An Indoor Hybrid WiFi-VLC Internet Access System

Sihua Shao*, Abdallah Khreishah*, Michael B. Rahaim†, Hany Elgala†,
Moussa Ayyash‡, Thomas D.C. Little†, Jie Wu§
*Department of Electrical and Computer Engineering, New Jersey Institute of Technology
†NSF Smart Lighting ERC, Department of Electrical and Computer Engineering, Boston University
‡Department of Information Studies, Chicago State University §CIS Department, Temple University
Email: *ss2536@njit.edu,†mrahaim@bu.edu, ‡mayyash@csu.edu, §jiewu@temple.edu

***Abstract*—Visible light communications (VLC) is emerging as a new alternative to the use of the existing and increasingly crowded radio frequency (RF) spectrum. VLC is unlicensed, has wide bandwidth, supports new levels of security due to the opacity of walls, and can be combined to provide both lighting and data communications for little net increase in energy cost. As part of a lighting system, VLC is ideal as a downlink technology in which data are delivered from overhead luminaries to receivers in the lighting field. However, realizing a symmetric optical channel is problematic because most receivers, such as mobile devices, are ill-suited for an optical uplink due to glare, device orientation, energy constraints.**

In this paper we propose and implement a hybrid solution in which the uplink challenge is resolved by the use of an asymmetric RF-VLC combination. VLC is used as a downlink; RF is used as an uplink, and the hybrid solution realizes full-duplex communication without performance glare or throughput degradation expected in an all-VLC-based approach. Our proposed approach utilizes a software defined VLC platform (SDVLC) to implement the unidirectional optical wireless channel and a WiFi link as the back-channel. Experiments with the implemented prototype reveal that the integrated system outperforms conventional WiFi for crowded (congested) multiuser environments in term of throughput; and demonstrate functional access to full-duplex interactive applications such as web browsing with HTTP.

Keywords*—*Hybrid system, Heterogeneous Network (HetNet), Software Defined Radio (SDR), Optical Wireless (OW), WiFi, Visible Light Communications (VLC), LiFi, Internet.

I. INTRODUCTION

The continuous growth in the adoption of mobile devices including smart phones, tablets, laptops, and now devices on the "Internet of Things" is driving an insatiable demand for data access to wireless networks. This overwhelming demand is rarely met today – one never complains about having "too much bandwidth" or "too fast service" to the Internet, especially when considering wireless access. Although wireless providers are deploying additional access infrastructure by means of new cells and WiFi end points, the limitation is becoming overuse of existing RF spectrum. This manifests as contention and interference and results in increase in latency and decrease in network throughput – a "spectrum crunch" [1]. To alleviate this problem, new approaches to realizing capacity at the wireless link are needed and optical technologies including visible light communications (VLC) are excellent candidates.

VLC technology provided with LED devices is characterized by high area spectral efficiency, unlicensed wide bandwidth, high security and dual-use nature [2]. For example,

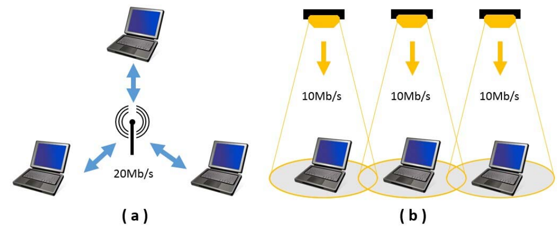

Fig. 1. Bandwidth density of (a) RF and (b) VLC

Fig. 1 shows how VLC can reuse spectrum efficiently in a small area. Case a) shows an RF channel in which three users share a 20Mb/s bandwidth, compared to Case b), a VLC-enabled environment, in which three users utilize individual 10Mb/s VLC channels, providing 10Mb/s more aggregate bandwidth than the individual RF channel. As a complementary approach to the existing wireless RF solutions, VLC is poised to overcome the crowded radio spectrum in highly-localized systems and become a promising broadband wireless access candidate to resolve the "spectrum crunch".

LED-based indoor VLC has attracted great attention in recent years due to its innate physical properties including energy efficiency and lower operational cost compared to conventional incandescent and fluorescent lighting [3]. Current research on VLC focuses mainly on physical (PHY) layer techniques such as dimming support, flicker mitigation, and advanced modulation schemes [4]. These efforts seek to achieve the highest data rates possible. However, higher-level networking topics must be addressed to enable interoperability in any practical network deployment [5]–[8].

Under a dual-use model, VLC is realized by overhead lighting – lights serve to provide lighting and also data access. However, providing an uplink in such a system is challenging due to potential energy limitations of mobile devices (that do not otherwise need to produce light for illumination) and potential glare from the produced light. In RF-sensitive and high-security applications, an optical uplink is possible with relatively high transmission speed [9]. However, in most RF-insensitive places such as homes, schools, offices, and supermarkets, an optical uplink is more difficult to justify. Mobile devices (e.g., labtops, smart phones, tablets) are energy-constrained. Equipping these devices with a power-hungry light source is impractical. To be efficient, VLC uplinks will need to use narrow beam widths which lead to challenges due to device motion and orientation with respect to fixed uplink receivers. Finally, VLC uplinks can produce glare which is

978-1-4799-6036-1/14 $31.00 © 2014 IEEE
DOI 10.1109/MASS.2014.76

uncomfortable to and undesirable for human users. Thus VLC remains a strong contender for the downlink channel but is better if complemented with an alternative uplink technology.

Alternative heterogeneous schemes, such as VLC and infrared [10], have been investigated by researchers in order to resolve the VLC uplink problem at the PHY layer. However, to make these approaches practical, we still need to address challenges in realizing upper layer protocols when such an asymmetric model is adopted. Moreover, the ubiquitous nature of WiFi with its omnidirectional characteristic can be readily be exploited as an uplink, especially if the use of VLC reduces congestion on the RF link as a heterogeneous network.

In this paper, we propose and implement a practical hybrid system comprised of typical IEEE 802.11 a/b/g/n technology and a VLC link, in which the unidirectional VLC channel is exploited to supplement the conventional downlink RF channel. Such a system was proposed and theoretically examined in [5]. Fig. 2 shows the basic configuration of this heterogeneous network. Such a system not only alleviates congestion caused by WiFi access contention, but also resolves the potential problems of uplink transmission in VLC networking. The main contributions of the work are the following: i) The design of an asymmetric system comprised of WiFi uplink and VLC downlink to increase overall network capacity with multiple users. ii) The implemenation of an integrated hybrid link that enables wireless Internet access via VLC downlink and WiFi uplink. And iii) analysis and experimentation to evaluate throughput under with TCP and UDP loading for interactive web browser traffic with different levels of congestion.

The paper is organized as follows. Section II reviews related work on hybrid WiFi and VLC systems. Section III describes the designed asymmetric system in detail including the router reconfiguration, packet capture and retransmission; and most significantly, the network-level operating system adaptations to achieve the asymmetric protocols. In Section IV, SDVLC and GNU Radio are presented to establish the unidirectional network functional link between two computers. Section V provides analysis and experimental results demonstrating the benefit of the proposed hybrid system. Section VI concludes the paper.

II. Related Work

Early work on hybrid systems integrating RF and VLC are based on simulation and analysis. To the best of our knowledge, none of these hybrid systems achieve practical system implementation yielding functional IP-based communication supporting web browsing or other Internet access.

A model for integrating WiFi and VLC luminaries has previously been proposed but not implemented [5] and represents the basis for the current work. In this model, broadcast/downlink VLC channels are proposed to supplement an existing RF channel. Handover techniques are defined for resolving discontinuities due to mobility and specifically to transfer between a symmetric RF link and the asymmetric VLC-RF link as a device transits an indoor space. In this prior work, the primary contributions are simulation and analysis of the downlink channel under the assumption of a reliable RF uplink.

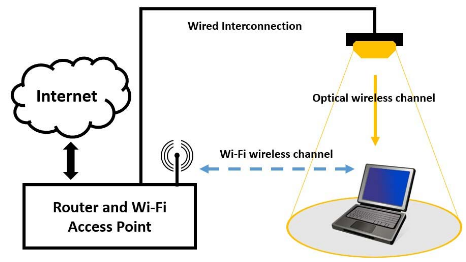

Fig. 2. Proposed hybrid WiFi and VLC network model

Device cost and energy consumption relative to data throughput have been investigated for a hybrid VLC system [6]. The authors show advantages for an RF uplink compared to a VLC uplink, but primarily as related to energy cost for transmission. This work motivates our interest in replacing the energy-expensive uplink with RF.

Energy-efficient connectivity for a hybrid radio-optical wireless systems has also been investigated [7]. In this work the authors show via simulation that connectivity and energy consumption depend on user device density, coverage range ratio between single-hop and multi-hop, relay probabilities, and mobility of the user. Although the proposed WLAN-VLC network model concludes the positive impact of a hybrid system, their approaches rely on ideal scenarios and prior assumptions.

Room division multiplexing (RDM) has been demonstrated under a hybrid VLC network model [8]. The core component of this hybrid system is the VLC network coordinator, which is responsible for RDM-based service division and distribution as well as for providing bidirectional interfaces between the outdoor and indoor communication infrastructure, especially the indoor interfaces for uplink WiFi access and downlink LED lamps. This work, however, does not appear to extend to full implementation of the network protocol stack nor implementation in the system kernel. Finally, the work is evaluated by waveform measurement without the signal processing and demodulation required for practical use.

Each of the aforementioned works focuses on simulation analysis without implementation of the full end-to-end system required to provide evaluation at the application layer. in contrast, in our work in this this paper we implement a practical hybrid WiFi-VLC wireless system, which enables the typical TCP connection between client and server without any reconfiguration at the server side. Data packets generated by user applications will be transmitted through WiFi and requested data from the server will be received via the VLC interface.

III. System Design

In this section, we present our novel hybrid system (Fig. 3) that integrates a VLC downlink (hotspot) and a WiFi access point that conforms to the IEEE 802.11 standard. The challenges of the integrated system and our proposed approaches are described below.

TABLE I. AN EXAMPLE OF STATIC ROUTING TABLE

Dst IP	Subnet Mask	Next hop	Metric
192.168.1.100	255.255.255.255	192.168.1.200	2

A. Challenge

The primary challenges of an asymmetric network implementation are as follows:

1) In a conventional network architecture, uplink and downlink data streams between client and server flow through the same routing path. A coordinator performing as an intermediate node is necessary in order to redirect the downlink data flow to a VLC hotspot. However, appending an additional device to a traditional network framework is redundant and requires a significant hardware upgrade. In Fig. 3, the router redirects downlink traffic to PC I and simultaneously provides PC II with an uplink wireless access point.

2) WiFi routers are ubiquitous, being used in offices, homes, and businesses, etc. This type of router bridges wide area networks (WANs) to local area network (LANs). Mobile devices connected to the same router are distributed in the same subnet. In addition, the router's IP address is allocated to the connected hosts as a gateway. One problem occurs when redirected data packets arrive at the relaying node which acts as a VLC access point. In Fig. 3, since the destination IP address of the data packets arriving at network interface card (NIC) A-1 is actually the IP address of NIC B-1, the packets will be forwarded back to PC II through the router instead of the VLC link if we activate the forwarding function on PC I.

3) In addition to the aforementioned issues, the most challenging issue exists at the client. Typically the client initiates a TCP connection with the server by a three-phase handshake. First, according to the open system interconnection (OSI) model, a connection establishment request segment is generated at the application layer. It is then encapsulated with TCP and IP headers at the network layer before being sent out through the NIC. After the request is transmitted to the server, the client starts listening to the socket with corresponding TCP port number and IP address, expecting a response from the server. Replied packets with different IP addresses or port numbers are not to be processed by the application which initiates the connection establishment. In other words, incorrect packets cannot be recognized by the application at client side. Fig. 3 shows how the asymmetric system with coexisting WiFi and VLC exactly encounters this problem. Requested packets are transmitted through NIC B-1 whereas the replied packets are received from NIC B-2.

B. System Architecture

Fig. 3 illustrates the hybrid system architecture of downlink VLC and uplink WiFi for indoor Internet access. Requested packets generated by the client (PC II) flow through the WiFi access point and arrive at the server. Replied packets from the server are forwarded through the router and relaying computer (PC I), and finally arrive at the client. To resolve the issues mentioned in the previous subsection, three procedures need to be executed as follows:

1) A static routing table inside the router is responsible for uplink and downlink separation. Rather than dynamically forwarding traffic, the router follows the manually-configured routing entry consisting of three items: i) destined IP address ii) subnet mask iii) next-hop router IP address. Table 1 shows an example of routing IP traffic destined for the 192.168.1.100/24 via the next-hop router with the IPv4 address of 192.168.1.200/24. In our proposed hybrid system, IP packets destined for NIC B-1 are redirected to NIC A-1.

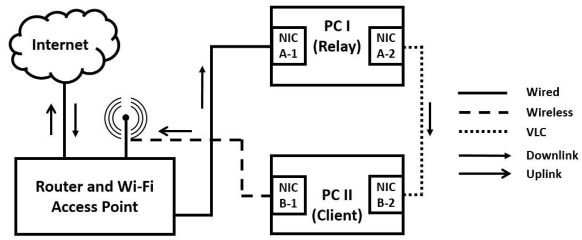

Fig. 3. Hybrid system architecture

Algorithm 1 Pseudo code of socket program

Initialization:
Define BufferSize MTU;
Set socket s for frames capture;
Set socket d for frames retransmission;
Bind socket s to NIC A-1;
Bind socket d to NIC A-2;

Iteration:

```
while 1 do
    Receive frames from socket s and store into buffer msg[BufferSize];
    if frame length > MTU then
        Continue;
    end if
    if frame desitination IP addr = IP B-1 then
        Change dest MAC addr to MAC B-2;
        Change src MAC addr to MAC A-2;
        Change dest IP addr to IP B-2;
        Compute IP checksum;
        Compute TCP checksum;
        Compute UDP checksum;
        Send modified frames to socket d;
    end if
end while
```

2) Aside from static router settings, IP packets that arrive at the relaying machine (PC I) must be transmitted through NIC A-2. In the Linux operating system, the IP packet forwarding function is activated by setting the ip_forward value under the path "/proc/sys/net/ipv4/ip_forward" from 0 to 1. Since the packets that arrive at PC I will be forwarded back to PC II through the router, if we activate the forwarding function, we must set the ip_forward value to 0. Instead, socket programming based on $SOCK\_PACKET$ type [11] is responsible for the packet relaying task.

We use the $SOCK\_PACKET$ mechanism in Linux to take complete control of the Ethernet. Receiving frames from the data link layer and placing a pointer which points to the first byte of each frame (start from MAC header), $SOCK\_PACKET$ is suitable for packet capturing and retransmission. In algorithm 1, we show the pseudocode of the

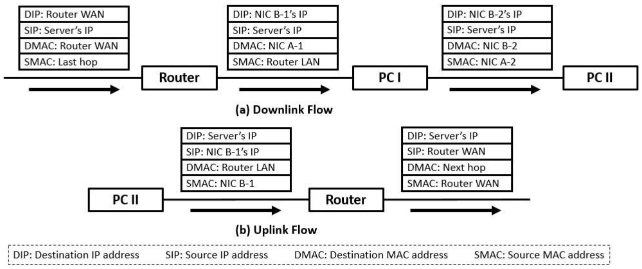

Fig. 4. MAC and IP headers of packets flow between server and client, a) shows downlink flow and b) shows uplink flow

socket program based on $SOCK\_PACKET$ type. We first define the receive buffer size to the maximum transmission unit (MTU) of the router. Then we set up two sockets of type $SOCK\_PACKET$ and bind them to specific NICs. After that, we start a loop that includes receiving, processing and re-transmitting. If the received packet length is larger than MTU, it should be discarded. Otherwise, we check the destination IP address of the packet. If it is the same as the IP address of NIC B-1, we manually modify the packet's MAC and destination IP address. Since IP/TCP/UDP checksum computations include the destination IP address, we recalculate the checksums before sending the packets to PC II.

3) After the packets with IP address of NIC B-2 as their destination arrive at PC II, the most challenging problem occurs. Because the application that initiates the TCP connection to the server is listening to the socket with IP address of NIC B-1 rather than NIC B-2, the arrived packets will not be processed when they reach the IP layer. Even if we change the destination IP address of packets to the IP of NIC B-1 on PC I, the packets will be ignored on PC II due to the incorrect interface they passed through. Finally, we figure out an approach that we call "operating system spoofing" to resolve this problem.

Operating System Spoofing: Suppose the IP addresses of NIC B-2 is 192.168.2.100/24 and the default gateway of PC II is 192.168.1.1/24 which is the router's IP address, then we need to delete that default gateway and add a new one within the subnet 192.168.2.0/24. For example, add 192.168.2.1/24 as default gateway. After that, we add an entry in PC II's ARP table (i.e. arp -s 192.168.2.1 ab:ab:ab:ab:ab:ab), in order to provide the non-existent IP 192.168.2.1 with a MAC address. So far, all packets generated by application on PC II will be forced to NIC B-2. And the most significant point is that all applications (i.e. web browser) will listen to the socket with IP address of NIC B-2 and expect the response.

After the routing table and ARP table modifications, we make a copy of each packet. These packets are to be sent out through NIC B-2. Regarding to the copying process, a socket of type $SOCK\_PACKET$ is utilized once again to capture packets flowing through the device driver layer of NIC B-2. After packet interception, we alter the source IP and MAC address of the copied packets to the IP and MAC address of NIC A-1. Also, we transform the destination MAC address to the router's LAN MAC address. With the change of IP address, IP checksum needs to be recalculated. After completing reconstruction of IP and MAC headers, the packets are transmitted through NIC B-1. Using this approach, from

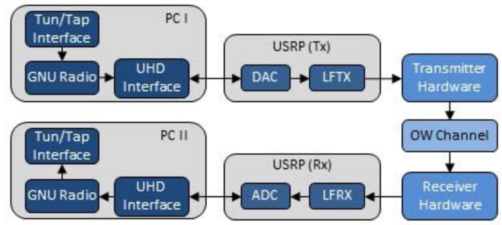

Fig. 5. Signal chain for SDVLC implementation

the router's point of view, the client's IP address is the IP of NIC B-1. However, from the user's point of view, they connect to the Internet with the IP address of NIC B-2. Fig. 4 illustrates the variation of IP and MAC headers of packets on the uplink and downlink flow paths.

IV. Software Defined Visible Light Communication

In order to implement the VLC link within our system, we utilize the GNURadio software-defined radio toolkit [12] with universal software radio peripheral (USRP) and an optical transmitter and photosensitive receiver as a replacement for conventional RF antennas. This SDVLC implementation [13] allows us to realize the VLC PHY layer and generate the simplex VLC link between the relay and the client.

In our hybrid implementation, the SDVLC link emulates the VLC NICs (NIC A-2 and NIC B-2) shown in Fig. 3. PHY layer signal processing and MAC layer protocols are handled within the GNURadio application. On the relay PC, the application links to the network layer through a virtual tunnel interface and digital samples of the PHY signal are sent over an Ethernet connection to the USRP with the USRP hardware driver (UHD) interface. The transmitting USRP handles the digital to analog conversion and potential carrier modulation is implemented on the low frequency transmitter (LFTX) daughter card. At the client, we use the low frequency receiver (LFRX) daughter card for carrier demodulation and analog to digital conversion is implemented on the receiving USRP. Digital samples are sent via Ethernet to the GNURadio application using the UHD interface and the sampled data are processed. The GNURadio application running on the client PC also connects to the network layer with a tunnel interface. The VLC front-end transmitter comprises a bias-T and MOSFET driven array of osram semiconductor LEDs (LUW CN5M). The bias is required to shift the bipolar signal generated by the USRP such that the input to the LED driver is within the linear range of the conversion. At the receiving end, a commercial photodiode with trans-impedance amplifier (PDA36A) is used to convert the optical signal back to the electrical domain. Fig. 5 shows the SDVLC signal chain.

For the PHY and MAC layer testing of the hybrid system, we utilize the tunnel.py example from GNURadio. This program implements a carrier sense MAC and OFDM modulation for the MAC and PHY layers, respectively. The OFDM modulation used in this implementation is a conventional RF OFDM with 1MHz center frequency. This is contrary to typical OW OFDM techniques [14], such as DC-biased optical (DCO) OFDM and asymmetrically clipped optical (ACO) OFDM,

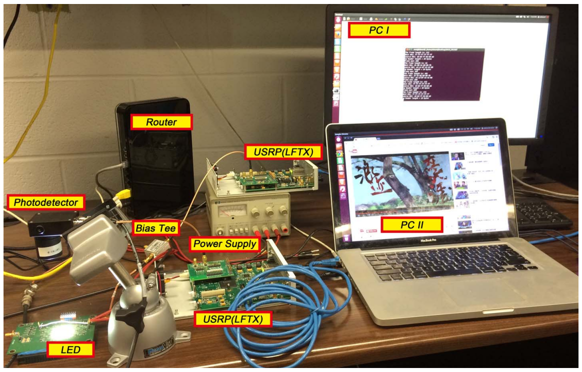

Fig. 6. Testbed for proposed system

TABLE II. ROUTING TABLE OF CLIENT

Destination	Gateway	Genmask	Flags	Metric	Interface
0.0.0.0	192.168.2.1	0.0.0.0	UG	0	gr0
169.254.0.0	0.0.0.0	255.255.0.0	U	1000	eth1
192.168.2.0	0.0.0.0	255.255.255.0	U	2	gr0

which utilize Hermitian symmetry in order to generate real valued baseband signals. We consider a DC biased version of traditional RF OFDM with low frequency carrier in order to work with the available blocks within GNURadio and maximize throughput while considering sample rate restrictions limited by the real-time signal processing constraints. In our investigation of the heterogeneous system, we utilize a 1MHz carrier and sample rate of 500Ks/s. Regarding the OFDM parameters, we observe a 512 point FFT with 200 occupied tones and a 128 sample cyclic prefix. Each tone implements BPSK modulation such that the raw throughput is 156.25Kb/s. All of these parameters are adjustable within the GNURadio implementation, however, these settings offer a reliable data stream for web browsing applications.

While the current hybrid system implements the OFDM modulation described above, we have also explored various VLC modulation techniques including on-off keying (OOK), DCO and ACO OFDM, and variable pulse position modulation (VPPM). As the system continues to develop, adaptive modulation will be incorporated such that the modulation scheme is dynamically modified to meet channel state information and dimming requirements.

V. EXPERIMENTS

A. Testbed

Our testbed consists of two PCs configured with Linux (Ubuntu 12.0.4 LTS), a NETGEAR Wireless Dual band Gigabit Router WNDR4500, two USRPs N210 integrated with LFTX and LFRX daughterboards, an analog LED driver board, a Si transimpedance amplified photodetector (PDA36A) with optical lens, and a Bias Tee (Fig. 6). The relay PC is equipped with Inter Corporation 82579LM and 82574L Gigabit Ethernet Controllers. The client PC is equipped with a Boradcom 802.11n Network Adapter and a Broadcom NetXtreme Gigabit Ethernet controller.

For the network configuration, the router's LAN IP address is set to 192.168.1.1/24 as default. Referring to Fig. 3, the IP addresses of NIC A-1 and NIC B-1 are manually configured to

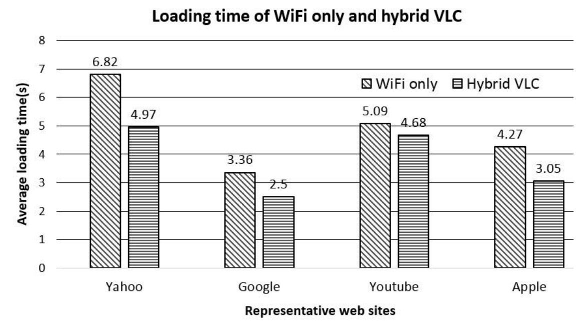

Fig. 7. Loading time in web browsing over WiFi only and Hybrid VLC

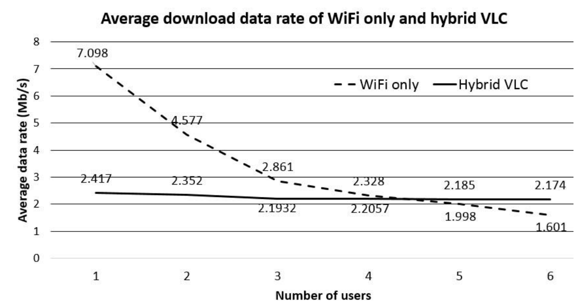

Fig. 8. Throughput comparison between WiFi only and hybrid VLC

192.168.1.200/24 and 192.168.1.100/24 respectively. TUNTAP PDU interfaces constructed in GNURadio are allocated with IP addresses 192.168.2.200/24 for NIC A-2 and 192.168.2.100/24 for NIC B-2. The IPv4 routing table in client PC is showed in Table 2. And an additional entry in the client's ARP table is added by typing "arp -s 192.168.2.1 ab:ab:ab:ab:ab:ab" in the command window with root privilege.

For VLC unidirectional link setup, a 2.0 VDC offset is supplied by the bias tee in order to drive the optical output in the linear range. Since the bias tee has a low frequency cutoff on the signal side, it is better suited for passband modulation with carrier frequency around 1 MHz. A 5.7-5.8 VDC input is assigned as the power supply. The gain of the photodetector is set as 20dB.

B. Results and Analysis

Given the above configurations for the SDVLC link within the hybrid system, the client downlink throughput is limited to approximately 150Kb/s. This throughput is restricted by the bottleneck of the software defined testbed implementation as opposed to the physical VLC channel. In order to make the performance of the downlink channel comparable to the WiFi only scheme, we replace the SDVLC link with an Ethernet cable. With Ethernet cable connecting PC I and PC II, Fig. 7 and Fig. 8 show the experimental results of the network implementation. In this way, we emulate the future development of our proposed hybrid system under the assumption that the VLC PHY will be able to achieve higher downlink throughput when implemented on an application-specific integrated circuit (ASIC) or field programmable gate array (FPGA) platform. Multiple groups have demonstrated real time throughput of over 100 Mb/s with a point to point VLC link [15]–[17].

For comparison, we show the performance of WiFi only and hybrid VLC in two scenarios: i) websites loading time in crowded environment, ii) average throughput with the increase of users access. All results are averaged over 10 experiments.

We first evaluate web browsing by selecting several representative web sites. Pingdom[1] online website speed test facilitates us to estimate the load time of the webpage. As shown in Fig. 7, we investigate the completion time of home webpages of yahoo, google, youtube and apple on one client located in the network comprised of 12 clients. Compared to WiFi only scheme, hybrid VLC system shows improved performance for the user device when multiple other users are contending for the RF channel.

Fig. 8 shows the average download data rate[2] of WiFi only and hybrid VLC schemes with an increasing number of contending user terminals. In our experiments, hybrid VLC download speed, which achieves 2.4Mb/s on average, is restricted by processing time of socket programming. Nevertheless, with the number of devices increasing in the same RF wireless access point, the bandwidth of each device declines sharply because of the CSMA/CA mechanism defined in the IEEE 802.11 standard [18]. Since additional WiFi users only interfere with the uplink channel of hybrid VLC link, the download speed of the hybrid VLC scheme decreases much more slowly than WiFi only as the number of user devices increases. Based on the performance examination of one client while other clients acts as RF channel contenders, hybrid VLC system outperforms WiFi only in term of throughput when the number of clients in the same LAN increases to 5.

VI. Conclusion and Future Work

In this paper described the design, implementation, and evaluation of a practical indoor hybrid VLC-RF system that achieves a full IP networking stack. The benefits of such a system are the ability to add capacity with VLC channels as downlink-only while retaining full uplink capability with existing WiFi. To achieve this goal we developed a hybrid solution to manage the asymmetric nature of the VLC channel, and the intricacies of routing packets over two media with different transmission characteristics. Congestion in WiFi networks inevitably deteriorates throughput for each user. Being complementary to WiFi access points, VLC downlink hotspots effectively alleviate contention and interference on the RF channel.

In our ongoing efforts we expect to extend the work to encompass dynamic handover and traffic routing based on measured real-time quality of the VLC channel. We also hope to increase the level of integration of the asymmetric network protocols to the level of an embedded controller suitable for more widespread adoption and manufacture. Given the benefits described in this work, we expect that VLC will contribute to the evolution of next generation heterogeneous wireless communication systems.

Acknowledgment

This work was supported in part by the NSF grant ECCS-1331018 and by the Engineering Research Centers Program of the National Science Foundation under NSF Cooperative Agreement No. EEC-0812056.

[1]http://tools.pingdom.com/fpt/.

[2]http://www.speedtest.net/.

References

[1] M. Kavehrad, "Optical wireless applications: A solution to ease the wireless airwaves spectrum crunch," in *SPIE OPTO*. International Society for Optics and Photonics, 2013, pp. 86 450G–86 450G.

[2] J. M. Kahn and J. R. Barry, "Wireless infrared communications," *Proceedings of the IEEE*, vol. 85, no. 2, pp. 265–298, 1997.

[3] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using led lights," *Consumer Electronics, IEEE Transactions on*, vol. 50, no. 1, pp. 100–107, 2004.

[4] S. Rajagopal, R. D. Roberts, and S.-K. Lim, "Ieee 802.15. 7 visible light communication: modulation schemes and dimming support," *Communications Magazine, IEEE*, vol. 50, no. 3, pp. 72–82, 2012.

[5] M. B. Rahaim, A. M. Vegni, and T. D. Little, "A hybrid radio frequency and broadcast visible light communication system." in *GLOBECOM Workshops*, 2011, pp. 792–796.

[6] C. Lee, C. Tan, H. Wong, and M. Yahya, "Performance evaluation of hybrid vlc using device cost and power over data throughput criteria," in *SPIE Optical Engineering+ Applications*. International Society for Optics and Photonics, 2013, pp. 88 451A–88 451A.

[7] H. Chowdhury, I. Ashraf, and M. Katz, "Energy-efficient connectivity in hybrid radio-optical wireless systems," in *Wireless Communication Systems (ISWCS 2013), Proceedings of the Tenth International Symposium on*. VDE, 2013, pp. 1–5.

[8] Z. Huang *et al.*, "Design and demonstration of room division multiplexing-based hybrid vlc network," *Chinese Optics Letters*, vol. 11, no. 6, p. 060603, 2013.

[9] S. Schmid, G. Corbellini, S. Mangold, and T. R. Gross, "Led-to-led visible light communication networks," in *Proceedings of the fourteenth ACM international symposium on Mobile ad hoc networking and computing*. ACM, 2013, pp. 1–10.

[10] K.-D. Langer and J. Grubor, "Recent developments in optical wireless communications using infrared and visible light," in *Transparent Optical Networks, 2007. ICTON'07. 9th International Conference on*, vol. 3. IEEE, 2007, pp. 146–151.

[11] D. Senie, "Using the sock-packet mechanism in linux to gain complete control of an ethernet interface," *Internet:.(Retrieved Apr. 24, 2002)*, 2002.

[12] G. Radio, "The gnu software radio," *Available from World Wide Web: https://www.gnuradio.org*, 2014.

[13] M. Rahaim, A. Miravakili, S. Ray, V. Koomson, M. Hella, and T. Little, "Software defined visible light communication," in *Wireless Innovation Forum Conference on Communications Technologies and Software Defined Radio (WInnComm SDR)*, 2014.

[14] R. Mesleh, H. Elgala, and H. Haas, "On the performance of different ofdm based optical wireless communication systems," *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 3, no. 8, pp. 620–628, 2011.

[15] J. Vučić, C. Kottke, S. Nerreter, K.-D. Langer, and J. W. Walewski, "513 mbit/s visible light communications link based on dmt-modulation of a white led," *Journal of Lightwave Technology*, vol. 28, no. 24, pp. 3512–3518, 2010.

[16] A. Khalid, G. Cossu, R. Corsini, P. Choudhury, and E. Ciaramella, "1-gb/s transmission over a phosphorescent white led by using rate-adaptive discrete multitone modulation," *Photonics Journal, IEEE*, vol. 4, no. 5, pp. 1465–1473, 2012.

[17] A. H. Azhar, T. Tran, and D. O'Brien, "A gigabit/s indoor wireless transmission using mimo-ofdm visible-light communications," *Photonics Technology Letters, IEEE*, vol. 25, no. 2, pp. 171–174, 2013.

[18] G. Bianchi, L. Fratta, and M. Oliveri, "Performance evaluation and enhancement of the csma/ca mac protocol for 802.11 wireless lans," in *Personal, Indoor and Mobile Radio Communications, 1996. PIMRC'96., Seventh IEEE International Symposium on*, vol. 2. IEEE, 1996, pp. 392–396.