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ANALYSIS OF VISIBLE LIGHT COMMUNICATION AND OFDMA SYSTEMS

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Abstract-In wireless communication system, the problem of using crowded radio spectrum can be minimized by the usage of vast unregulated free light spectrum, commonly referred as visible light communication (VLC). Even though duplex communication, user mobility and handover mechanisms are becoming challenging tasks in a VLC system. This paper proposes a hybrid network model of VLC and orthogonal frequency-division multiplexing access (OFDMA) in which the VLC channel is served only for downlink transmission, whereas OFDMA channels are used for uplinks in any location or for downlinks only without VLC hotspots coverage. A unique protocol is proposed which includes the access, horizontal and vertical handover mechanisms for mobile terminal (MT), in order to overcome the user mobility among different systems. An enhanced VLC network proposal and its frame format are described to resolve the problem of multiuser access in every hotspot. Additionally, the capacity of this hybrid network is evaluated by a new metric ρ is defined to evaluate the capacity of this hybrid network as the spatial density of inter arrival time of MT requests in $s^{-1}m^{-2}$ under the assumption of the homogenous Poisson point process (HPPP) distribution of MTs. When compared to OFDMA systems, capacity and performance of the hybrid network is improved by analytical and simulation results.

Index Terms-Capacity analysis, horizontal and vertical handover, hybrid visible light communication-orthogonal frequency-division multiplexing access network, VLC frame format.

I. INTRODUCTION

Visible light communication (VLC) refers to the system that uses light-emitting diodes as the transceiver to achieve high-speed communication. It utilizes visible light as the medium instead of radio waves where optical beams are used to carry data through the atmosphere or vacuum. LED lights can be used as internet access points. VLC signals represent information flow by switching LED bulbs on and off within nanoseconds. The visible-light waves cannot penetrate through walls, so that the transmission range is shortened and the information is confined within the wall. However, this feature makes it more secure from hacking. Even light reflected off of the walls can help in achieving the transmission rate of 70 Mbps, which is sufficient for many applications. The modulation on the LED is done by using on-off keying (OOK), and pulse-amplitude modulation (PAM), etc. The wireless networking community has already realized a spectrum shortage crisis due to the huge increase of wireless traffic. VLC uses the visible light spectrum which has no limitations on capacity. It can provide a high speed, and highly-available hotspot to offload the congested data traffic. It uses VLC channel for downlink transmission and OFDMA channel for uplink transmission.

Visible light communication (VLC) is emerging as a solution for overcoming the crowded radio spectrum for wireless communication systems [1]. VLC uses a vast unregulated and free spectrum without electromagnetic interference to support data communication and illumination in indoor environments where new energy-efficient LED materials and devices will replace old incandescent and fluorescent lighting [2]. A simplified vertical handover mechanism was presented, and the downlink throughput in three cases: 1) utilizing only the Wi-Fi channel; 2) all downlink traffic is operated by VLC; and 3) transfer to VLC channel using the simplified handover mechanism once Wi-Fi channel has reached its capacity have been analyzed. One of major problem in investigating a communications system is how to develop an information environment for low power consumption and ecology. Recently, a method for low energy consumption is proposed by using visible light from an LED illuminator as a medium for wireless digital communications. A new full-duplex multi access system for LED-based wireless communications using visible light. In this system, an optical access point not only can send and receive data signal for communications, but also is an illuminator for common lifeline. In order to ensure the affinity with popular Ethernet networks, an optical CSMA/CD method is proposed for optical wireless transmission. The effectiveness of this system is demonstrated in a 1-to-n high-speed optical interconnection of 100Mpbs [3, 4]. Compared to traditional wireless communication technologies, the VLC physical medium is unregulated by the FCC (US) and has no identified health risks (i.e., no risks distinct from that of current lighting systems). The features of directivity (Line-of-Sight or LOS) and high obstacle impermeability provide secure data transmission within a closed indoor environment. Leveraging these attributes, VLC technology is highly applicable to indoor environments where new energy efficient LED materials and devices will replace old incandescent and fluorescent lights. However, FSO communications become more difficult unless terminals hold fixed positions (i.e. in front of a desk, sitting on a chair, etc.). Mobile communications via VLC in an indoor environment are challenging due to occlusions that can occur due to orientation or physical obstructions in an indoor volume [5]. As user demand for data services continues to increase tremendously, wireless networks have to provide higher capacities and spectrum efficiency[6].However, spectrum allocation charts show that most of the spectrum is already allocated under license [7]. In addition, the broadcast nature of the RF channel allows for mobile connectivity but creates problems with interference between devices communicating to a host in close proximity.

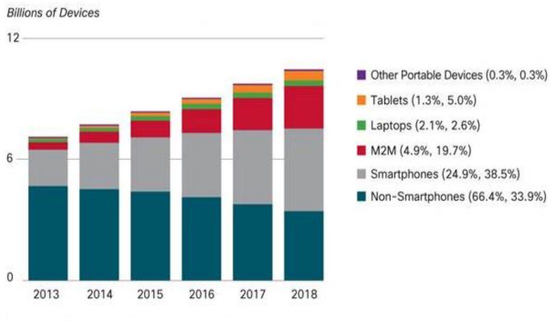

Fig.1. Global Mobile Devices and Connections Growth

In this paper, we propose a hybrid VLC-OFDMA network model that consists of *M* VLC hotspots, one access point (AP) of OFDMA system [e.g., Long Term Evolution (LTE) base station or Worldwide Interoperability for Microwave Access (WiMax) AP], one server, and numbers of mobile terminals (MTs). AP and VLC hotspots are linked to the server via wired connections. In this model, VLC channel is only used for downlink transmission, whereas OFDMA channels are served for uplinks in any situation or for downlinks only without hotspots coverage. Our model can be implemented in places where an OFDMA system (e.g., LTE or WiMax network) of users

The contributions made in this paper are threefold. First, we propose a novel protocol combined with access, horizontal, and vertical handover mechanisms for MT. Unlike previous studies, we take into account the mobility of MTs, thus triggering the horizontal handover mechanism to keep VLC connection stable whenever MT moves among different hotspots and to operate the vertical handover protocol whenever MT moves on the edge of VLC and OFDMA systems. Second, a new VLC network scheme and its frame format are presented. A unique ID is allocated for every VLC hotspot to make the server localize MT to trigger the appropriate handover mechanism. Third, we define a new metric ρ to evaluate the capacity of this hybrid network as the spatial density of inter arrival time of MT requests in $s^{-1}m^{-2}$ under the assumption of the homogenous Poisson point process (HPPP) distribution of MTs. Large value of ρ demonstrates high capacity. In Section II, we propose a hybrid VLC-OFDMA system model and give the system definitions. Section III illustrates the protocols of MT, server, and AP, including access, horizontal, and vertical handover mechanisms. Section IV evaluates the hybrid system performances theoretically and gives the numerical simulation results under different scenarios. Finally, conclusions are drawn in Section V. Visible light communication (VLC) is emerging as solution for overcoming the crowded radio spectrum for wireless communication systems.

II. SYSTEM MODEL

We consider a hybrid system of OFDMA and VLC networks containing *M* VLC hotspots and one AP of the OFDMA system, which are linked to the server via wired connections. Fig.1 shows this conceptual system. The VLC hotspot

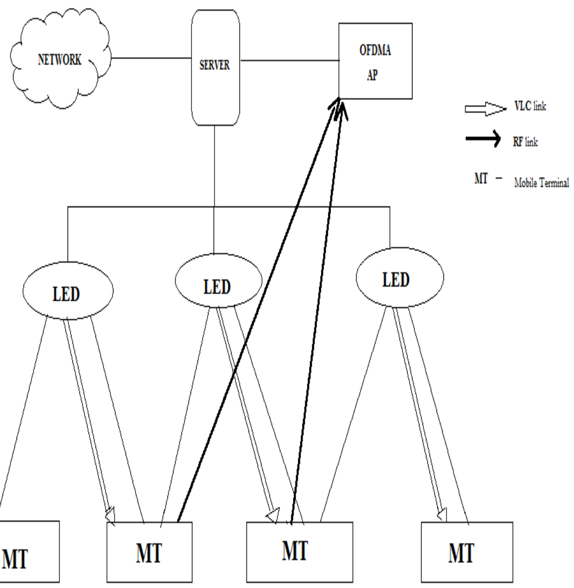

Fig. 2. System model.

which is mounted on the ceiling of the room, contains an array of LEDs as transmitters and also for illuminations. The transmitter in our model uses a Lambertian optical source, of which the brightness to an observer is the same regardless of the observer's angle of view. As a result, the projection of a hotspot on the ground can be regarded as a circle. MTs moving across the room will trigger the horizontal handover among different VLC hotspots or the vertical handover between VLC and OFDMA systems. The detailed protocols of handover are discussed in Section III. The VLC receiver is equipped in every MT to detect light signal when entering into the coverage of hotspots. We denote the area of the room, which is covered by the hybrid system, as *S*. The covered percentage of the VLC system is expressed as α which means that the covered area of total hotspots is αS, $\alpha \in [0,1]$.

As shown in Fig. 1, the server has knowledge of the locations and unique IDs of all hotspots. It receives feedback from MTs if they access the coverage of hotspots. The feedback information from MTs includes the received *ID segment* of the covered hotspot and the received light intensity. The server locates MT by decoding the *ID segment* and allocates the download transmission to the designated hotspot or AP. Definitions of packet formats in the VLC system and the allocation mechanism of the server are detailed in Section III.

The OFDMA system is used to deal with the access requests on uplink channels and transmit signals on downlink channels if MTs are out of the hotspot coverage or light channels are blocked. We assume that the numbers of downlink and uplink sub channels are Kd and Ku, respectively. All the OFDMA sub channels can be used for uplink requests if $\alpha = 1$, which means that Kd could be set to 0. However, when VLC has small coverage, the OFDMA system has to balance the numbers of uplink and downlink subchannels reasonably and fairly in order to maximize the total transmission capacity.

For MT, it equips with an OFDMA transceiver and a light detector (i.e., VLC receiver). These make MT send request messages using RF and download packets via RF or visible light. It depends on whether MT is on the coverage of hotspots. When MTs pass through different coverage of hotspots, horizontal handover occurs, and vertical handover is designed when MTs leave out of the coverage of the VLC system. In Section III, we detail the definitions, mechanisms, and protocols of the horizontal and vertical handover mechanisms.

Uplink and downlink Model

We model the distribution of MTs as an HPPP and assume that the time between two consecutive demands of MTs for service in the system (or interarrive time) is exponentially distributed. We define $\rho(x)$ as the spatial density of interarrival time in s−1m−2, constant in time. Hence, for a given region H, the mean inter arrival rate is $\lambda = \int H\, \rho(x)dx$ in s−1. Because every MT sends uplink requests via OFDMA, we model this process as a queue M/M/Ku, where Ku is the number of uplink OFDMA sub channels. Therefore, the uplink outage probability is defined as the unstable probability of the queue.

Downlink channels are divided into two parts in this hybrid system; one is the OFDMA downlink and the other is the VLC downlink channels OFDMA downlink channels are utilized only when MTs are

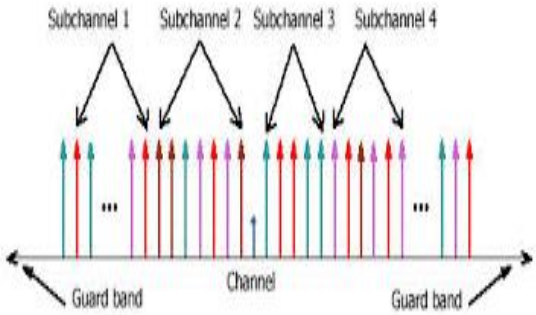

Fig. 3. Example of OFDMA subchannels.

out of hotspots coverage or fail to access to VLC system. We assume that the downlink transmission rate is N times the uplink rate. For the physical layer of OFDMA downlink channel, the subcarriers are distributed to different users at the same time so that multiple users can be scheduled to receive data simultaneously. For the VLC downlink, we only consider the accessing failure probabilities of MTs rather than outage probabilities. Outage events are neglected in this system because of the fairly short distance between hotspots and VLC receivers of MT and limited coverage of each VLC hotspot.

III. SCHEME AND PROTOCOLS

VLC hotspots are mounted on the ceiling, and the projections on the ground are circles. We use the same frequency of light in the VLC system in order to reduce complexity. Hence, MTs within the overlapped areas of contiguous projections cannot receive signal via the VLC system because of co channel interference; they switch to the OFDMA system. Under this scenario, vertical handover protocol is designed. Multiple hotspots are synchronized via wired connections by the server. The frame format of VLC packets for every hotspot, which consist of two parts. The first part is the *head* packet. It contains the combinations of *ID segment* and the sequences for synchronization and training. Synchronization sequence is used for MTs to synchronize MT receivers and hotspot transmitter. Training sequences are used for MTs to detect light intensity and report the light channel conditions to the server via the OFDMA system. *ID segment* assigns a unique binary sequence for each hotspot to be identified by the server. If an MT is within the overlapped area, it will detect the light signal but cannot decode the *ID segment* of the hotspot successfully because of the interference. In addition, the MT sends the information to the server that it locates in the overlapped area. As a result, the server can judge whether the MT enters into the overlapped areas according to the feedback of the MT in order to trigger the vertical handover. The other part of the VLC signal is the data transmission packet. The mechanism of time-division multiple access (TDMA) is implemented in the hotspot. On the coverage of every hotspot, each MT utilizes one time slot for downloading data in one frame. If the number of MTs is larger than the maximum number of time slots, the latest accessing MTs can only receive data from an OFDMA system rather than from a VLC network.

Protocols

Although the protocols presented in this paper are designed based on the system model, they are also applicable to the scenarios that the adjacent projections of hotspots do not overlap with each other. MTs apply for the uplink channels via the control channels of OFDMA system. We set Timer 1 to avoid endless loop in the applying process. Once this process fails, MTs cannot access a VLC or OFDMA network. If MTs enter into the coverage of hotspots, they wait until receiving the *head* of one frame of VLC packet. Then, they upload the received *ID segment* and light channel conditions to the AP via the uplink channels. Timer 2 is set to limit the waiting time to access the VLC system. If the waiting time is larger than the value of Timer 2, MTs switch to OFDMA system. AP receives the accessing requests and sends successful or failure feedbacks to MTs based on the number of idle OFDMA channels. AP transfers the request packets to the server if those are VLC requests. Otherwise, the OFDMA system accepts the access of MTs when the channels qualities meet outage constraints. When the server receives the request from AP, it decodes *ID segment* of VLC packet. Meanwhile, it sends failure information of time slots allocation to MT via the OFDMA control channel when the decoded ID belongs to the overlapped areas. If the decoded ID falls onto non overlapped coverage, the server locates the serving hotspot while it transmits the slots allocation information to the MT via OFDMA control channel. According to this, MT can acknowledge the sequence number of downloading slots. When MTs receive this information successfully, they can download data via VLC system until one frame ends. However, if the data reception fails, the event of horizontal or vertical handover in Step F may happen. When MT moves from one hotspot to another, it will first enter into the overlapped coverage, which makes reception data error due to co channel interference. It reports reception failure information to the server via AP in order to make the hotspot release the time slots for other accessing MTs. The same situation happens when MT approaches the edge of the VLC network and it will handover to the OFDMA system. In addition, if the waiting time is not larger than Timer 2 and MTs do not receive any feedback about slots allocation, they wait for random duration and try to send VLC requests again. In this hybrid system, vertical handover, which means that MTs switch from OFDMA system to VLC or *vice versa*, is accomplished by the cooperation of MTs and the server. Vertical handover of VLC to OFDMA can be denoted as the flow from Step C to Step E; the other pattern of vertical handover is denoted as the flow from Step A, Step B, and Step C to Step D.

The horizontal handover emerges when MTs cross one hotspot to another. After waiting for random duration in Step G, MT uploads a new *ID segment* and channel conditions if it enters into new hotspot coverage via receiving a refreshed *ID segment*, although Timer 2 is out. Based on this, horizontal handover is accomplished. However, vertical handover will replace the horizontal handover if MT cannot yet receive slot allocation information after waiting random duration and Timer 2 is out simultaneously.

IV. PERFORMANCE EVALUATION

In the hybrid system, the evaluation of capacity is usually difficult. In this paper, we use the maximum spatial density of MTs' accessing requests as the measurement and evaluate the influences of other system parameters. Moreover, numerical simulations are also presented here.

A. Maximum Spatial Density Analysis

As it has been discussed in Section II, we model a queue for OFDMA uplink channel and downlink channel, respectively. We analyze the maximum spatial density ρ based on the stable constraints. Stability is defined as a state where all the queues
in the system are stable. If the arrival and departure rates of the system are stationary, stability can be checked using Loynes' theorem

Uplink and downlink Channel of OFDMA: As for the OFDMA uplink channel, the queue length at slot t is defined as

$$u(t) = (Q(W) u(t-1) - X(W) u(t))+ + Y(W) u(t),$$

where $X(W)\ u\ (t)$ is the stationary number of departure packets at slot t, which relates to the processing ability of AP; subscript u and superscript W denote uplink channel and OFDMA network, respectively; $Y(W)\ u\ (t)$ is the number of arrival packets, which increases with spatial density ρ; $(x)+$ is defined as $(x)+ = \max(x, 0)$. Based on the assumptions in Section II, we model the uplink queue as M/M/Ku. Hence, the cumulative distribution function of waiting time

The stable constraints of the uplink queue are decided by the spatial density ρ and the processing speed of AP. Thus, large ρ may result in the instability of the queue, and we use the successful probability of uplink requests to quantify this constraint, which is $\pi 0$ of in our model denotes the probability of no requests, i.e., $\pi 0 = e - \rho S$, which is according to the assumption of HPPP distribution of MTs where $r = \rho S/(Ku\mu) < 1$, μ is the processing rate of AP, and Tth is the threshold of waiting time, which means that MT fails to access if it waits for a time larger than Tth. The queue length of the downlink channel at slot t is defined as $Q(W)$,

$$d(t) = (Q(W) d(t-1) - X(W) d(t))+ + Y(W) d(t),$$

where $X(W)\ d\ (t)$ and $Y(W)\ d\ (t)$ are the stationary numbers of departure and arrival packets at slot t of downlink channel in OFDMA system. The average arrival number of packets at slot t per accessing request of MTswhere $1\{\ \cdot\ \}$ is the indicator function; $O(W)\ d$ denotes the event ofsuccessful OFDMA downlink transmission; $O(W)\ u$ is the event of successful OFDMA uplink transmission; $O\ (V\ )\ d$ is the event of unsuccessful VLC downlink transmission, which means that the packets requested by MTs enter into

OFDMA downlink queue only when the VLC transmission outage events occur on the VLC network coverage; and OV and OV are the events with and without VLC coverage, respectively.

B. VLC Accessing Time and Handover Delay

The process of accessing to VLC system can be divided into three parts: 1) MT applies for the uplinks in OFDMA system; 2) after detecting VLC signal, MT uploads the *ID segment* of the hotspot and the light channel conditions via OFDMA network to the server; and 3) the server locates the hotspot served for the MT and broadcasts the slot allocation packets through the light channel. After receiving the successfully, MT accesses to VLC system. Therefore, the accessing time to VLC can be denoted as TaV represent the accessing time and the uplink and downlink transmission delays of the OFDMA system, respectively. tp is the processing time of the server and AP. $t$wait is the waiting time for MT to receive slot allocation information, which is related to the resource allocation time of the server and transmission delay and propagation delay of uplink and downlink channels.

C. Numerical Simulations

We assume that the AP can cover the room completely with a certain rate. As a result, the outage probability of OFDMA downlink is set to zero in the simulation. The maximum spatial density ρm against different coverage rates of VLC network in various number of hotspots with $Ku = Kd = 10$, $\mu = 10$. As shown in Fig. 6(a) and (b), ρm slightly decreases with α when $M = 1$, $\alpha > 0.4$, and $L = 10$ and $M = 1$, $\alpha > 0.2$, and $L = 2$. This is because larger coverage of VLC results in sending more accessing requests by MTs. While the total number of time slots for the hotspot is limited, the requests will be accepted by OFDMA rather than VLC network if their number exceeds the total number of slots. However, given α, large M, which denotes smaller VLC coverage of every hotspot, is similar to a microcell in order to serve more MTs. Large value of M (e.g., $M = 6, 11, 16, 21$) also results in lower failure accessing probability to the VLC network. It makes more opportunities to access VLC to increase ρm without limitation of the number of OFDMA downlink subchannels. As we assume that the distribution of MTs is modeled as HPPP, ρm remains the same value between VLC and OFDMA networks. Hence, the maximum spatial density ρm in VLC is influenced by the density in the OFDMA system. It makes more opportunities to access VLC to increase ρm without limitation of the number of OFDMA downlink subchannels. As we assume that the distribution of MTs is modeled as HPPP, ρm remains the same value between VLC and OFDMA networks.

Hence, the maximum spatial density ρm in VLC is influenced by the density in the OFDMA system.

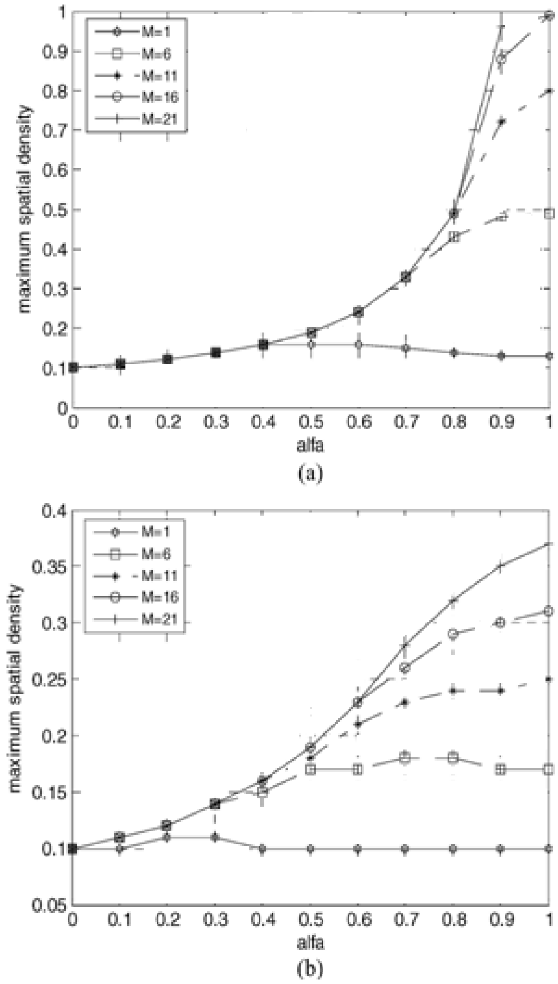

Fig. 6. Maximum spatial density *ρm* against *α* with (a) *L*=10 and (b) *L* = 2.

V. CONCLUSION

In this paper, a hybrid VLC-OFDMA network Model is proposed, with *M* VLC hotspots, one OFDMA AP, one server, and numbers of MTs. Server is linked to AP and VLC hotspots via wired connections. In this model, VLC channel is served only for downlink transmission, whereas OFDMA channels are used for uplinks in any location or for downlinks only without VLC hotspots coverage. A novel protocol is proposed combined with access, horizontal, and vertical handover mechanisms for MT to resolve user mobility among different hotspots and OFDMA systems. A new VLC network scheme and its frame format are presented to deal with multiuser access problems in every hotspot. In addition, a new metric *ρ is defined* to evaluate the capacity of this hybrid network as the spatial density of inter arrival time of MT requests in s−1m−2 under the assumption of the HPPP distribution of MTs. On varying the system parameters such as VLC coverage rate *α*, number of uplink and downlink channels *Ku* and *Kd*, and processing rate of AP *μ*, numerical simulations on spatial density *ρ* are obtained. Analytical and simulation results show large improvements in the capacity performance of the hybrid, when compared to OFDMA system.

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