Network Solutions for the LOS Problem of New Multi-User Indoor Free Space Optical System*

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Abstract–Recent developments in solid-state light-emitting diode (LED) materials and devices are driving a resurgence in the use of free-space optics (FSO) for wireless broadband communication. This technology uses the visible spectrum provided by "white" LEDs, which are becoming ubiquitous in lighting and has some desirable properties competitive with existing radio frequency (RF) communications. By leveraging the low-cost nature of LEDs and lighting units there are many opportunities to exploit this medium for widespread optical communication deployment. The optical medium, however, has distinct characteristics that must be managed, such as directionality and susceptibility to noise sources in the visible spectrum.

In this paper we present a new indoor FSO communication system, also known as a visible-light communication (VLC) system that achieves satisfactory data rates while supporting multiple access under line-of-sight (LOS) constraints. A hexagonal device design is proposed and investigated in the context to two communication protocols designed to manage point-to-point and point-to-host cases. Theoretical analysis and simulation of the two protocols using this hexagonal transceiver design indicate suitability for addressing high data rate communications between peer devices; or between multiple devices using the peer-to-host model. A new medium access control (MAC) scheme will also discussed.

Keywords: Free Space Optics, Visible Light Communication, Medium Access Control

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1 Introduction

RF communication is an incumbent and evolving technology that will remain useful for the foreseeable future. However, there are both opportunities with the use of free space optical spectrum and some limitations on the use of RF. RF suffers from several constraints that prevent it from being used in certain scenarios. For next generation of wireless communication technologies, with the development of new laser diodes (LD) and LED materials, researchers [6] believe that FSO presents a viable and promising supplemental technology to the RF system by enabling short-range indoor applications in addition to existing outdoor long range applications. Nowadays, due to the development of new energy-efficient LED materials and devices, replacing old incandescent and fluorescent lights with "white" LED lights will undoubtedly happen in the future [1]. These small and power-efficient devices give rise to more interesting wireless communication applications for both indoor and outdoor scenarios as a medium for modulated FSO communications. Researchers are attracted by the opportunities here because of the low-cost and volume production of LED devices for lighting [2, 3, 4, 5, 6].

Many existing demonstrations of FSO communication systems using visible light exist. Pang et al. constructed a system with visible LEDs for traffic light-based communications in 1999 [7]. This group set up the system with 441 red ultra-bright LEDs in the lab over 20 meters. The system can achieve data rate of 128 kbps.

The prototype developed by Douseki et al. [8] is an indoor application for communication within a range of 40 cm deployed as a desktop lamp without batteries. Power for this system is obtained from a solar cell that also acts as a photon detector for receiving data. This prototype can support transmissions up to 100 kbps under its illumination at the distance 40 cm.

The prototype described by Wada et al. [9] is an extension of a pixelated system [10] for long-range outdoor applications. It uses a LED array for traffic light as a transmitter and a high speed camera as a receiver. The authors claim it can achieve a speed of 2.78 kbps within a 4 m range under laboratory conditions.

At the University of Oxford, Minh et al. have developed a prototype [11] that can achieve 100 Mbps. However, it currently only works within a very short range (10 cm).

Little et al. at Boston University have demonstrated a short range (3 m), duplex, point-to-point, white-LED system with the rate of 56 kbps [12] developed with readily-available electronics and LEDs, demonstrating the viability, simplicity, and low cost of VLC solutions rather than their upper bound in terms of achievable data rates. The same team has also created a prototype that delivers in excess of 1 Mbps while providing both illumination and communication at several meters and has been demonstrated as an array of seven luminaries in the form of overhead spot lighting.

However, like every other new technology, FSO communication using visible light is still in the early stage of development and has many problems or limitations that need to be solved. One such problem is signal occlusion of the LOS channels.

Although visible light is more able to be reflected due to its larger refractive index than Infrared (IR), both still suffer from path loss that can make the receive signal-to-noise ratio (SNR) poor. Multi-Spot Diffusing (MSD) [13] provides a solution by beaming the signal to the ceiling to form several reflected light sources with Lambertian illumination pattern. However, the transmitter needs to be located at a desktop level and fixed to provide stable light sources. In our work, and in this paper, we introduce two network solutions for this problem through the use of relays for data through other nodes or hosts.

The paper is organized as follows. In Section 2, the model of our system is introduced with performance parameters. The details of our network solutions are provided in Section 3. Simulation and theoretical analysis are discussed in Section 4. Introduction of our Multi-user system is covered in Section 5. Section 6 concludes the paper.

2 The FSO System Model

The model for our proposed FSO communication system that supports of multiple access and mobility is illustrated in Fig. 1.

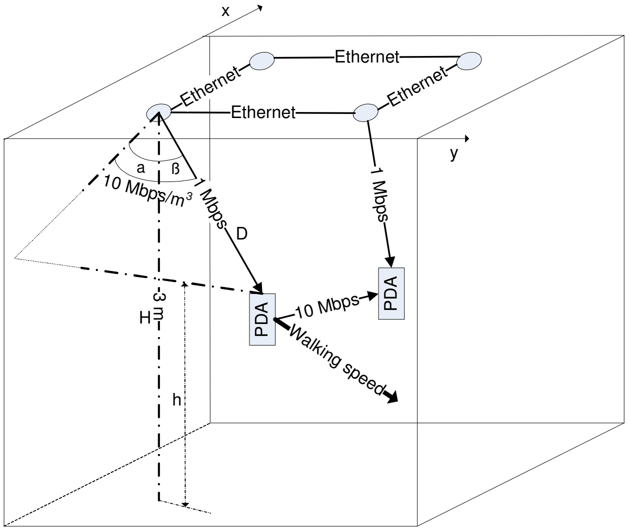


Figure 1: Proposed FSO system model for indoor applications

In this system, we assume the transmitter provides a transmission rate of 10 Mbps at a distance up to approximately 3 m. Using multiple transmitters, the total throughput provided per square meter area is 10 Mbps/m^2. When multiple access is supported, each user has a downlink throughput of up to 1 Mbps under the satisfaction of the total rate requirement. User mobility is supported without sacrificing performance.

We propose a device in the form of a hexagonal cylinder as shown in Fig. 2 for the user device at the desktop level. The original idea was to use a honeycombed sphere as proposed by [14]. However, this design is not suitable for us; with tens of LEDs on each face, hundreds of LEDs are required making the size and cost be impractically large if conventional LEDs were used. Furthermore, in our system, each face is assigned to one of two jobs explicitly. For honeycombed sphere, there are faces with field of view (FOV) between horizontal and vertical. Therefore, for whichever job is assign to them, they will cause interference to the faces assigned to the other job.

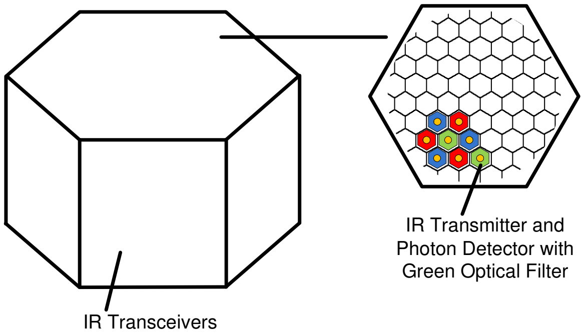


Figure 2: Desktop level user device illustration (IR transmitter for all faces; visible light receiver for top face and IR receiver for the rest)

Our planned system will include additional features that are not investigated in this paper. These include ad hoc LOS networking, MAC and potentially OFDM with other signaling techniques.

The top face, which is responsible for the communication with the base station, is different from the other faces. If the white light from lamp consists of independently controlled red, green and blue components, the receivers can be equipped with one, two, or three different optical color filters as indicated in Fig. 2. This provides multiple communication channels, allowing services to use separate channels and providing a higher data-rate.

The other faces are responsible for communicating with other user devices. Since the transceivers on each face are independent from those on other faces, simultaneous communication can be enabled between multiple user devices. Furthermore, since the 360 degree range of directions is covered by multiple faces, the link model can be approximately point-to-point (quasi-point-to-point). In addition, FOV of the side faces can be much narrower than that of the top face. These advantages can greatly reduce multipath distortion and optical background noise, allowing the transceiver design to be much simpler. However, this angle diversity is achieved at the expense of spatial reuse.

Another advantage of this design is that it can support mobility and solve the non-LOS blocking problem which is especially important for point-to-point link model. The details of which will be covered in the following sections.

3 Proposed Solutions for LOS Blocking

As mentioned before, LOS is required to provide continuous connectivity. Although signal reflection still exists, this approach suffers from a high path-loss due to the absence of a direct path, severely limiting the data-rate. Based on the system model we introduced, two possible solutions for this problem.

3.1 Peer-to-Peer Protocol

The first protocol solves blocking by using node-to-node multi-hop communications between user devices. Essentially, when blocking happens between two nodes, the source node will search through other nodes in the network to find a multihop path. The procedure is introduced as follows:

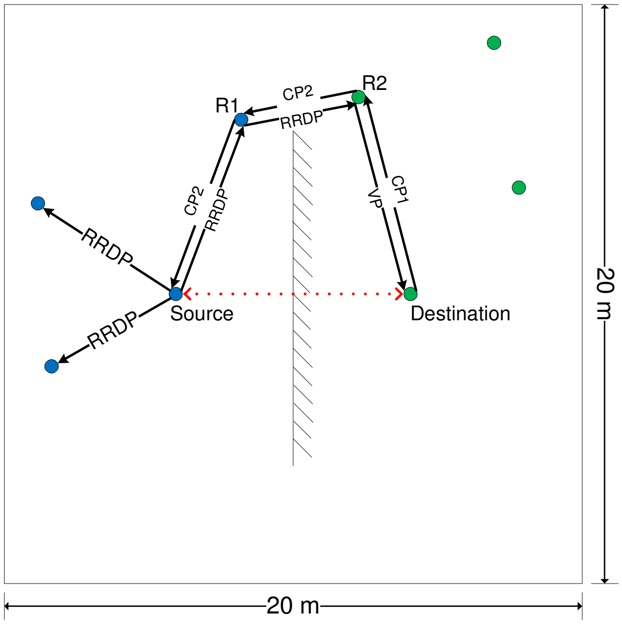


Figure 3: Peer-to-Peer protocol illustration (blue dots: neighbors of source; green dots: neighbors of destination)

3.1.1

When the connection between two nodes is interrupted, the source node first checks if the destination node exists in the LOS of any other face. If yes, the nodes can reestablish the link through the faces with the LOS path. If not, the other node is either out of range or blocked, both situations require additional steps. In the meantime, the destination node will update its local neighbor table by sending out Neighbor Discovery Packet (NDP) with identifying information and depth count.

3.1.2

The source node first checks its own local table to see if a route already exists to the destination node. If yes, the source node sends a validation packet (VP) to check the route and reestablish the link if link is valid.

3.1.3

If no such route exists in the local table or if the path is no longer available, the source node sends a Reactive Route Discovery Packet (RRDP) with a preset forward depth count to look for a rendezvous node that has a path to the destination node. If after a given period of time (associated with forward depth count), no response is received from any node, the system considers that no such rendezvous node exists and terminates the transmission.

3.1.4

If a rendezvous node does exist, when it receives such a RRDP, it will send a VP as mentioned in step 2). If no response is received, the source node's entry will be deleted from rendezvous node's neighbor list.

3.1.5

If all possible rendezvous nodes fail to find any valid paths, the source node will not receive a response before the timeout and will terminate the transmission. Otherwise, the rendezvous nodes will send back confirm packets (CP) with the path information. From the available routes, the source node will choose the best one to reestablish the connection.

These steps and scenario are illustrated in Fig. 3.

3.2 Peer-to-Host Protocol

The other protocol includes hosts at the ceiling level in our system for relaying the data. We consider the network as a two-layer geometry; nodes and hosts. Between every two peer nodes, there is only direct transmission and no multihop. Otherwise, the source node has to go through the host(s) to reach the destination node. We consider this in detail in the following steps.

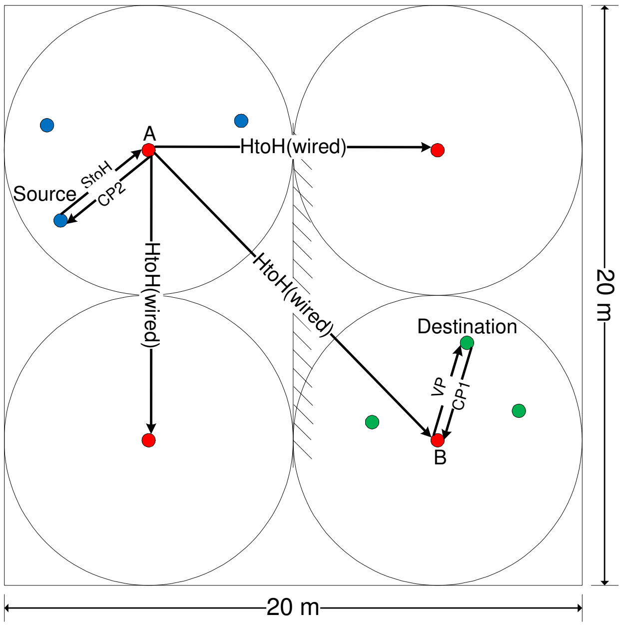


Figure 4: Peer-to-Host protocol illustration (red dots: host; blue dots: user devices under host A; green dots: user devices under host B)

3.2.1

The first step is very similar to that of the peer-to-peer protocol. The source node will first try to find alternative direct contact with destination node through other faces, and reestablish the link through new faces on both devices if available.

3.2.2

If there is no direct contact, source node will send a Source-to-Host (StoH) packet to its own host (Host A). The host then checks its node list to find out if the destination node is also under its coverage. If yes, a VP will be sent to check the availability.

3.2.3

If destination node is not in the list or there is no confirmation, host A will send out a similar request, Host-to-Host (HtoH) packet, to all its neighbor hosts in the local network (for example, all other ceiling lamps in the same office room).

3.2.4

Every peer host will check its own node list based on the information in HtoH. If the destination node exists, the corresponding host (Host B) will also need to check the link validity.

3.2.5

Similarly, if after a given duration, no response is received because either no host has destination node in its list or the link no longer exists, we consider the transmission terminated. Otherwise, the destination node will confirm the link to B, and then B will confirm to A and the source node, so that the link can be reestablished.

Similarly, these steps and scenario are illustrated in Fig. 4.

4 Connection and Rate Performance Analysis

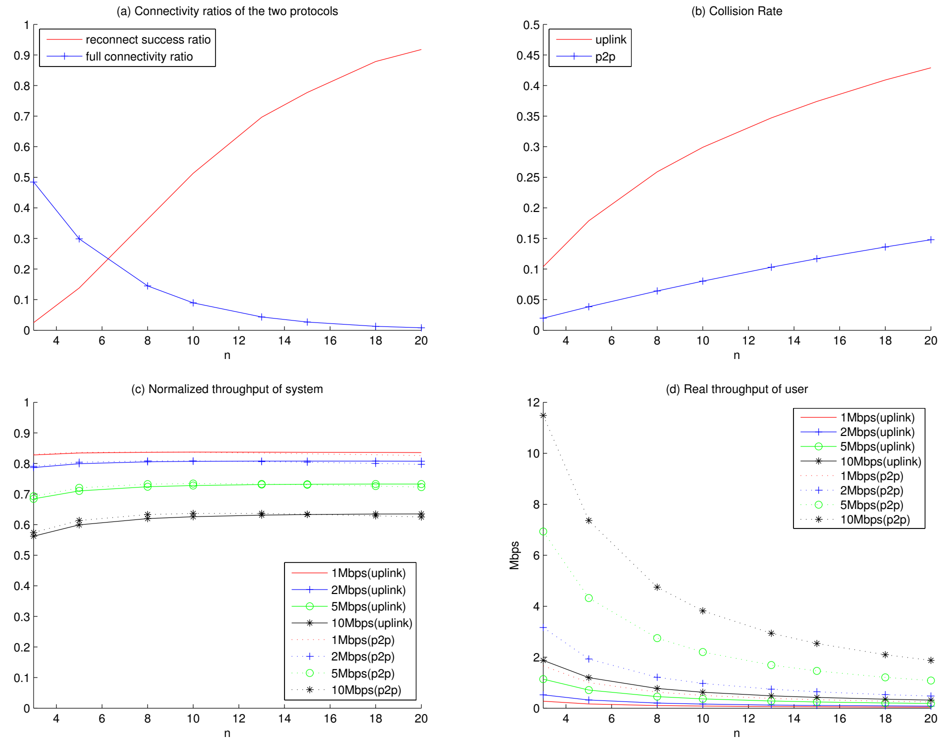
We first discuss two simulations of the connection performance.

For the Peer-to-Peer protocol, the scenario we consider is a 20 m x 20 m room. The forward depth count is set to 2 and the neighbor depth count is set to 1. The communication range is a radius of 10 m. We run the simulation 10,000 times for each case with different amount users. The transmission is between two nodes located at (6,10) and (14,10). The obstruction is a wall from (10,4) to (10,16). We calculate a Reconnect Success Ratio for different numbers of users. The ratio is calculated as how many times a successful multi-hop path can be established over total amount of the simulation runs for each case.

For the Peer-to-Host protocol, the simulation analysis is different. First, the nodes (6,10) and (14,10) are located close to the center of the room and they are not always under the coverage of a host. Therefore, the discussion of the reconnect success ratio between them becomes meaningless. Secondly, if the two depth counts are chosen sufficiently large in the first simulation, full connectivity can always be achieved. However, in Peer-to-Host protocol, only if the nodes are within the coverage of the host, will the full connectivity be achieved. Therefore, instead of Reconnect Success Ratio, we consider Fully Connectivity Ratio for this protocol. This ratio is calculated as the possibility of all nodes are under the coverage of base stations. We use the 4 hosts in the same scenario and the coverage radius of each host of 5 m, corresponding to half of the room side length.

The two scenarios are illustrated in Fig. 3 and 4.

Fig. 5(a) shows that the peer-to-peer protocol needs more nodes to achieve a higher reconnection success ratio. When the number of users reaches 20, the ratio is more than 90%. However, more nodes will increase the number of packets needed to discover the routes.


(a) Connectivity ratios of the two protocols

(b) Collision Rate

(c) Normalized throughput of system

(d) Real throughput of user

Figure 5: Performance analysis of the two protocols

For the network, this overhead equals $AverageEntry * \sum_{k=0}^{forwarddepth-1}(AverageEntry-1)^k$. For example, when there are 20 users in our simulation, each entry contains an average of 7.67 neighbors, which results in an overhead of up to 58.7 routing packets. Similarly, the overhaed for each node is the entry amount in the neighbor table. In our simulation, we only consider neighbors that are one hop away, which results in an average of 7.67 neighbors for each of the 20 users. If the depth of the search increases to 2, this overhead will increase to 13.1 neighbors.

In contrast, Fig. 5(a) shows that although the peer-to-host protocol makes the architecture simpler (the overhead to the whole network is always 1, and only the host needs to store the entry information), the guarantee of full connectivity may not be good enough for a large number of users if hosts have limited coverage. In the peer-to-peer protocol, the node can increase the depth count to reach the destination, which also increases the complexity. However, in peer-to-host protocol, the node in the shadow has no way to transmit or receive information.

Since, we adopt CSMA/CA as MAC solution, the discussion of the throughput performance will start with a theoretical model for CSMA/CA from [15]. Therefore, instead of simulations, the following analysis and Fig. 5(b)(c)(d) are based on theoretical derivation. By using this model and customizing it to our specific architecture, we can identify the packet transmission probability, τ, and the conditional collision probability, p (shown in Fig. 5(b)). Considering a CSMA/CA scheme with a contention window of W and maximum backoff stage of m (W

and m are not included in the previous simulations), from [15] we have

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+pW(1-(2p)^m)}.$$

We consider the worst case that every node always has a packet to deliver. For the uplink communications from nodes to host, if more than one node chooses the current time slot to transmit, a collision will occur at the host. So, for n nodes,

$$p = 1-(1-\tau)^{n-1}.$$

For node-to-node (p2p) communications, the analysis is more complex. We know that the user device has six faces, so the transmission from nodes which are not within the FOV of face sending the packet are not going to interfere. Even for the node within that FOV, if they don't have packet to transmit at the same time slot, the collision will not occur. Therefore, the new collision probability is

$$\begin{aligned} p &= 1-\sum_{k=0}^{n-1}\binom{n-1}{k}(\frac{5}{6})^{n-1-k}(\frac{1}{6}(1-\tau))^k \\ &= 1-(1-\frac{1}{6}\tau)^{n-1}. \end{aligned}$$

By solving these two formulas we are able to have a unique pair of results for τ, p. Before evaluating the throughput, we need to set parameters that affect packet timing. Based on 802.11 MAC specifications, we set them as shown in Table 1. ACK, RTS and CTS are three MAC packets defined for four-way hand-shaking scheme. SIFS and DIFS are two time interval between different types of packets defined in 802.11.

Three possible cases exist for each time slot during a transmission procedure: empty time slot when every node is in the backoff contention window, failed transmission when there are more than one nodes sending out the RTS, and successful transmission when only one node is trying to send out the RTS. Therefore, based on the CSMA/CA scheme, reference [15] shows

$$\begin{aligned} T_{succ} &= \frac{RTS}{rate}+SIFS+\delta+\frac{CTS}{rate}+SIFS+\delta+\frac{Header}{rate} \\ &+\frac{Payload}{rate}+SIFS+\delta+\frac{ACK}{rate}+DIFS+\delta, \\ T_{fail} &= \frac{RTS}{rate}+DIFS+\delta. \end{aligned}$$

We define normalized throughput as the ratio of the real statistical rate, which is the average device throughput under worst case, over the capacity of the device. Therefore, based on the derivation in [15], we have the formula for it:

$$S = \frac{n\tau(1-\tau)^{n-1}(Header + Payload)/rate}{(1-\tau)^n\sigma + n\tau(1-\tau)^{n-1}T_{succ} + (1-(1-\tau)^n - n\tau(1-\tau)^{n-1})T_{fail}}.$$

To calculate the real throughput for an uplink transmission, we need to multiply S by the device capacity (maximum rate), and to calculate the aggregate throughput of node-to-node links, further multiply the number of faces on each device, since all faces can work in parallel without interfering with each other.

By splitting the horizon into 6 parts, the probability of collision can be greatly reduced as shown in Fig. 5(a). This is because the area that can introducing collisions has been reduced to one sixth. Fig. 5(c) shows that the node-to-node scheme, however, doesn't give much of an efficiency boost over uplink transmission. This increase in efficiency is limited because τ is not very large so that its increase does not substantially improve the overall system performance. Also, we see that high speed can result low efficiency since the time ratio of payload will be decreased by increasing the rate. Even though, due to the parallel transmission ability, the real throughput can still be greatly improved. Suppose if the rate capacities for uplink and node-to-node transmission to be 2 Mbps and 10 Mbps respectively, Fig. 5(d) shows that in the four-user case for uplink transmission, each user can have an average rate of 422 kbps, and for node-to-node communication, the average rate is over 9 Mbps, giving the transmission on every face a minimum rate in excess of 1.5 Mbps. Since the performance is calculated under the worst case scenario, in which every node always has packets to send, these results represent the lower bounds of the possible performance.

Table 2 generalizes our observations.

Table 1: Packet timing parameters [15]

Payload size	8184 bits
MAC header	272 bits
PHY header	128 bits
ACK	112 bits + PHY header
RTS	160 bits + PHY header
CTS	112 bits + PHY header
Propagation delay (δ)	1 μs
Slot time (σ)	50 μs
SIFS	28 μs
DIFS	128 μs

5 The Multi-User System

The analysis in the previous section suggests the requirement for a multiple access system. Currently, at Boston University, a new VLC system which will support multiple-to-multiple transmission is under developing. The first stage of this development will enhance the ceiling level hosts to be more computationally powerful in order to process multiple tasks from different nodes simultaneously. The host will also be able to automatically detect, block and remove nodes in its coverage.

Several solutions for Mutiple Access Control exist. Time division multiple access (TDMA) is a scheme of simplicity. However, it is inefficient when users only need to occasionally transmit. Limitation on the modulation bandwidth and the number of available optical channels that can be obtained from current LEDs also prevent the adoption of frequency division multiple access (FDMA) and wavelength division multiplexing (WDM). Code division multiple access (CDMA), though, is ideally suited for mobile networks where many transmitters each generate a small amount of traffic at irregular intervals. However, CDMA requires much more powerful hosts that are more complex and typically consume more power.

For these reasons, CSMA/CA is a good solution that should work with static VLC system. However, the support for mobility required by most indoor wireless applications leads us to a new MAC scheme for VLC system. Since our current VLC transceivers are directional, new nodes cannot detect the channel status by carrier sense (CS). The proposed scheme still includes the similar handshaking and backoff mechanisms within CSMA/CA. So, the conclusion of Section 4 remains valid for our system.

Unlike the original CSMA/CA scheme, our new scheme gives host more control over transmissions. Essentially, the host periodically updates its node list, and the nodes reply with task requests using the backoff mechanism. The host can also dynamically allocate channel resource based on tasks' priority. This handshaking mechanism is similar with 4-way RTS/CTS, and will be modified to fit our VLC system. The Fig. 6 illustrates the procedure.

Although we don't have the hexagonal transceiver yet, the current device can still support

Table 2: Comparison of two protocols

Performance	Peer-to-peer	Peer-to-host
Complexity	High	Low
Overhead	High	Low
Mobility	Low	Medium
Speed	High	Low
Interference	Low	High
Overhead to Host	No	Yes
Outdoor Extension	Yes	No

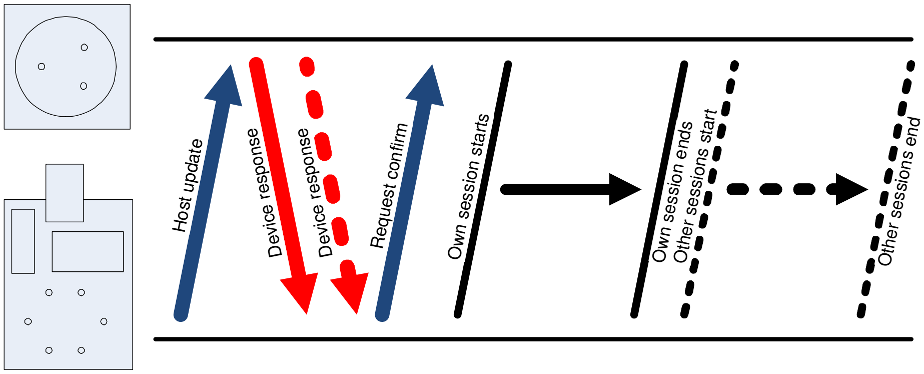


Figure 6: New MAC solution illustration (top square device: user device; bottom rectangular device: base station)

this peer-to-host protocol. This device, as shown in Fig. 7, consists of a transmitter, a receiver and a power supply. The transmitter consists of two parts. The first part was designed to switch current toward and away from the LED; when the LED should be off, current is switched away from it to discharge any capacitance across the LED. The other part was designed to maintain the desired current through the LED when it is supposed to be on.

The typical performance of the transceiver at 2Mbps is shown in Fig. 8, with the transmitter input shown as the yellow signal and the receiver output shown as the green signal.

Recently, an improved design which utilizes a current-mirror to regulate the current through the LEDs was developed.

Furthermore, this new design offers many benefits over the older one:

- It can be easily modulated to multi-level signaling, allowing more data to be sent per cycle;
- It pre-biases the LEDs, allowing them to switch on faster;
- Each LED driver can support more LEDs, reducing the overall costs;
- Its design is simpler, which reduces costs, improves reliability, and facilitates modeling;
- It eliminates many problematic parts;
- Unlike in the older design, LEDs can remain on without signal.

6 Conclusions

In this paper we propose a next generation FSO communication system using visible light that exploits relaying and multiple access with a hexagonal line-of-site transceiver configuration.

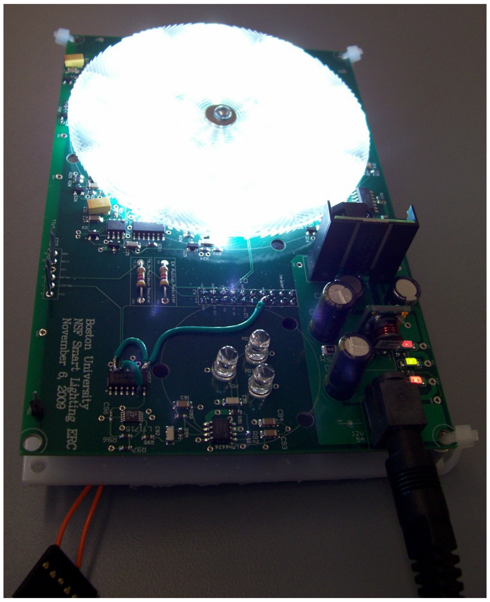


Figure 7: Current VLC prototype for indoor applications (the LED driver is in the top half of the photograph, lighting the white LEDs under a lens)

We introduce two network solutions for the LOS problem. From the discussion in previous sections, we know that both protocols have advantages and disadvantages. The peer-to-peer protocol leverages a narrow beam and narrow field of view from the proposed device and thereby can have good performance in terms of speed without a central host. The peer-to-host protocol, in contrast, is simpler and easy to implement, but due to the diffuse link model and interference, is less amenable to high data rates and requires a host to be available.

The adoption of each protocol depends on the desired behavior of the communication model. When the application requires a high throughput, the first protocol is most appropriate. If the application produces short bursts of data or the data rate requirements are relaxed as in many industrial automation scenarios, then the second protocol is a good choice. It is simpler and can readily support mobility of devices. Applications like in-office P2P messaging, in-building location services and the like can use the second protocol.

A new 2 Mbps transceiver has also been introduced with benefits over our older one.

For the next, the new MAC scheme will be analyzed and compared with existing schemes. Implementation and demostation will be followed to give experiment results.

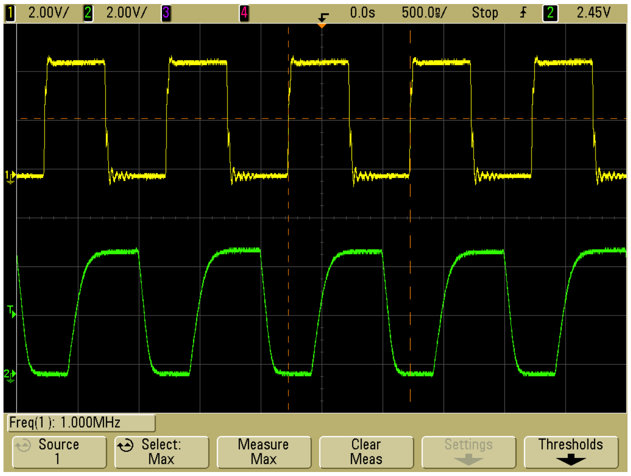


Figure 8: Waveforms of transmit and receive signals

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