This ensures uninterrupted connectivity to the end devices even when VLC is not available (e.g. at night or in dark indoor spaces). Third, the power line backbone can be used by multiple, distributed LEDs to communicate, coordinate and/or synchronize their transmissions to the receivers so that the co-channel interference is reduced.

3. POTENTIAL AND DESIGN CHOICES

In this section, we describe how PLiFi architecture opens up new

[1] One LED luminaire (bulb) can contain many LEDs, but in this work, we refer to it as an LED only for brevity.

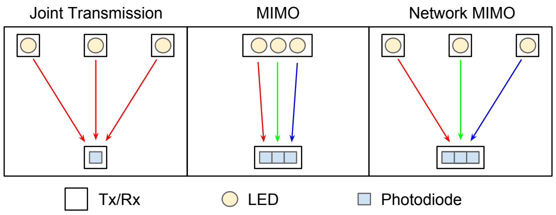

Figure 2: Comparison of (a) VLC joint transmission CoMP, (b) VLC MIMO and (c) network MIMO with VLC; The LEDs are spatially separated in (a) and (c), while (b) uses array of co-located LEDs; Different color arrows indicate different parallel data streams.

opportunities for the WiFi-VLC network design and discuss various design choices associated with them.

(1) MAC Design: As mentioned before, it is challenging to provide link layer reliability for the VLC downlink in the absence of any feedback from the end devices. In PLiFi, the end device can use the WiFi uplink for sending a NACK for the MAC frames that are lost or corrupted in the LED-to-device transmission. Once the NACK is received by a WiFi AP, it can notify the corresponding VLC AP over the wired connection (Ethernet and power line) to retransmit the frame. The packet loss ratio can also be used by the coordinator for detecting poor VLC link and forcing vertical handover (from VLC to WiFi) of the device.

The choice of MAC layer for VLC plays an important role in achievable downlink capacity. Different from WiFi omni-directional antennas, the LEDs have much smaller Field-Of-View (FOV) which restricts their light emission towards their central axis with beamwidth smaller than 180^o. Because of the restricted FOV of different LEDs, their relative positioning and the absence of any light sensing photodiode, it is difficult for one LED to detect another LED's transmission. This means that CSMA/CA cannot be used for medium access in the VLC downlink transmission. In other research, the use of CSMA/CA in VLC either assumes VLC uplink (IEEE 802.15.7 [8]) or bidirectional LEDs [9]. However, with power line interconnection between the LEDs, they can exchange RTS/CTS packets for collision avoidance over PLC, but it still does not facilitate carrier sense functionality. On the other hand, the power line interconnect can be used to implement other VLC MAC protocols such as TDMA, Optical CDMA or OFDMA (refer to [10] for a survey). For example, LEDs can coordinate their transmission schedule over the power lines to ensure collision free transmissions.

(2) Ethernet-PLC and PLC-VLC Modems: In a single AP case, one Ethernet-PLC modem is sufficient to serve the power line network of a home or a small business. On the other hand, each VLC transmitter requires a PLC-VLC modem to serve the small VLC cells. Since LED deployment is likely to be comparatively denser, this can increase the overall deployment cost. However, since PLC-VLC modem only requires demodulating PLC signals (OFDM in HomePlug AV2) , low-cost customized chipset can be developed for the purpose. The LED modulation is known to be low cost especially considering the dual use of illumination. For the enterprise networks, multiple Ethernet-PLC modems might be necessary (e.g. one for each WiFi AP), given that the PLC signals attenuate beyond a certain distance. This is also beneficial as it can divide the power line medium into multiple collision domains with low inter-domain interference.

(3) VLC CoMP and MIMO: A typical room in a home or an office is equipped with multiple LED lamps to provide sufficient illuminance. With the availability of power line interconnections, it is possible for the LEDs to employ CoMP transmissions. In a common form of CoMP, multiple LEDs can synchronize to transmit the same signal to a receiver to improve the SINR. Due to small cell radius and dense deployment, CoMP can be especially beneficial in PLiFi architecture to improve VLC performance. We evaluate the advantage of using CoMP joint transmission in Section 4.2.

Apart from CoMP where one data stream is transmitted from multiple LEDs to a receiver, PLiFi can enable *network MIMO* in VLC. In RF communication, MIMO is designed to leverage the spatial diversity where different spatial paths achieve diverse gain. Such diversity gains are limited in VLC MIMO because spatial paths between the transmitter (array of co-located LEDs) and the receiver (array of photodiodes) are very similar (less diverse) indoors. This decreases the spatial multiplexing gains of VLC MIMO. However, a *VLC network MIMO* is feasible with PLiFi. In network MIMO, multiple distributed LEDs can transmit parallel data stream in an interference-free manner to an array of photodiodes as shown in Fig. 2. The use of distributed LEDs can achieve higher spatial diversity gains compared to VLC MIMO. Such network MIMO requires tighter synchronization [11, 12], which is feasible in PLiFi as the LEDs are already connected via power lines.

Apart from these, PLiFi provides a framework to create a variety of new applications such as visible light sensing in smart spaces [13], localization [14, 15] etc.

4. PRELIMINARY RESULTS

We first evaluate the performance of data communication over the power lines and then the impact of mobility and co-channel interference.

4.1 Power Line Network

Our objective is to understand how well state-of-the-art COTS PLC devices perform in terms of achievable data rates and coverage, and whether or not they are suitable for interconnecting the LEDs as proposed by PLiFi. In our experiments, we use ZyXEL PLA5405 Ethernet-PLC [16] modules with Qualcomm QCA7500 [17] PLC chipset. The QCA7500 implements HomePlug AV2 PHY and MAC along with a support for 2×2 MIMO.

We use two Ethernet-PLC modules in a university building with an area of approximately 1300 square meters (Fig. 3). For the server module, we connect one end of the modem directly to a power socket and the other end to a Linux server using Ethernet. Similarly, the client module is connected to a power socket and a laptop. We move the client module to different power sockets throughout the building while running iperf between them. Fig. 3 shows the UDP throughput for different client locations. We observe that within the same room, our COTS devices can achieve data rates in the range of 300-400 Mbps. For the neighboring rooms (approximately at 8 meters distance from the server), the iperf throughput is observed to be in the range of 200-300 Mbps. The observed throughput drops with increasing distances as expected due to the attenuation of PLC signals. At farther distances (beyond 25 m), the throughput reduces to less than 50 Mbps. However, for distances in range of 14-25 m, it is possible to achieve data rates in the range of 50-100 Mbps.

These coverage and data rate results show that today's PLC standard and devices are suitable for networking LEDs as proposed by PLiFi. For enterprise scenario, where more than one Ethernet-PLC modems can be used, the transmission power on the PLC transmitters can be controlled to manage the interference. For single WiFi AP scenario, data rates and coverage observed in Fig. 3 is likely to be sufficient to cover the distances in a home or a small business.

It is known that the use of other electrical appliances affects the

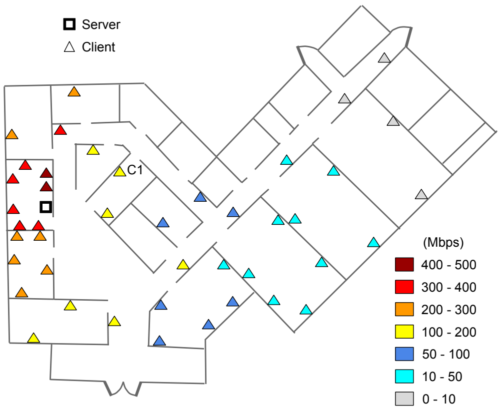

Figure 3: PLC data rates and coverage in a building.

performance of PLC (HomePlug AV evaluation in [18]). However, in our experiments, we use new generation HomePlug AV2 devices, and a variety of electrical appliances (e.g. kitchen appliances like microwave, refrigerator; office equipment like computers and peripherals) were already in use throughout the building floor during the time of experiments. We observed the highest standard deviation across all client locations to be 4.7 Mbps at location C_1 in Fig. 3. Although PLC performance in our experiments was relatively stable, a comprehensive characterization in controlled settings is necessary with different electrical loads and building types.

4.2 Visible Light Mobile Network

We now evaluate visible light communication in real-world scenarios with user mobility and different transmission schemes. Our goal is to understand (i) how these factors affect the received signal strength? and (ii) How coordination between LEDs can be used to overcome the performance degradation?

Most off-the-shelf LED bulbs use lens and other reflective fixtures around the LEDs to distribute the light in different directions depending on their intended application. This can cause the signal propagation to vary significantly from the emission pattern of bare LEDs. We use an off-the-shelf LED (TCP RL10DR427K [19]) with 650 lumens as the transmitter. We modify its circuitry to control it through an embedded board (BeagleBone Black [20]) and transmit OOK signals. The transmitter (BeagleBone, LED circuitry and power supply) is shown in Fig. 4. The signal is received by a receiver composed of a photodiode connected to a BeagleBone Black board. For evaluation, we use two different photodiodes with different lens and FOV.

We use the two photodiodes to measure the radiant intensity of the LEDs (referred as RSS) at different receiver positions and orientation. We report normalized RSS since the absolute values vary significantly for different lens and photodiodes.

In order to investigate the effect of receiver movement and orientation changes on RSS, it is necessary to understand the emission pattern of LEDs. Let us assume the luminous flux emitted by a LED is F_T. The received flux (F_R) depends on receiver's relative position and orientation which is shown in Fig. 5(a). Here, the angle between transmitter's normal axis and the transmitter-receiver line is referred as irradiation angle (β). The angle between receiver's normal and the transmitter-receiver line is called incident angle (α). Let the distance between transmitter and receiver be D. The voltage generated by the photodiode is proportional to the area of the photodiode where the photons are collected. It is known from [21, 22] that the luminous path loss (L_L) can be calculated as

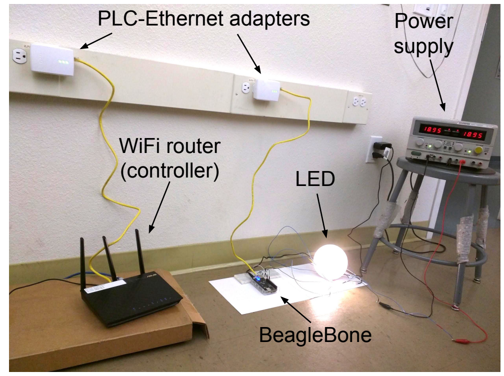

Figure 4: PLiFi Testbed: VLC transmitter includes a BeagleBone Black board (data source), modified LED and a power source; The VLC transmitter and WiFi router (controller) are connected through power line (PLC-Ethernet adapters in our testbed)

follows,

$$L_L = \frac{F_R}{F_T} = \frac{(m+1)A}{2\pi D^2} \cos\alpha \cos^m\beta \qquad (1)$$

where m is the order of Lambertian emission. Most commonly used LEDs are pure Lambertian emitters where $m = 1$. We evaluate three main factors - (1) distance (2) irradiation angle and (3) incident angle - in terms of receiver signal strength. We study these factors as they are primarily affected by user and device movements. The experiments reported in this work were done in a dark room at night with no other light sources. As mentioned in [21], the effect of ambient sunlight and other noise sources (e.g. fluorescent or incandescent lamps) can be removed using bandpass frequency filtering.

User Mobility: The distance and irradiation angle vary when user moves around the LED transmitter (change of location) in a VLC cell. Hence, it is interesting to understand how the RSS changes when varying the distance the irradiation angle. For measuring the impact of distance variation, we point the LED and photodiode to each other (incident and irradiation angles are 0^o) in a horizontal plane and vary the distance between them. Fig. 5(b) shows the normalized RSS as measure by the photodiode. The RSS drops sharply as the distance increases, in perfect accordance with inverse square law as per Equ. 1. Next, we measure the received power while varying the irradiation angle. The distance is fixed and the incident angle is also set to 0^o. This means that even though the irradiation angle changes, we ensure that photodiode also directly pointing to the LED. From Equ. 1, it is known that RSS follows a cosine function of the irradiation angle (β). Fig. 5(c) shows the observed and theoretical RSS with variation in β. It is observed that cosine function accurately models the irradiation pattern of Lambertian LED.

When the user is moving, her actions can introduce large variations in receiver's orientation. A change in orientation can vary the incident angle as shown in Fig. 5(a). As per Equ. 1, RSS also changes as a cosine function of the incident angle (α). Fig. 5(d) shows the observed RSS with variation in incident angle. It is seen that the observed RSS does not follow the cosine curve, but instead, drops much faster with increase in the incident angle. This is due to lens's narrow FOV which is not modeled in Equ. 1. The FOV is shown in Fig.5(a). As different lens have different acceptance angle to concentrate the received light (similar to camera sensor) on the photodiode, the incident light could be partially blocked based

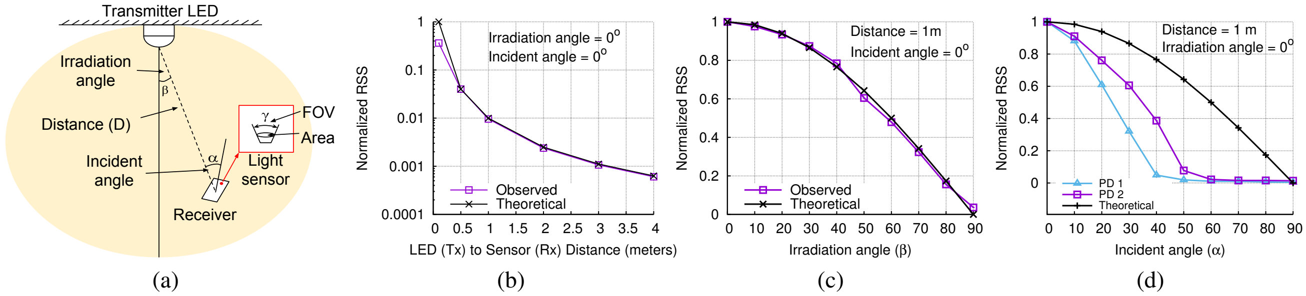

Figure 5: (a) Relative positions of Tx and Rx; Theoretical and observed RSS degradation with increase in (b) Tx-Rx distance, (c) irradiation angle and (d) incident angle.

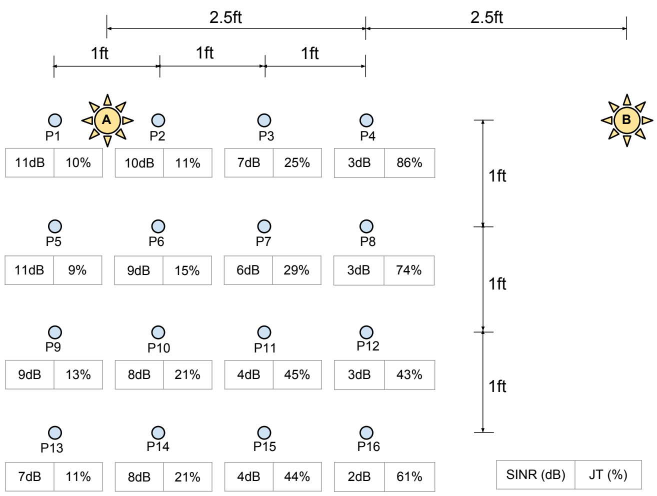

Figure 6: Observed SINR (dB) at different client locations, and percentage gain of utilizing joint transmission (JT%); Receiver's SINR is calculated for LED A as transmitter and LED B as interferer.

on the FOV when receiver orientation changes. We validate this using two photodiodes with different lens FOV, and the corresponding RSS values are shown in Fig. 5(d). As expected, the lens with larger FOV results in higher RSS when α changes compared to smaller one. Generalizing further, if the FOV is 180^o, a closer match to the cosine curve is expected. Note that the FOV-related degradation was not observed in distance and irradiation angle experiments because in both of those cases, the light sensor was directly pointing to the LED (without any orientation changes).

Individual vs. Joint Transmission: We now show how PLiFi can enable informed coordination and control between the LED transmitters. A typical room is usually equipped with multiple LEDs to meet the illumination requirement. Without any coordination, each LED transmitter can choose to transmit different data, causing harmful co-channel interference between the adjacent LEDs and reducing the achievable data rate. However, with PLiFi, it is possible for a receiver to provide feedback to the controller using the WiFi uplink. The receiver can feedback real-time SINR to the controller, and the controller can use the SINR to estimate the channel state and dynamically change the transmission scheme. We consider two transmission schemes:

(1) Individual Transmission: If the SINR is higher than a predefined threshold, which means that the receiver is much closer to one LED transmitter and farther from other LED interferers, each LED can independently transmit its own separate data to its clients. In PLiFi, this can be implemented through all PLC-VLC modems in a room operating independently.

(2) Joint Transmission: If the SINR is below the threshold, the client can be in an overlapping area of illumination of the LED transmitters. In this case, the controller can configure the LED transmitters to transmit the same data to eliminate any interference. Such coordinated, joint transmission can be implemented in PLiFi by synchronizing the PLC-VLC modems of the LEDs so that they can transmit identical signals.

We now evaluate the feasibility of individual vs. joint transmission using our PLiFi testbed. Here, two LED transmitters are affixed on the ceiling of a university lab room at a distance of 5 ft. Both the LED transmitters contain modified circuitry of LEDs and are controlled through BeagleBone Black. As shown in Fig. 4, the BeagleBone Black boards are connected to a WiFi router (Asus RT-AC68U) through power line[2]. The router is flashed with our custom firmware to enable real-time controller functionality. The receiver BeagleBone is also equipped with WiFi interface to connect to the controller and provide SINR feedback.

Fig. 6 shows the SINR measured by a receiver at 16 locations (4 ft. $\times$ 4 ft. grid). The vertical distance between the LEDs and the receiver is 4 ft. The first box in each observation presents the observed SINR for the client when it receives individual transmission from LED A. In this case, LED B acts as an interferer by transmitting different data. The second box presents percentage increase in SINR when both LED transmitters transmit the same signal through joint transmission. It can be observed that as the receiver moves away from LED A and towards LED B, the SINR decreases sharply under individual transmission scheme. However, due to the SINR feedback over WiFi, the controller chooses joint transmission in such cases, increasing the SINR drastically. For example, for location P_4, the SINR increases by 86% under joint transmission. It is also observed that for location P_{13} in far edge of both LEDs, joint transmission yields insignificant improvement in SINR.

5. RELATED WORK

Physical layer design for VLC has received much attention in last few years (refer to [10] for a survey). This includes different modulation techniques like OOK, OFDM, CSK and different MAC protocols such as TDMA, OFDMA, CDMA and CSMA. Although, this research either deals with increasing the data rate of one link or

[2]For this paper we use PLC-Ethernet modem as a bridge between Beaglebone Black and WiFi router. Design of PLC-VLC modem is part of our ongoing work

assumes an Ethernet backbone connecting the LEDs. Power lines have been used for LED dimming [23] and achieving synchronization between WiFi APs [11]. Authors in [24] showed how power lines can be used to broadcast through LEDs but did not provide any solution for uplink or WiFi integration which is necessary for VLC MAC design, CoMP and MIMO. Some recent research [4, 25, 14] has considered the use camera sensor for VLC reception. PLiFi does not put any restriction on the type of receiver (camera sensor or photodiode), although the camera sensor is known to be energy expensive and slow (lower sampling rate) compared to the light sensor. In a related work, [26] demonstrated the use of WiFi uplink for VLC. However, it does not discuss any techniques for interconnection between LEDs. In the past, [27] has explored the use infrared for uplink communication. The use of WiFi uplink is clearly preferred over infrared due to its ubiquitous availability. Visible light is also shown to achieve highly accurate indoor localization [14, 15], and PLiFi can be used as a framework to implement such services. Screen-to-camera NFC has received a lot of attention recently [28], however, our focus in this work is on design of high-speed Internet access network.

6. CONCLUSIONS AND ONGOING RESEARCH

In this paper, we proposed PLiFi- a network architecture for combining WiFi and VLC through the use of power lines. It was shown that PLiFi can overcome the limitations of VLC by taking advantage of omni-present WiFi and power line networks. It provides low-cost interconnection between LEDs and to Internet, seamless integration with WiFi for uplink and coverage, and robustness to device mobility in VLC. In our ongoing research, we extending the PLiFi design to combat RSS variations and SINR degradation observed by the receiver due to shadowing events, user mobility and/or device orientation changes. This includes the design of an integrated PLC-VLC modem (instead of the PLC-Ethernet bridge used in our current setup) and high-speed LED front-end. Our design also includes strategies for vertical (between VLC and WiFi) and horizontal (between LEDs) hand-off of clients based on the uplink feedback.

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