Enabling Physical Link for Flying Light Specks

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ABSTRACT

The Flying Light Speck (FLS) is a compact drone designed with versatile light sources that emit diverse colors and textures, offering adjustable brightness levels. This technology plays a crucial role in realizing the concept of holodecks, where a collective swarm of FLS units collaborates to provide illumination through algorithmic operations and seamless real-time information exchange. This necessitates a proper physical link (PHY) among the FLS drones, imposing stringent requirements on the network infrastructure. This paper presents the essential requirements, explores various technologies suitable for establishing the physical links, and proposes a comprehensive evaluation plan to compare and assess the candidates.

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1 INTRODUCTION

An FLS is a miniature-sized drone mounted with one or multiple light sources, capable of creating diverse colors and textures with adjustable brightness [5]. They possess the capability to detect a user's touch and offer kinesthetic feedback through force exertion [4, 5]. Their versatile application spans from entertainment purposes like illuminating gaming characters on tabletop surfaces to providing crucial assistance in healthcare scenarios, such as real-time separation and diagnosis of different organs captured through MRI scanning. Typically, the creation of these 3D objects comprises a multitude of FLS units, often numbering in the millions.

To enable such applications, FLS demands the execution of decentralized algorithms to determine drone movements and content for display. While some of such information can be pre-calculated and disseminated to FLS units offline, many FLS-supported applications necessitate real-time instructions from the Orchestrator, as well as the exchanging sensory data collected by each FLS. For instance, FLS units might capture real-time obstacles (e.g., other FLSs) and dynamically illuminate motion amid complex environments (e.g., adjusting color and brightness based on real-time environmental background). A suitable physical link (PHY) among FLS units is thus essential for successful delivery of such information, serving as the cornerstone for communication and ensuring optimal data transmission performance. We note that, higher-layer protocols (e.g., MAC) are also crucial for efficient PHY link utilization, such as scheduling different devices to share the PHY link. We leave this topic for future study.

This study focuses on the physical link (PHY) that facilitates communication between the individual FLSs and the Orchestrator components [6]. In this work, we will start by describing essential requirements for the physical link, encompassing both performance metrics (such as latency) and user-oriented attributes (such as feasibility and mobility). Furthermore, our paper presents an array of cutting-edge communication technologies, providing an in-depth comparison across all dimensions. To ensure a well-informed choice, we propose a comprehensive 3-stage evaluation plan to test performance within FLS applications.

Our contributions are as follows:

- Study of Physical Link Requirements (§2): We will discuss the requirements on establishing a physical link to enable the FLS applications.
- Discussion on Existing Technologies (§3): We will provide an analysis of several prominent technologies, comparing their strengths and weaknesses.
- Proposal for Evaluation Steps (§4): We will elaborate on the evaluation plan on the physical link candidates

2 REQUIREMENTS FOR FLS PHY

This section delves into the essential requirements for the physical layer (PHY) link among FLSs, which are dictated by real-world usage scenarios and practical FLS applications. These requirements encompass various aspects that dictate the optimal performance, resilience, and usability of the physical link within a swarm of FLSs. We acknowledge that some aspects of the requirements below have been discussed in a separate paper currently under review [7].

Latency The ideal point-to-point communication demands low latency, typically requiring a response time of less than 36 milliseconds [8]. Swift reaction times are crucial, especially when an FLS receives user input, necessitating rapid communication with adjacent FLSs. Failure to respond within this threshold leads to perceived lag in applications.

Throughput The FLS poses a rigorous demand for throughput in its point-to-point connections, aiming for a scale of Mbps. With millions of devices in play, each unit must effectively manage its traffic and communication while responding to user input. It is important to highlight that the throughput requirement could be moderated by adaptive range, allowing fewer nodes to share bandwidth, thereby reducing the overall throughput demand.

Power Consumption Effective power management is critical for the FLS due to its limited power source. Optimizing data transmission to be power-efficient is a fundamental requirement for sustaining prolonged operation without the necessity for frequent recharging. Overconsumption of power has broader implications,

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potentially generating excess heat, which, in turn, poses safety risks and can lead to automatic shutdowns to prevent system damage or hazards. Therefore, power efficiency is not solely a means to prolong operational duration, but also a critical factor in maintaining system stability and safety by managing thermal conditions within permissible limits.

Scalability Scalability is a pivotal factor for the physical link design, particularly when aiming to support a vast network of millions of FLS devices. However, achieving scalability in such networks often encounters various challenges. One prominent hurdle lies in the design architecture of the physical link itself. For instance, if the frequency band utilized for communication encompasses only a limited number of sub-channels, this restriction could present a significant impediment when attempting to facilitate access across the channel for a multitude of devices. Such constraints may lead to inevitable conflicts and congestion, ultimately impeding the seamless scalability of the network. It is important to clarify that our current focus in this paper is on the PHY choice for FLS communication. While a well-designed Medium Access Control (MAC) layer is crucial for efficiently managing channel access in networks with millions of devices, we defer its discussion to our future studies.

Robustness Ensuring robustness in signaling is pivotal, where mission-critical information is transmitted with minimal interference. Mitigating noises and minimizing interference and multi-path fading, despite challenging with stringent power requirements, is crucial for reliability. Although higher layers could schedule retransmission to overcome the data corruption, it is demanding to have lower error rate so that the transmission does not unnecessarily flood the channel with excessive retransmission.

Range The communication range requirement is usually on the level of centimeters. It could be 1-3 centimeters to 10 centimeters, depending on the characteristics of the point cloud being illuminated and the dimensions of a display. Dynamic radio range adjustments are demanded to greatly optimize the algorithm execution and convergence rates, as proven in [1]. This is because the execution time of an algorithm may depend on the number of FLSs participating in its execution, and a dynamic range imposes less work on other FLSs by reducing the number of bytes they receive and discard.

Mobility The signals must remain robust and successful, whether FLS units are stationary or in motion. Decoding success rates should not significantly degrade due to mobility. The potential obstacles encountered during the movement shall not prevent the communication.

Usability Since the hardware is going to be mounted on the FLS which is flying with a moderate speed, the hardware for the physical components should be light weight (ounces) to maximize the flight time. The hardware should also not visibly increase the size of the FLS, so that millions of FLS could co-exist in the area.

Other considerations While non-urgent, additional considerations include signal security to thwart attacks and preserving user privacy in transmissions, ensuring that eavesdroppers cannot extract information from the networks.

3 ENABLING PHYSICAL LAYER (PHY) FOR FLS

3.1 Feasible PHY Options

In this paper, we specifically focus on short-range wireless communication technologies. Long-range communication usually consumes too much power (e.g., 5G), or incurs very long latency (e.g., LoRa [2]) in order to achieve the extended communication range. These characteristics are not suitable for FLS applications, given their unique requirements.

We will delve into a range of short-range communication technologies for FLS scenarios, including Wi-Fi Direct (Wi-Fi), Bluetooth Low Energy (BLE), Zigbee, Z-Wave, Near Field Communication (NFC), RFID (Radio-Frequency Identification), Visual Light Communication (VLC), and Infrared.

We note that these technologies encompass not only the physical (PHY) link but also the media access control (MAC) layer, such as the 802.11 standard for Wi-Fi MAC. For the purpose of this paper, our focus will primarily concentrate on their physical link aspects. Their link-layer processing typically involves software-based procedures, which might be adaptable to FLS scenarios, but delving into these adaptations is beyond the scope of our current research.

3.2 Discussion on Possible Physical Links

We summarize how each technology would facilitate the requirements for FLS, as summarized in Table 1. We provide a detailed explanation as below.

Wi-Fi Wi-Fi direct (or Wi-Fi) utilizes orthogonal frequency-division multiplexing (OFDM), which effectively divides signals across multiple channels, enhancing data rates and ensuring robust communication. It boasts wide compatibility, extensively used in diverse devices, from smartphones to various smart home appliances. However, Wi-Fi presents a significant challenge due to its relatively high power consumption, which could lead to increased heat generation and potentially disrupt the normal operation of FLS units. A promising variant, low-power Wi-Fi based on the 802.11ax standard [3], operates with significantly reduced power requirements. Another concern of using Wi-Fi for FLS is latency. However, the primary reason for long delay does not originate from the physical link. Actually, mitigating collisions during Wi-Fi's random access-based operations in MAC would be critical to addressing the issue. Advancements like Wi-Fi 6's new scheduling mechanisms [3] might offer proper solutions.

Bluetooth Low Energy (Or BLE) Bluetooth technology operates through frequency-hopping spread spectrum (FHSS) in the 2.4 GHz ISM band. Its low-power features make it an appealing choice for FLS communication. However, despite Bluetooth's ability to hop between different frequencies to reduce interference, it remains susceptible to issues in crowded frequency bands that can introduce interference problems.

Zigbee Zigbee utilizes direct-sequence spread spectrum (DSSS) or offset quadrature phase-shift keying (O-QPSK) modulation techniques in the 2.4 GHz or sub-1 GHz bands. This technology is low-power and ideal for battery-operated devices. Yet, it presents limitations in data rate when compared to Wi-Fi and may face interference issues due to frequency range limitations, especially when

Table 1: Comparing different physical link for FLS communication. † stands for for further study.

Technology	Latency	Throughput	Power	Scalability	Robustness	Range	Mobility	Usability
Wi-Fi	✓	✓	†	✓	✓	✓	✓	✓
Bluetooth	✓	✓	✓	✗	✓	✓	✓	✓
Zigbee	✗	✗	✓	✓	✓	✓	✓	✓
Z-Wave	✗	✗	✓	✓	✓	✓	✓	✓
NFC	✓	†	✓	✓	✓	✓	✓	✓
RFID	✗	✗	✓	✓	✓	✓	✓	✓
VLC	✓	✓	✓	✓	†	✓	†	†
Infrared	✓	✓	✓	✓	✓	✓	†	†

operating with millions of nodes. Latency remains a significant hurdle for practical usage of Zigbee technology.

Z-Wave Z-Wave uses a form of frequency-shift keying (FSK) within sub-1 GHz frequency bands. It excels in device compatibility and signal security. However, similar to Zigbee, Z-Wave faces challenges regarding throughput and potential interference.

Near Field Communication (NFC) NFC employs inductive coupling at 13.56 MHz for communication across very short ranges, typically a few centimeters. This ultra-short range aligns well with the requirements for FLS applications. Although NFC has a relatively limited data rate of around 400kbps, its use of extremely close-range communication could potentially mitigate the demand for higher data rates, as only a small cluster of devices share the wireless bandwidth.

Radio Frequency Indentification (RFID) RFID commonly uses amplitude-shift keying (ASK) or frequency-shift keying (FSK) modulation, typically in low-frequency (LF), high-frequency (HF), and ultra-high-frequency (UHF) bands. It employs extremely low-cost tags for identifying and tracking objects, featuring minimal power consumption and impressive scalability. However, its drawback lies in the very low data rate and slower communication (tens of milliseconds), which limits its suitability for real-time data exchange for FLS.

VLC VLC holds immense promise due to its high bandwidth and low power consumption, leveraging the already-mounted LEDs on each FLS for signal transmission. However, a significant challenge emerges from preventing interference between communication signals and the LED display's illumination for holodecks. Additionally, VLC communication requires specialized 360-degree cameras to capture signals between neighboring FLSs. The mobility of FLS units becomes a critical factor due to the requirement for direct line of sight between communicating modules.

Infrared Infrared communication, akin to VLC, harnesses the transmission of data through light. By operating at a slightly longer wavelength, beyond the visible spectrum of human eyes, it is invisible to human eyes. This provides a potential solution to avoid the interference issues faced by VLC. However, adopting Infrared communication faces similar issues as VLC: deploying the hardware on FLS and obstruction during mobility require strategic positioning of the communicating devices to maintain line-of-sight communication.

Summary Upon analysis, it is evident that each of the popular technologies presents certain limitations for FLS communication. For instance, Bluetooth lacks the scalability needed for millions of devices, proving an insurmountable challenge. Conversely, there are potential improvements with Wi-Fi, NFC, and VLC/Infrared, although they each encounter their unique hurdles.

Exploring low-power alternatives for Wi-Fi, addressing the range-throughput tradeoff for NFC, and tackling interference concerns for VLC/Infrared are significant areas that need to be studied further. These investigations will be pivotal in finding the most suitable communication solution for FLS applications.

4 EVALUATION PLAN

Methodology The evaluation will consist of three stages. We will start by using a software emulator to assess the potential of each technology in addressing the identified issues. Next, a Software-Defined Radio (SDR) testbed will be constructed to test various physical links in a real-world setting. The final stage involves mounting the solutions on actual FLSs for practical flight tests. Throughout these stages, we will assess properties mentioned in §2, such as inducing motion or noise during testing to evaluate mobility and robustness.

The three-stage evaluation aims to assess options with minimal cost and risk. Trace-based emulation analyzes actual FLS traffic to comprehend requirements and eliminate impractical options theoretically, avoiding complex hardware implementation. SDR-Based evaluation serves as a proof-of-concept, testing traffic on real physical channels using a single programmable SDR device to implement all candidate technologies. This provides insights into physical choices from a real-world perspective without the need for specialized hardware purchase and mounting on the FLS. Ultimately, FLS-based testing constitutes the real field test in the final stage. It is worth noting that, if the trace-based emulation identifies 1 or 2 clear winners, we may opt for real Commercial off-the-shelf (COTS) devices equipped with the candidates for quick tests, substituting the SDR-based implementation.

Trace-Based Emulation Generating data traces from distributed algorithms will be the first step. These traces will record FLS locations over time, as well as packet sources, destinations, and sizes. These data traces will be fed into simulation tools such as ns3 to emulate success rates and other relevant performance metrics.

SDR-Based Prototype To test various RF-based technologies, we'll utilize Software-Defined Radio (SDR) devices. SDR technology will allow us to program different protocols using software and examine real RF transmission through devices like USRP or LimeSDR. For infrared and VLC technologies, programmable cameras equipped with these features will be procured. A small-scale network with 4-5 nodes will be created for technology evaluation.

Testing with Real FLSs The final stage involves mounting small modules onto real FLSs for comprehensive evaluations. Initially, point-to-point testing will be conducted, followed by testing within a more complex network mimicking real distributed algorithms.

5 DISCUSSION

Cross layer impact It is essential to recognize the close relationship between the physical layer (PHY) and higher layers in network communication. A robust PHY design may not fully address issues related to latency and speed, which are critical concerns in higher layers. Revisiting PHY options alongside higher-layer networking issues becomes important as the interaction between layers often necessitates a trade-off or adjustment to enhance overall system performance.

Dual-Stack Solution Implementing a hybrid solution that incorporates multiple wireless capabilities within FLS networks presents an intriguing approach. Adapting the communication technology based on the real-time environmental context and specific application requirements could provide a comprehensive and dynamic communication system for FLS.

Customized Solution Creating a tailored wireless technology specific to FLS networks offers a promising avenue. Designing a custom solution involves delving into various technical aspects, including physical layer modulation, network coding, and signal processing. Additionally, exploring the feasibility of mass-producing and integrating this new technology into commercial FLS hardware is a significant challenge that requires careful consideration.

6 CONCLUSION

This paper explores various cutting-edge short-range communication technologies to assess their compatibility with the rigorous demands of FLS communication. Wi-Fi, NFC, and light communication demonstrate substantial promise, although each holds distinct advantages and challenges. Our proposed 3-stage evaluation methodology aims to further analyze these options, seeking the most beneficial solution for practical FLS applications. This comprehensive study lays the groundwork for the evolution of FLS-based holodecks, representing a fundamental step toward their potential future applications in reality.

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