An Indoor Hybrid WiFi-VLC Internet Access System

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Abstract

Abstract—In recent years, visible light communication (VLC) has emerged as a complementary technique to overcome limitations of the crowded radio frequency (RF) spectrum. Its superior characteristics include unlicensed wide bandwidth, high security and dual-use nature. Nevertheless, mobile devices are not equipped with illuminating components, which are utilized as transmitters in downlink data transmission. Targeting a high quality and robust uplink channel, high power light sources turn to be unsuitable for mobile devices with limited battery life. Furthermore, VLC uplink requires a directional optical transmission beam that can lead to significant deterioration of throughput given the potential rotation and/or movement of devices. With the above-mentioned design challenges, the uplink mechanism becomes a fundamental problem for bidirectionalVLC. In order to alleviate congestion in the RF shared medium as well as resolve the back-channel issue of VLC networking, we propose a real-time indoor hybrid WiFi and VLC system for realizing Internet surfing. In this hybrid system, downstream data flow is transmitted by light emitting diodes (LED), whereas the upstream data flow is forwarded through WiFi connectivity. Our designed system utilizes flexible software defined VLC (SDVLC) to implement the unidirectional optical wireless channel. Experimental results reveal that the integrated system outperforms conventional WiFi for crowded environments in term of throughput.

Keywords – *Heterogeneous Network (HetNet),Software Defined Networks (SDN), Optical Wireless (OW), WiFi, Visble Light Communication (VLC), LiFi, Internet.*

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1. Introduction

Due to drastically growing commercial demands of wireless access services, available RF bandwidth is getting exhausted. As a result of severe congestion in the RF shared medium, network performance decreases sharply with contention and interference. This phenomenon is called the "spectrum crunch" problem [1]. For the sake of satisfying future requirements of individual users or enterprise groups, novel approaches capable of providing the aggregate capacity to serve more users need to be developed.

VLC technology, with its superior characteristics including high area spectral efficiency, unlicensed wide bandwidth, high security and dual-use nature, emerges as a complementary technique [2]. Fig. 1 compares a) an RF channel in which three users share the 20Mb/s bandwidth, to 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" problem.

The 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 old incandescent and fluorescent lighting [3]. Current works on VLC focus mainly on the physical (PHY) layer techniques, such as dimming support, flicker mitigation, and advanced modulation schemes [4]. The primary goal of PHY layer research is to enhance data rates within the constraints of VLC, which includes short range coverage, dimming control, flicker insensitive to human eyes, etc. Based on the PHY layer efforts, researchers have begun to investigate the higher layer techniques required for practical VLC networking [5]–[8].

Although dual-use VLC integrates data communication and illumination functionalities, the uplink mechanism comes to be a non-negligible issue for VLC networking. In electromagnetic-sensitive and high-level security applications, uplink VLC is possible with relatively high transmission speed [9]. However, in most electromagnetic-insensitive places such as home, school, office, supermarket, VLC is unsuitable for uplink in practical scenarios. The reasons are as follows: i) Mobile devices (i.e. labtop, smart phone, tablet) are energyconstrained. Equipping these devices with a light source strictly for communications costs large amounts of power, which makes uplink VLC a challenging problem. ii) Uplink VLC with narrow beam-width requires transmission beam to be orientated to a fixed direction. Slight movement or rotation could significantly affect throughput, which is unsuitable for mobile

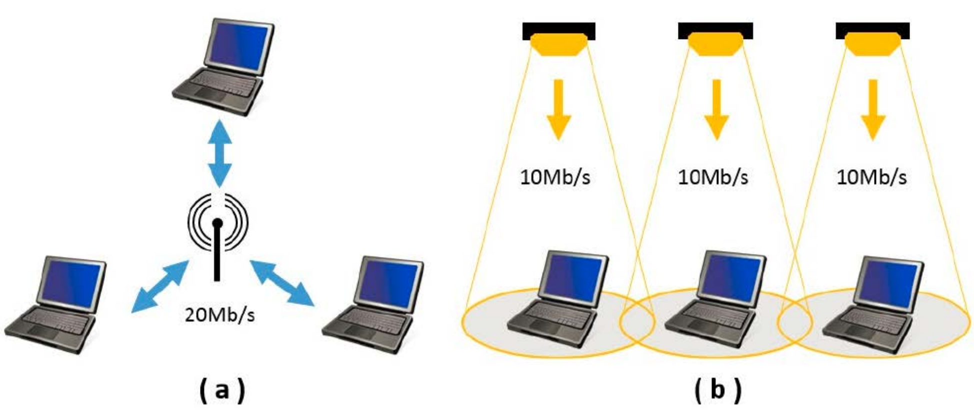

Figure 1: Bandwidth density of (a) RF and (b) VLC

devices. iii) Uplink visible signals can affect the indoor illumination and cause discomfort to human eyes. Taking these inconvenient aspects into consideration, VLC is ideally suited as a complementary downlink-only technology within a heterogeneous network.

Alternative heterogeneous schemes, such as VLC and infrared [10], have been examined by researchers in order to resolve the VLC uplink problem. Nevertheless, to our knowledge, a network enabled heterogeneous VLC and WiFi system has not been implemented. In our daily life, WiFi communication is more prevalent than other techniques and this infrastructural technology provides a non-intrusive channel as well as a relatively large coverage area. In next generation wireless systems, the stress on WiFi WLANs will continue to grow due to the increasing complexity of wireless applications and an increasing number of devices as cellular networks opportunistically offload traffic to the more localized WLANs. Therefore, heterogeneous systems that supplement the traditional WiFi system with highly localized VLC access points deserve further investigation.

In this paper, we 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. In summary, we make the following main contributions: i) We design an asymmetric system comprised of WiFi uplink and VLC downlink. With that, additional bandwidth can be provided to account for the growth in network traffic. Meanwhile, the conventional RF channel is reserved for uplink data transmission. ii) We implement an integrated hybrid link enabling wireless Internet access via VLC downlink and WiFi uplink. iii) With typical TCP and UDP connection, we evaluate download data rate and web sites loading time of our designed system and compare them with that of the traditional WiFi only scheme across various degrees of congestion.

The paper is organized as follows. Section II explains some related works of hybrid WiFi and VLC systems. Section III describes the designed system in detail, including the router reconfiguration, packet capture and retransmission, and most significantly, the network-level operating system spoofing. In Section IV, SDVLC and GNU Radio, which establish the unidirectional network functional link between two computers, are presented. Section V shows experimental results and analyzes the benefit of this proposed hybrid system. Conclusion and future work are drawn in Section VI.

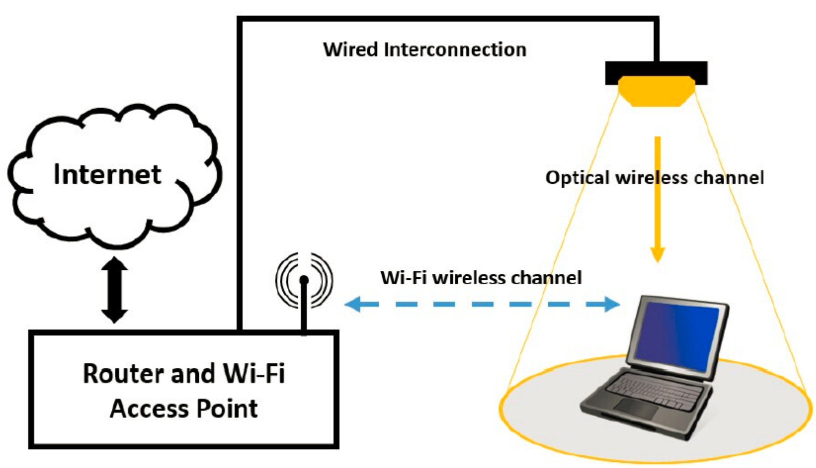

Figure 2: Proposed hybrid WiFi and VLC network model

2. Related Work

Early work on hybrid systems integrating RF and VLC were based on simulations. To the best of our knowledge, none of them realized the practical Internet access. An indoor hybrid system model that integrates WiFi and VLC luminaries was proposed in [5]. It was a previous work from researchers within our group and it presented the basis of the system we have implemented. The authors suggested to utilize broadcast VLC channels to supplement the RF channel and proposed handover techniques for transferring between a symmetric RF link and the asymmetric VLC-RF link. The primary contribution of this work was based on simulation and analysis of the downlink channel while uplink was assumed to be reliable. The model framework was presented, however, the system was not implemented.

Device cost and energy consumption over data throughput criteria of a hybrid VLC system was studied in [6]. The authors explicitly summarized the superiority of an uplink RF channel compared to an uplink VLC channel. Moreover, performance evaluation on the proposed system was carried out to study the throughput as a function of device cost and power consumption, respectively. Sufficient simulation results arouse the motivation of replacing intrusive visible light for uplink by a conventional RF back channel. However, their evaluation only included simulations.

Energy efficient connectivity of the hybrid radio-optical wireless system was also investigated in [7]. The researchers analyzed the feasibility and potential benefits of using this heterogeneous network. Their simulation results revealed that connectivity and energy consumption depend on user terminal density, coverage range ratio between single-hop and multihop, 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.

Some researchers demonstrated a room division multiplexing (RDM) based hybrid VLC network in [8]. The core component of their designed 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. Nevertheless, their approach did not mention how user terminals can activate applications (i.e. web browser) with network protocol stack built in operating system kernel. In addition, experimental throughput was evaluated by waveform measurement without the signal processing and demodulation required for practical use.

All of the above-mentioned works focused on simulation analysis without implementing any application with Internet access. In 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.

3. System Design

In this section, we present our designed hybrid system, shown in Fig. 3, integrating a VLC hotspot and WiFi following the IEEE 802.11 standard. The challenges of the integrated system and our proposed approaches are described below.

Table 1: 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

3.1 Challenge

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

1) In 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 traditional network framework is redundant and requires a large scale of hardware updating. In Fig. 3, the router redirects downlink traffic flow to PC I and simultaneously provides PC II with an uplink wireless access point.

2) In our daily life, routers equipped with WiFi access point are used prevalently in many environments such as office, home and restaurants, etc. This type of router interconnect wide area network (WAN) and local area network (LAN). 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 issues mentioned above, the most challenging point lies on the client. Generally the client initiates TCP connection with the server by a three-phase handshaking procedure. First, according to the open system interconnection (OSI) model, a connection establishment request segment is generated at the application layer. Then it is 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 can not be recognized by the application at client side. In Fig. 3, the asymmetric system coexisting WiFi and VLC exactly encounters this problem, for the reason that requested packets are transmitted through NIC B-1 whereas the replied packets are received from NIC B-2.

3.2 System Architecture

Fig. 3 describes 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) Static routing table inside the router takes the responsibility of 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's IP address. Table 1

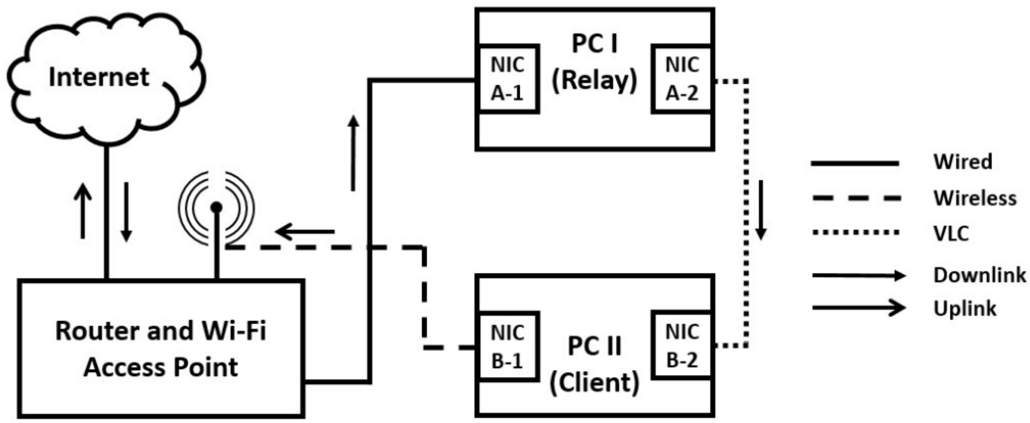

Figure 3: Hybrid system architecture

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.

2) Aside from static router settings, IP packets that arrive at relaying machine (PC I) are required to be transmitted through NIC A-2. In Linux operating system, the IP packets 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 need to set the ip forward value to 0. Instead, socket programming based on *SOCK PACKET* type [11] is responsible for the packet relaying task.

To gain the complete control of a Ethernet interface, we use the *SOCK PACKET* mechanism in Linux. 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, the pseudo code of the socket program based on *SOCK PACKET* type is presented. 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 retransmitting. 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

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
```

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 the router's point of view, the client's IP address is the IP of NIC B-1. However, from 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.

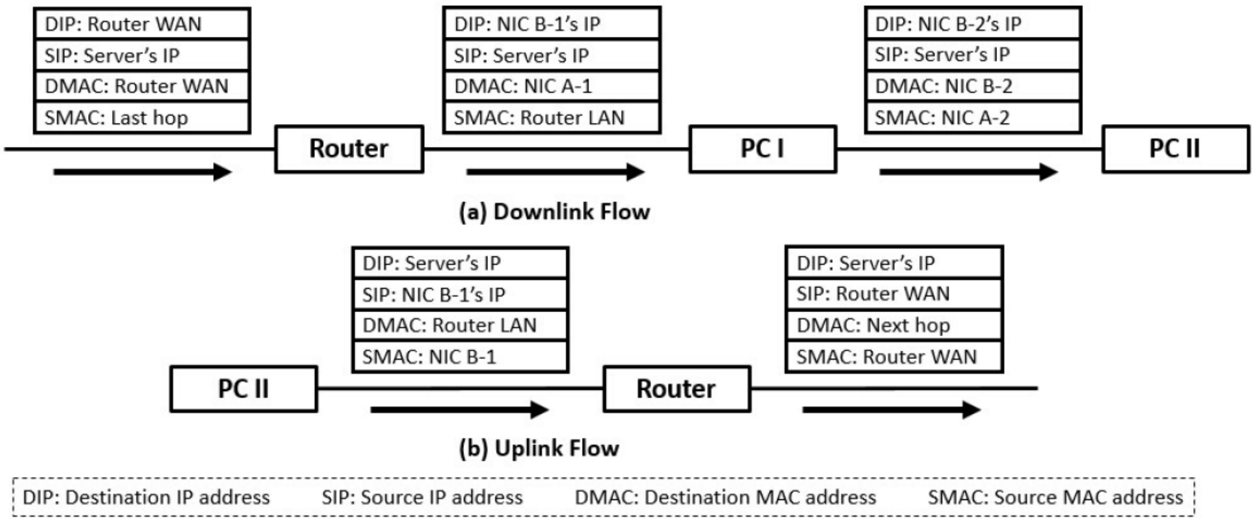

Figure 4: MAC and IP headers of packets flowing between server and client, a) downlink flow and b) uplink flow

4. 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, 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

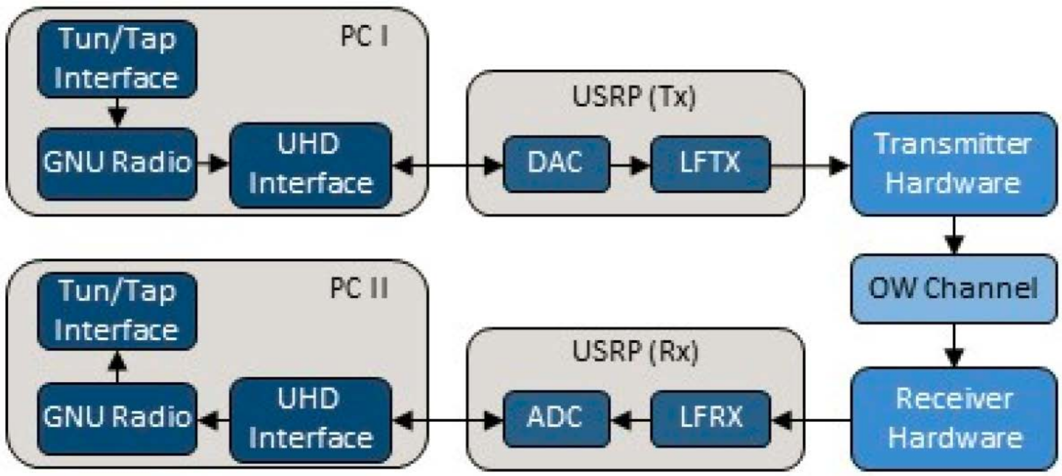

Figure 5: Signal chain for SDVLC implementation

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.

5. Experiments

5.1 Testbed

In Fig. 6, our testbed consists of two PCs with Linux operating systems (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. 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 network configuration, 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 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, 2.0 V DC 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

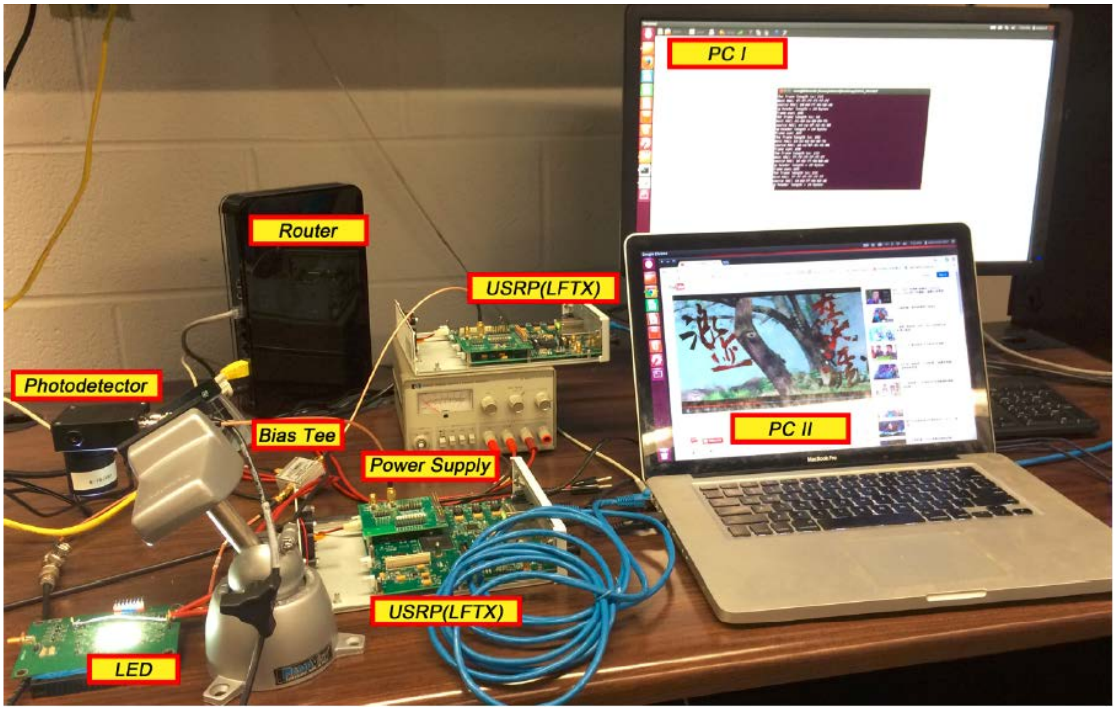

Figure 6: System testbed

better suited for passband modulation with carrier frequency around 1 MHz. A 5.7-5.8 V DC input is assigned as the power supply. The gain of the photodetector is set as 20dB.

5.2 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].

Table 2: Client routing table

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	gr1

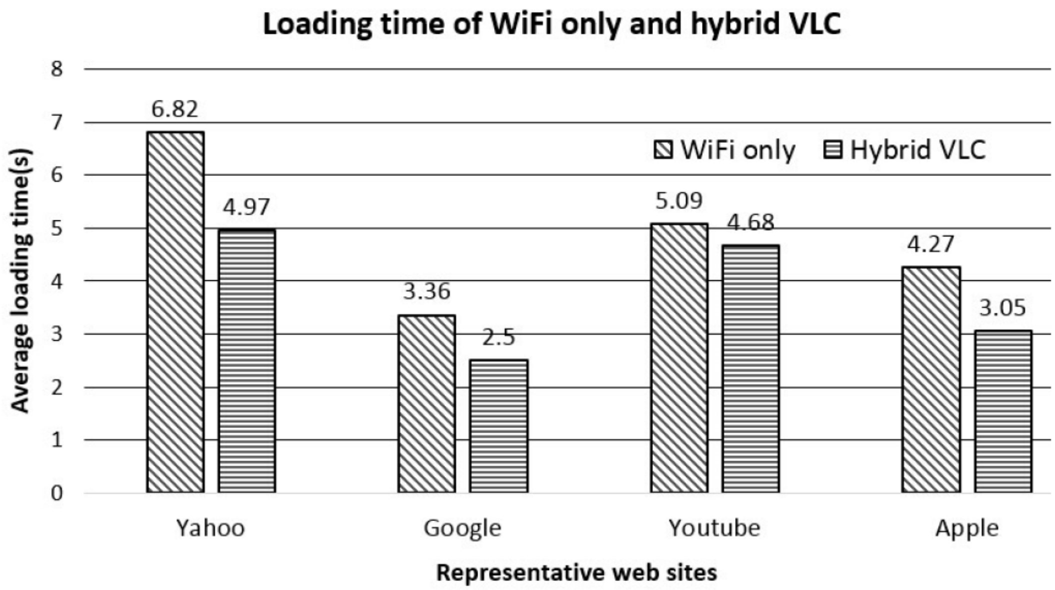

Figure 8: Website loading time over WiFi only and Hybrid VLC

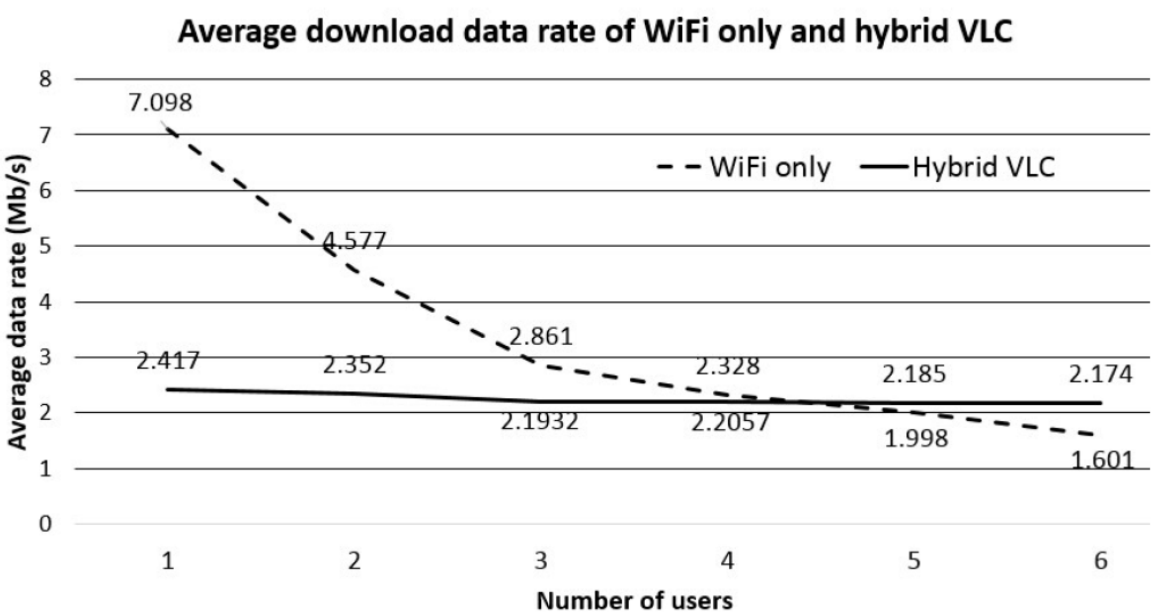

Figure 7: Throughput comparison between WiFi only and hybrid VLC

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.

6. Conclusions and Future Work

In this paper, we have proposed the design of a practical indoor hybrid system with Internet access using VLC technology as a supplementary downlink channel to conventional WiFi connectivity. Congestion in WiFi networks inevitably deteriorates throughput for each user sharply. Being complementary to WiFi access points, VLC hotspots effectively alleviate contention and interference on the RF channel. Besides, we analyze the superiority of a hybrid VLC-WiFi network compared to a traditional WiFi network in terms of average data transmission rate and web browsing loading time against number of users.

As future work, the hybrid system will encompass dynamic handover and traffic routing based on real time quality of the VLC channel. Besides, optical driver and relaying function can be integrated into an embedded system, which performs visible light modulation as well as packets processing. With this hybrid system being commercialized, mobile devices equipped with bidirectional WiFi transceiver and VLC receiver modules could experience Internet services in the coverage of VLC hotspots. Given the benefits described in this work, we expect that VLC will contribute to the evolution of next generation heterogeneous wireless communication systems.

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