Evaluating LED-Camera Communication for Drones

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ABSTRACT

This work explores the idea of using LED-camera communication for drone communication. In particular, this research positions the idea of using optical wireless links using LED transmitters and camera/image sensor receivers to communicate between ground and drones and between drones. While the concept opens an opportunity for a complementary line-of-sight (LOS) technology to radio frequency (RF) wireless to enable drone communication, it also raises fundamental research questions as to the ability to communicate under harsh mobile settings inherent to drones. To this end, in this paper, we present an empirical study of LED-camera communication performance for ground-drone communication under different mobile settings or *trajectories* of the drone. Through a bit-error-rate (BER) metric based evaluation of the performance, we evaluate the quality of drone-ground uplink and downlink LED-communication under real-world mobile conditions. Through insights from the BER evaluation, we highlight the fundamental challenges to be addressed that limit the practicality of drone visible light communication (VLC).

CCS CONCEPTS

• **Computer systems organization** → **Embedded and cyber-physical systems**; • **Hardware** → **Emerging technologies**.

KEYWORDS

Drones, Visible Light Communication, Camera, Unmanned Aerial Vehicles, Mobility

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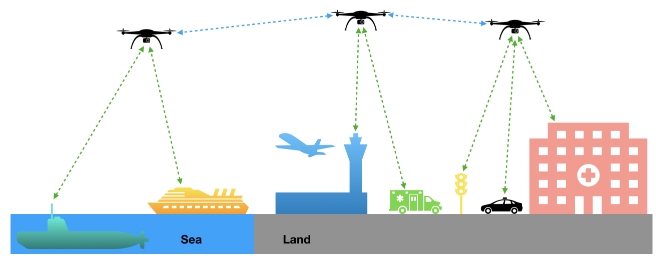

Figure 1: Conceptual illustration of drone based use-cases for LED to camera communication.

1 INTRODUCTION

Unmanned Aerial Vehicles (UAVs), popularly known as drones have become an essential part in the planning of IoT[1–3], next-generation infrastructures[4]. With advances in communication technologies and infrastructure to support the same, drones are being perceived more than a simple aerial sensing unit. The concept of using drones as an aerial base station has gained increased momentum. Communication between drones and ground stations can be extremely valuable for a wide array of applications ranging from safety-critical to communication relaying to enabling last-mile connectivity. Currently, the most popular choice for drone communication has been using radio frequencies (RF) [5, 6]. However, the fundamental challenges of RF communication such as the eavesdropping potential, propensity to be hacked, and the fact that radio spectrum is highly cluttered pose key questions to the usage of RF for drone communication. Clearly the choice for the best communication medium for drones is an open question, and for which RF, though a strong contender, has key limitations, thus opening the need to explore other modalities.

Conceptually, drone-ground and drone-drone communication links use over–the–air medium, and such links typically do not have obstacles/obstruction in signal path–in majority of use-case scenarios (see Figure 1). The fact that in most of the communication scenarios, drone-ground and drone-drone communication links will be over line-of-sight (LOS) channels, opens up opportunities for using LOS communication modalities for drone communication. In this regard, in this work we explore the use of optical wireless communication in the visible light spectrum using light emitting diodes (LED) as transmitters and image sensor or cameras as a receiver, also referred in literature as LED-Camera communication.

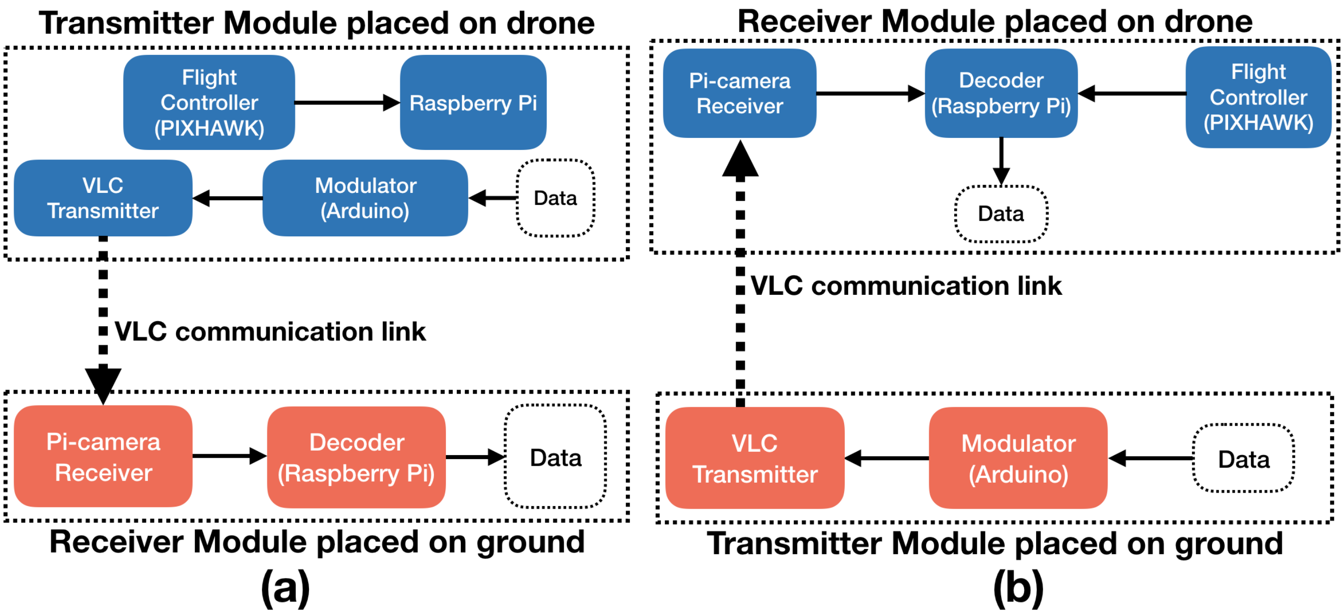

Figure 2: Drone LED-Camera Communication Modalities. (a) Camera receiver on ground and LED transmitter on drone, (b) LED transmitter on ground and Camera receiver on drone. The modulator is implemented on an Arduino and uses ON-OFF Keying (OOK).

Prior work from the author has also positioned the idea of using visible light communication (VLC) in drones [7] using LEDs and optical receivers. VLC can offer several advantages over RF communication such as high data capacity, dual usage of illumination and communication, and is challenging to sniff unobtrusively thus improving link security. In addition, drones, as almost as a default, are/will be equipped with cameras for its regular use for footage capture or advanced visual sensing/computer vision. This provides a built-in infrastructure to enable drone camera communication.

The problem of enabling LED-Camera communication under mobile settings is an open research question yet to be solved and has also been a focal point of research in recent times. A drone communication cannot be ever considered as zero-mobility or static, even if it were to hovering (we show its impact on communication performance later in the paper) above an area/object of interest. There has been only a limited number of investigations on enabling optical wireless communications in drones [8] and a common premise in prior works is the availability (hence good understanding) of the drone optical wireless link.

While the experiences and learning from developing VLC technology for over a decade can be applied in the drone use-case, however, the fundamental notion of enabling robust VLC under mobile settings is key, and in fact is the foundation for drone optical wireless communication. In this regard, in this work, we first explore the drone LED-Camera communication modality from addressing the mobility challenges. As a first step, this work-in-progress research studies drone mobility and its impact on LED-Camera communication quality. Through, a real-world experimentation based approach, this work presents an empirical evaluation of LED-Camera communication quality using the bit-error-rate (BER) as the metric. In summary, the contributions of this paper are:

1. Design of an experiment setup for drone-ground LED-Camera communication in (i). downlink mode (LED on drone, Camera on ground) and (ii) uplink mode (LED on ground, Camera on drone).

2. Experimental evaluation of drone LED-Camera communication under different drone mobility trajectories, including vertical motion, hovering, straight-line motion, circular motion, take-off, and landing. The evaluation uses BER as the metric for quantitative representation of quality of communication performance and for comparison.

2 RELATED WORK

This work builds on the conceptualization of using visible light communication on drones [7], which positioned the fundamental challenges in enabling practical drone-VLC. This paper focuses on studying the impact of drone mobility on the optical wireless link. Recently, authors in [8] have proposed a method for using VLC in UAVs in order to provide flexible communication and illumination with minimum power utilization. They present a two-step approach to solve this problem. The first step is to find the optimal UAV location for a given cell association and the second step is to find optimal cell association assuming fixed UAV locations. These sub-problems are solved by applying randomized incremental construction to obtain the optimal UAV locations and a greedy algorithm to obtain a sub-optimal cell association. The estimated UAV locations and cell associations are iteratively optimized to minimize the power consumption. Though this approach demonstrates a power efficiency improvement by 38.5%, this research does not take into account the potential outages and throughput variability due to the movements of the UAV(s).

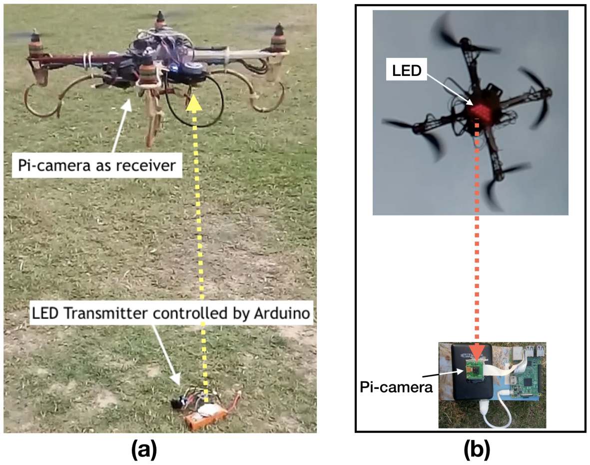

Figure 3: Experiment setup of drone LED-Camera communication. (a) UPLINK: LED transmitter is on the ground and the RaspberryPi controlled camera receiver is on the drone with the camera facing the ground along the drone's vertical axis. (b) DOWNLINK: LED transmitter is on the drone and the RaspberryPi controlled camera receiver is on the ground with the camera facing the sky along the drone's vertical axis.

LED-Camera communication has been a topic of significant research interest over the last half-a-decade. The work [9, 10] present a LED-to-camera communication system that enables a ceiling lamp used for illumination to communicate to diverse off-the-shelf cameras that use rolling-shutter technology. [11] develops an energy efficient approach for LED camera communication using smartphone camera as receiver, while [12] uses reflected-light (passive) detection for LED camera communication, overall aiming to harness the photons as much as possible. [13] proposes the modulation of ambient light using various reflective surfaces for communication, and [14] presents a LED to smartphone camera communication system using CSK (Color Shift Keying) modulation technique, and have demonstrated data rates of 5-7 kbps. [15] studies the LED-camera channel model using Markov-modulated Bernoulli process and develops a network simulator *CamComSim* that captures this model. In [16], the authors have designed a 60bps LED to smartphone camera link for positioning in augmented reality based applications. In [17, 18], the authors use the LED-camera communication channel for imperceptible signaling through display screens to camera receivers.

3 EXPERIMENTATION SETUP

The main focus of this phase of the research is to conduct experiments in real-world drone mobility conditions. We set up an experimental drone LED-Camera communication platform in an open ground setting with no obstructions for the drone mobility for over a half a kilometer radius. As shown in Figure 3, the setup consisted of a prototype 4-propeller drone which we built from scratch using off-the-shelf components. The drone is capable of a speed up to 4m/s and has a battery life of about 15 minutes. The drone hosts a 9-dimensional IMU and a GPS module. The LED-Camera communication is setup using two identical transceiver modules, which each hosts a LED transmitter, controlled by an Arduino [19], and a RaspberryPi camera [20] capable of capturing video frames at 30 frames-per-second (FPS) at ultra HD resolution, controlled by a RaspberryPi [21] module. The experiments were conducted across two modalities, which basically differed based on the which acts as a transmitter and which one as the receiver. The UPLINK mode uses the drone transceiver module as the camera receiver for the data transmitted from the LED on the transceiver module placed on the ground. The DOWNLINK mode uses the drone transceiver module as the LED transmitter which communicates the data to the camera on the transceiver module placed on the ground. The hardware setup architecture for these modalities is shown in Figure 2.

Hardware configuration of the transceiver. The transmitter consists of an Arduino microcontroller, a 25 Watt LED, 9V battery, a driver module (L293D). The transmitter is configured to modulate a random bit stream (stored in a file) using ON-OFF-Keying (OOK) at a transmission rate of 15 bits/second. We choose this transmission rate in obeyance with the Nyquist criterion, for the receiver sampling rate limitation of 30 FPS – in camera communication, each image frame is treated as a sample. We note that the RaspberryPi camera is indeed capable of up to 200 FPS, however it limits the image resolution. Since the main goal of our experiments is characterizing mobility, we retained the resolution at its highest value (ultra HD) for which the camera is constrained to 30 FPS. The receiver module consists of a RaspberryPi camera[20], a Raspberry Pi[21] compute module, and a 5V power source. The RaspberryPi is used for multiple puposes; control the camera, execute control code for the transceiver functions, and execute control code for executing LED transmission code on the Arduino.

4 EXPERIMENTATION METHODOLOGY

Data transmission. The data to be transmitted is modulated using on-off keying(OOK) on the LED and transmitted at 15 bits per second using UDP packet communication. Each UDP packet is separated using start (101010) and stop bits (00000). The payload was a 4 bit symbol which was generated from a random bit stream source and mapping to a value between 0000 and 1111 in a random order fashion. The data transmission continued in a loop across the experiments.

Data reception. The optical signals from the LED are picked up as light intensity patterns on the piCamera image frames. We specifically choose piCamera as the camera module in our experiments, as it is light in weight and low-power, thus suitable to be integrated on a drone. The scripts running on the Raspberry pi perform two important tasks. First, picamera records a video footage at 30 fps, with the RaspberryPi's Unix (operating system) timestamps annotated on the video. Second, the drone state information is transmitted from 3DR Pixhawk 1[22] (drone's control module) to the Raspberry pi using a serial connection. This information include timestamps, GPS information (latitude and longitude), altitude, velocities along cardinal axis (X, Y and Z), and angular rotations (roll, pitch and yaw). This drone metadata is captured at 50Hz using a pymavlink[23]

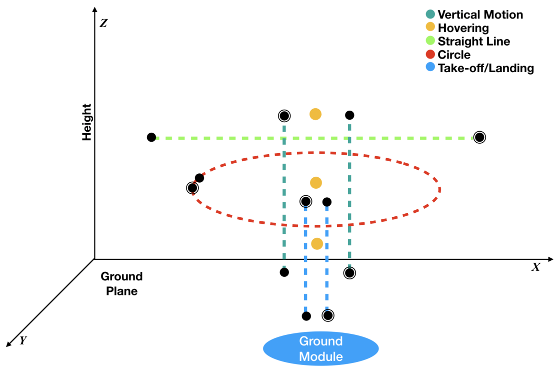

Figure 4: Evaluated Trajectories of Drone

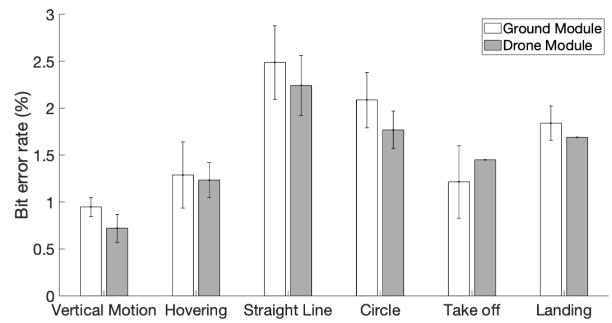

Figure 5: BER of LED-Camera communication under different drone mobility trajectories for uplink (Ground Module) and downlink (Drone module).

library in python, which are stored on Raspberry pi as a text file during each experiment trial.

Data processing. The decoding of bits from the video and further analysis is conducted offline. To decode bits from the video, we first locate the LED on each sampled image using color based segmentation computer vision technique. The pixels corresponding to the LED are localized, and the average pixel intensity value of this *region of interest* is calculated. Using a binary hypothesis, the LED status is estimated as ON (bit 1) if the ROI avg. pixel intensity is greater than a threshold, and OFF (bit 0) otherwise. The threshold intensity is computed for each video in each experiment trial through a calibration process that involves computing mean value of the ON and OFF status of the LED ROI in each video snapshot (per experiment). We use the calibrated thresholding to make sure of a robust ground-truth dataset for computing the BER. The time-stamped meta data from the drone which includes its velocity, altitude, GPS coordinates and IMU readings, are matched with the experiment trails and video frames. The BER is computed for each of the mobility trajectories, as the ratio of the total number of erroneous bits to the total number of bits transmitted in each experiment's window.

5 EVALUATION

We present the experimental evaluation study of LED-Camera communication under different real-world drone mobility configurations. Using BER as the metric, we focus our evaluations along two dimensions: (i) mobile trajectories (drone movement types), and (ii) altitudes (heights).

5.1 Mobility trajectories

In addition to be able to fly across a line or a curve trajectory like any other aircraft, commercial and recreational UAVs or drones have unique movement capabilities such as hovering in mid-air, ability for vertical take-off and landing, and ability to quickly changing the direction of motion. The propeller based aerodynamics allows drones to stay (hover) at one position for a long time and accelerate and change trajectories very quickly. While such degrees of motion open a plethora of applications for drones, sustaining robust communication links, especially those requiring LOS, is extremely challenging. In this regard, we set up to study the performance of the LED-Camera communication under these realistic drone trajectories. In particular, with the ground as the reference, in this work we evaluate our drone system across 6 different motion trajectories:

- **Hovering:** drone staying afloat with propellers ON at a fixed location and altitude above the ground.
- **Vertical Motion:** drone flying vertical towards the sky and reverse direction after certain altitude and fly down towards the ground.
- **Straight Line:** drone flying in a straight line, parallel to the ground plane at a fixed altitude.
- **Circle:** drone flying along a circle centered around a target on the ground with a fixed radius, whose circumference is parallel to the ground plane and at a fixed altitude from the ground.
- **Take-off:** drone taking-off along the vertical axis, from a complete halt position on ground to flying towards the sky.
- **Landing:** drone landing by flying down along the vertical axis, from a certain altitude to complete halt position on the ground.

We note that the key difference between the vertical motion and take-off and landing, is that in the vertical motion scenario the drone has already taken off and is either hovering at a certain altitude or flying along a certain trajectory at a certain altitude. We illustrate all the 6 trajectories[1]. of the drone that we have considered in our experiments in Figure 4.

We conducted extensive experiments that involved capturing a series of 2 min long video sequences for each trial across each of the 6 trajectories. We chose 2 min for each trial window as we had to consider the drone battery lifetime (15min). Overall, we collected about 2000 frames worth of data (about 1000 random bit stream) for each of the trajectory cases. In our experiments, the straight line trajectory was over a 9m line-segment with the transceiver module on the ground at the center, and the circle centered the module with a radius of 4.5m. The altitude for these trajectories was 10m from the ground, which was also the maximum altitude tried in our entire experimentation.

We report the BER under different trajectories in Figure 5. We can observe that the BERs, in general, is relatively higher than other

[1]Short video snapshots of these trajectories can be found at https://youtu.be/pBq8NFXrR5I

Altitude	BER (%)	
	UPLINK	**DOWNLINK**
Low(2-3m)	0.74	0.81
Medium(6-7m)	1.7	1.42
High(9-10m)	1.9	1.6

Table 1: BER at different altitudes.

reported VLC and camera communication system under vehicular use-cases. We believe this is because of the unstable nature of drones; even under slight tilt the angular variation between the vector joining the LED and camera centers can significantly change the signal to noise ratio (SNR), thus leading to erroneous bits. Also, it is to be noted that these evaluations are recording the raw BER without any consideration of error control coding and optimization mechanisms. The next observation is that the BER for straight line and circular trajectories are worse than others. We posit that this could be due to the increased chances of link failures due to outages, due to the LED being out of the camera view, which can happen more often in these trajectories. Based on how we set up the uplink and downlink cases, the channels being symmetric, we expect that the BER will be very close to each other, which we can observe in our experiment results as well. We observe a unique reversal of order in the take-off and landing case where the downlink BER is higher than that of uplink. Our explanation to this is that, when the LED is placed on the drone the amount of shaking and vibrations (more unstable) is much higher than when the LED is placed on the ground. This reflects on the large variations in pixel ROI of the LED on the camera frames and also motion blur. While we have ensured the LED tracking has zero errors due to our calibration efforts, the other camera and lighting artifacts, especially due to motion, have not been addressed. These results show the impact of such artifacts and reminds us of the open challenges and reality of using optical wireless communication on drones.

5.2 Altitudes

In another set of experiments, we set the drone to hover over the transceiver module on the ground at different altitudes. The drone we have built has some stability issues under hovering (a common problem for drone manufacturing/engineering) which caused the drone to be wavering the altitude during hover. Our experiments have a complete record of every motion of the drone and based on the altimeter and IMU readings, we posit that our experiments set the drone over three altitude regions: LOW (2m-3m), MEDIUM (6m-7m) and HIGH (9m-10m). We report the average BER over 5 trials, each of 2min duration, for each altitude region in Table 1. We observe that the BER increases with height, which is consistent with our understanding of optical wireless links where the communication quality degrades with distance between the transmitter and receiver. We also observe that that BER for uplink and downlink cases are very close to each other for each height, as observed in the other trajectories as well. This result also highlights and confirms our hypothesis that even when the drone hovers it is not static (no motion) – we observe from the BER numbers that hovering is also probably not the best possible motion scenario for a drone.

6 DISCUSSIONS

6.1 Example Applications

The integration of VLC technology with drones can lead to plethora of novel applications in drone-ground, drone-drone, and hybrid communication areas. This will lead to a connected infrastructure that will support secure communication between drones and the environment. Some drones are equipped with sensors and are used to survey an area or map a 3D structure. In these scenarios, drones send the sensor readings to the nearby remote station. Drones also communicate their state information(latitude, longitude, altitude, battery, etc) with the ground station, especially in GPS-denied scenarios. All these types of communications can be efficiently done by visible light.

6.2 Mobility Challenges

The mobility of drones will lead to rapid changes in the distance between the transmitter and receiver. Drones constantly try to balance themselves in the air which leads to frequent changes in its orientation. The change in orientation angle (roll, pitch, and yaw) of the drone also leads to link loss as the alignment of the transmitter and receiver will change. The effect of stability and on-board vibrations of the drone on the VLC link is also yet to be tested for the system. Although the effect of these factors can be reduced if the used drone has a standardised design, robustly built quality, and gimbal mechanism for the camera. Drones are very agile in nature and can rapidly accelerate to higher speeds. The higher velocity of drone with respect to the ground module can result in erroneous reception of useful data. In [24], the authors discuss and address some of the limitations of VLC in a highly mobile environment where both transmitter and receiver are free to move like swarm of robots. The effect of different velocities, and other parameters of the drone under various trajectories, on the VLC link remains to be extensively studied under defined conditions.

6.3 Improving data rates and coverage

In order to use drones as aerial VLC hotspots or transmit videos from the drone, high data rate is the primary requirement. The data rate can be improved by using novel higher order modulation schemes, enhanced encoding schemes, advanced receivers, and leveraging different emitter and photo-detection/imaging characteristics. As a part of the planned future work, we plan to study the impact of error-correcting codes on the throughput. We also plan to explore MIMO techniques with array emitters and reception to improve coverage and data rates in drone VLC.

7 CONCLUSION

This work studied the BER performance of drone LED-camera communication through an experimental trace based analysis under different drone mobility conditions. The drone mobility situations considered included hover, vertical motion, flying along straight line and circle, taking off and landing. The reduction in BER and inconsistency in link sustenance under different mobility conditions highlight the impact of motion on quality of information delivery using drone VLC. The results also indicate the symmetry between uplink and downlink conditions in ground-drone VLC use-cases.

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