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Enabling Smart Healthcare Applications Through Visible Light Communication Networks

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ENABLING SMART HEALTHCARE APPLICATIONS THROUGH VISIBLE LIGHT COMMUNICATION NETWORKS

by

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ABSTRACT

Future smart healthcare operations are envisioned to require the support of high performance wireless networks. Researchers are presented with a problem, however, as the hospital environment brings unique challenges to the application of traditional radio-frequency wireless communication networks due to health concerns and electromagnetic compatibility standards. To meet these challenges and support the advancement of high quality healthcare, we propose the use of an alternative wireless technology in visible light communication (VLC). Contributing to the growing interest in VLC amongst researchers, we construct both a VLC network simulation testbed as well as real-world testbed to serve as a platform for the development of this rapidly advancing technology. Using these testbeds, we implement and evaluate media access control protocols for VLC in both device-to-infrastructure and device-to-device networks, focusing on application scenarios relevant to healthcare environments.

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1. INTRODUCTION

The wireless communication requirements of hospitals are ever-increasing as medical sensing technologies and smart healthcare operations continue to advance. For example, real-time patient monitoring is becoming increasingly important in hospitals as it can help doctors and nurses detect and respond to changes in a patient's condition quickly. Robot-assisted wireless networks have also attracted the attention of researchers in applications such as precision surgeries, medication delivery, or assistance in high-risk environments (e.g., the COVID pandemic). Looking forward to the future, medical holography shows great potential in surgical planning and guidance, medical education and training, and medical simulations. All of these above-mentioned applications in future hospitals will require advanced networking capabilities to support the growing number of connected medical devices and high-date-rate demand. Therefore, care must be taken to ensure that the networks employed in hospitals are capable of supporting this rapid growth and assuring the highest quality of care possible. However, hospital environments and future smart health applications pose significant challenges to wireless networking system design due to the following characteristics:

Electromagnetic Interference Limitation: Hospitals are subject to electromagnetic compatibility (EMC) standards and are thus responsible for controlling the level of electromagnetic interference (EMI) produced by wireless communication. This is because hospitals contain critical EMI-susceptible medical devices, including Electro-CardioGrams (ECG), Electro-encephaloGrams (EEG), and Magnetic Resonance Imaging (MRI) [1].

High Demand Limitation: In addition to concerns regarding EMC, there is also a desire for hospital networks featuring high bandwidth and low latency capabilities. Real-time video conferencing, for example, is a notoriously data-hungry application that is utilized quite often in hospital environments. Video conferencing is an indispensable tool to enable co-ordination between the many physicians, medical specialists, and surgeons that collaborate to make high quality care possible. Furthermore, many people living in rural areas rely on remote telemedicine conferencing as a way to receive medical advice and communicate with their care team. Medical imaging also produces large amounts of data that may need to be transmitted wirelessly. This is becoming increasingly prevalent, as portable imaging equipment such as wireless ultrasound devices increase the convenience and speed of common hospital procedures. The strain on hospital wireless networks is also due in part to the recent advancement of smart healthcare operations. As in many areas, there is a growing trend in hospitals towards interconnected, internet-enabled medical devices and data-driven applications for patient care.

The challenges towards meeting the demands of these smart healthcare operations mirror those in supporting the growth of internet-of-things (IoT) networks, and future hospital networks should be designed to support a high density of wireless devices.

Wireless Security Limitation: Finally, hospital environments introduce challenges regarding the security of wireless networks. Hospital networks must handle large amounts of potentially sensitive data pertaining to patient health. This kind of protected health information (PHI) is subject to federal regulation such as the health insurance portability and accountability act (HIPPA). Healthcare providers are required to ensure the confidentiality of all PHI and safeguard against any anticipated threats to its security. In addition, future precision medical applications may require the transmission of highly private patient information such as their genetic information and lifestyle factors. This forces hospitals to consider carefully how the data passing through their wireless networks is treated, as wireless forms of communication are susceptible to a number of security vulnerabilities such as eavesdropping and man-in-the-middle attacks.

Unfortunately, the current existing RF-based networking systems cannot address the above-mentioned challenges because: (i) The omnidirectional propagation and highly penetrative nature of RF make it difficult to ensure EMC with hospital equipment. Moreover, the International Agency for Research on Cancer of the World Health Organization classifies radio-frequency-radiation (RFR) as a class 2B potential human carcinogen [2]. The current available RF spectrum is limited and becoming increasingly crowded due to the massive amount of wirelessly connected devices and data-rate-hungry applications, thus making RF-based wireless networks cannot support the low-latency and broadband requirements of applications in future hospitals.

To overcome the limitations of RF-based networks, researchers have been investigating new spectrum technologies. Visible light communication (VLC) has been envisioned as a promising communication technology for hospital wireless networking systems, as it offers several advantages over traditional wireless communication technologies such as WiFi and cellular networks as discussed below:

- *EMI-free Communication:* VLC makes ensuring EMC with sensitive medical equipment simple as it does not produce harmful EMI. This comes with the added benefit of being highly compatible with legacy RF-infrastructure, allowing hospitals to seamlessly integrate VLC technology to their networks with relative ease. Additionally, the light waves used in VLC are perfectly safe for long-term human exposure and thus raise no concerns over adverse health effects.

- *High Performance Communication:* VLC has the potential support the high bandwidth requirements of advancing medical applications. This due to the fact that it makes use of a large, currently unregulated portion of the electromagnetic spectrum, operating at frequencies within 430 and 790 THz for the carrier signal. Having comparatively more available bandwidth enables the creation of higher capacity wireless networks than is possible with RF. Furthermore, the directed nature of VLC signals plays a key role in its achievable network performance. Unlike RF signals, VLC exhibits a high degree of spatial re-use. Many VLC-enabled devices can be densely deployed in the hospital environment without causing significant interference, further enhancing overall network throughput.

- *Secure Communication:* The use of directed VLC signals also helps in enhancing the security of hospital wireless networks. Capturing or inserting network data requires an attacker to have close-proximity, line-of-sight access to the target node, foiling most attempts at eavesdropping or similar attacks. This makes it far easier to ensure the security of sensitive patient information as it travels across wireless networks.

- *Green & Accessible Communication:* In addition to the solutions it brings towards meeting the specific networking challenges of the hospital environment, VLC also employs low-cost, low-complexity hardware components and can reduce energy consumption.

1.1. VLC NETWORKING

VLC-based networks can be classified into two communication models: device-to-infrastructure and device-to-device. In the following section, we will briefly elaborate the characteristics and the enabled applications of each one.

1.1.1. Device-to-Infrastructure (D2I).

In the D2I model, the wireless exchange of data occurs between VLC-enabled devices and the current existing lighting infrastructure. As shown in Figure 1.1, the infrastructure for these networks can come in the form of low-cost LED devices that serve as both a network node and a source of illumination. Some of the key benefits that characterize D2I networks are an increase in the achievable speed and reliability, the ability to serve many applications simultaneously, and the ability to reuse the infrastructure for future applications. In hospital environments, D2I VLC networks may be used to replace or reduce the amount of RF infrastructure needed. Once installed, these networks can support a variety of applications such as internet access, indoor positioning, patient monitoring, and guidance/control of robotic agents.

An important consideration for D2I networks involving multiple VLC nodes is how to enable communication with the rest of the network. When installed into the existing lighting infrastructure, VLC devices typically do not have LoS to enable multi-hop communication. Additionally, installing data cables can offset the low-cost benefit of VLC networks, especially for large infrastructure projects such as hospitals. One proposed solution to this is to combine VLC with powerline communication (PLC) to create hybrid networks where media access is performed by VLC devices and data is carried via AC power cables to a PLC modem.

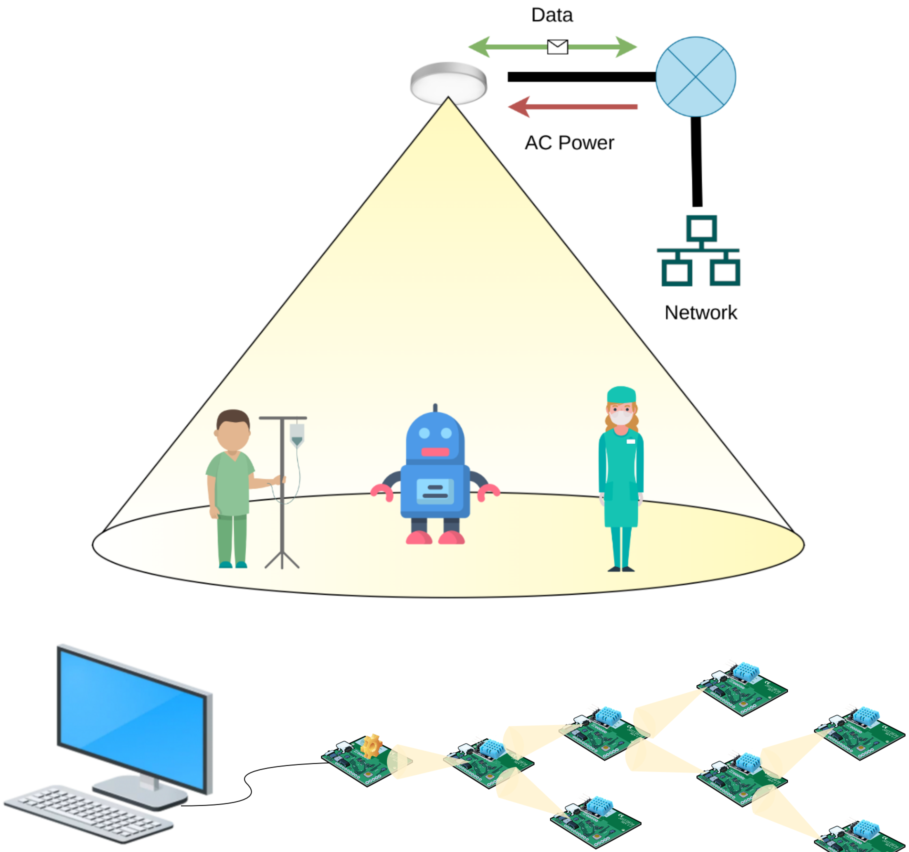

Figure 1.1. D2I network (top), D2D network (bottom)

1.1.2. Device-to-Device. In this mode of communication, VLC-based wireless nodes are arranged to communicate with each other. This type of network is characterized by rapid deployment and scalability. Through bidirectional, multi-hop communication, the range and coverage area of the network can be extended arbitrarily simply by adding new nodes. Such networks are often referred to as visible light ad-hoc networks or LANETs, and they show great potential in hospital environments for the ability to provide on-the-fly EMI-free wireless communication. Examples of enabled applications for D2D networks include environmental monitoring and outbreak response in infectious disease hospitals.

The rest of this paper is organized as follows. In section 2.1, we review related work into the types of applications in healthcare environments that would be enabled by the adoption of VLC networks. In section 2.2.1, we comment on the current state of experimental testbeds for the development of VLC networks. In section 3.1 we propose a novel, priority-aware MAC protocol that is designed to meet the QoS requirements of the hospital environment. In section 3.2 we design and implement a simulation testbed and evaluate the proposed protocol in a simulated D2I VLC network. In section 4.1 we describe our process of implementing a real-world VLC testbed for evaluating the empirical performance of D2D VLC networks. In section 4.2 we validate the successful operation of this testbed towards the application of indoor environmental monitoring using the ALOHA MAC protocol. Finally, we discuss future work in section 5.1 and conclude with closing remarks in section 5.2.

2. LITERATURE REVIEW

2.1. VLC-ENABLED APPLICATIONS

While VLC can certainly be used for many standard applications that we have come to expect from wireless networks such as wireless internet access, another motivation to adopt VLC in hospitals comes from the unique applications that optical communication opens the door to. The following sections will discuss some of the advantages that VLC offers in various monitoring, sensing, and localization scenarios.

2.1.1. Monitoring. Healthcare as a whole has been trending increasingly towards preemptive care and promotion of well-being rather than diagnosis and treatment of existing conditions. With that in mind, monitoring of patient vitals and hospital conditions has become a very important part of daily hospital operations. This section will go over the various ways that wireless communication technologies, particularly VLC, can serve medical professionals in designing more effective and convenient monitoring systems.

2.1.1.1. Indoor environment monitoring. VLC can be applied to assist in monitoring not only the condition of patients, but also to monitor the environmental conditions of the hospital itself. Indoor environmental monitoring (IEM) systems are indispensable to the hospital environment for the applications they enable. A collection of wireless sensor nodes are placed around the area of interest to collect and report on information such as temperature, humidity, CO2 concentration, particulate matter (PM) concentration, motion, and noise levels. These systems aid hospital administrators in monitoring and maintaining a controlled environment, ensuring optimal conditions for patient recovery, identifying and responding to incidents, and enabling data-driven smart healthcare operations.

VLC-based indoor environment monitoring systems are desirable for providing low-latency communication for health-critical data. In addition, VLC eliminates concerns surrounding EMI-susceptible medical equipment when deploying such systems in

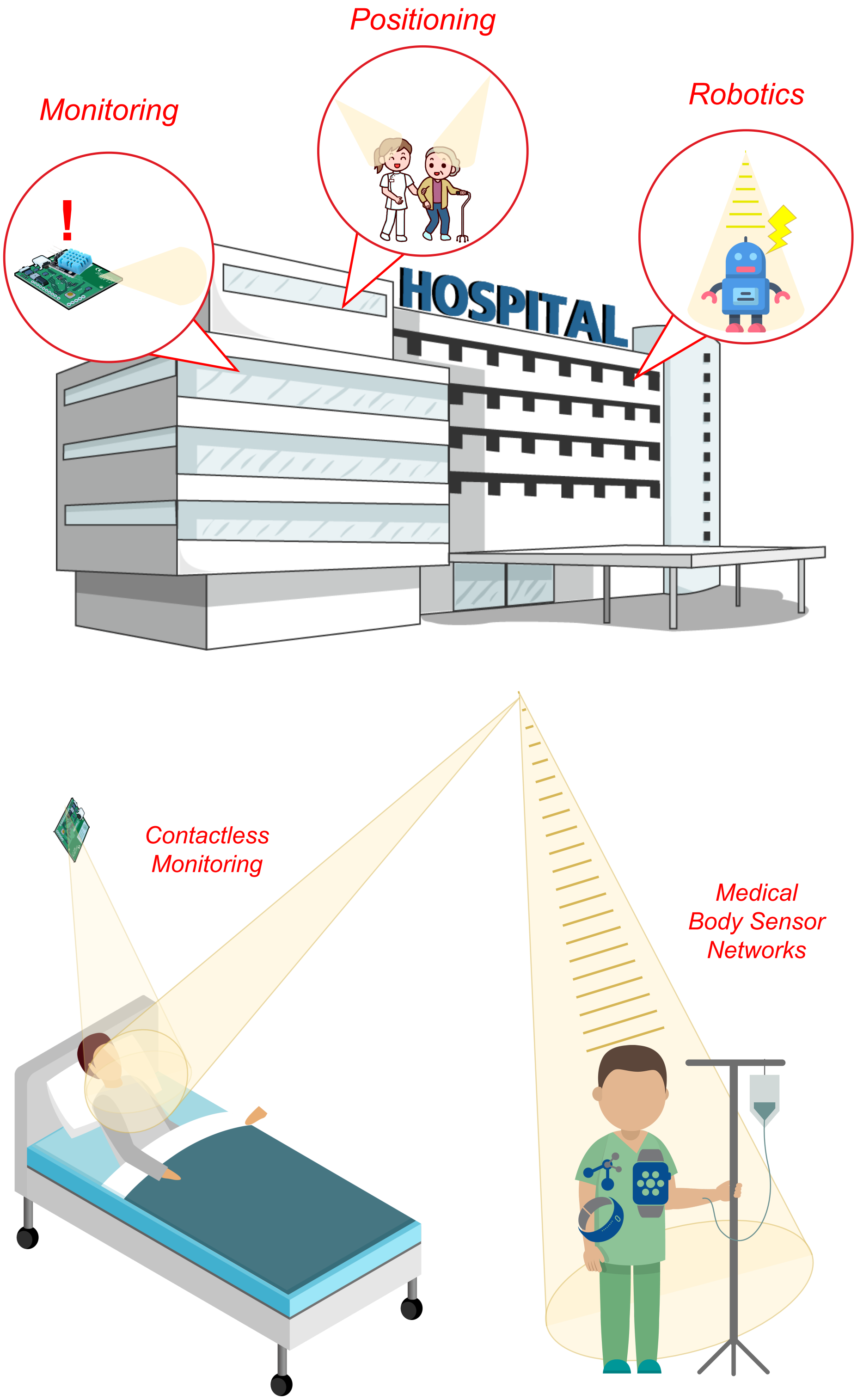

Figure 2.1. VLC application scenarios

RF-restricted areas of the hospital. Sensor nodes can be deployed in simple point-to-point configurations, or more complex networks depending on application requirements. If on-demand deployment and self-configuration are desirable, such as in time-critical scenarios (ex. an outbreak of infectious disease), then an arbitrary number of VLC-enabled sensor nodes can be employed in the form of a LANET. In future smart hospitals with multipurpose lighting fixtures, sensor nodes can also be combined with actuators for automatically adjusting hospital conditions and receive control signals from overhead lights.

A recent study demonstrating the efficacy of VLC-based IEM systems can be found in [3]. Authors implement and operate a system for monitoring airborne particulate matter, an important consideration for hospitals where micrometer-size particles in high concentrations can have a severe affect on individuals with cardiovascular conditions and a general adverse affect on patient recovery. One particularly important contribution of this study is how they manage enabling multihop communication among nodes. Multihop communication is seen as a key enabling technology for VLC-based IEM systems as it vastly improves effective coverage area and scalability. The authors also take on another VLC-related challenge in extending the range of communication through the use of a planoconvex lens. Light waves tend to attenuate quickly, limiting the achievable distance at which VLC-enabled systems can communicate. An optical lens placed at the transmitter focuses the light and allows for viable communication at a distance of 13.5m with a single link, an impressive result that lends well to a practical implementation of this technology.

2.1.1.2. Medical body sensor networks. Very commonly within healthcare environments, it becomes necessary to monitor a patient's vital signs to identify any trends or changes in their condition. These patient monitoring scenarios have often been employed through connected systems of sensors and medical equipment. Such systems can be referred to as Medical Body Sensor Networks (MBSN). Though many hospitals still rely on wired connections to support these MBSN, there is a growing desire to develop wireless MBSN. Wireless, wearable sensors have the potential to allow for greater mobility of the patient as well as easier configuration for hospital staff. RF-based MBSN technologies have been a subject of research, but there are several challenges that make VLC-based sensors a desirable alternative. The biomedical data transmitted within MBSN requires precise accuracy, and some of the medical equipment used is EMI-susceptible. Furthermore, VLC for patient monitoring has explored as it does not produce EMI and is safe for long-term human exposure.

When designing VLC-based MBSN, it is common to consider a hybrid system utilizing VLC downlink and infrared (IR) uplink channels. Mulitpurpose light fixtures serve as access points, sending control signals and establishing connection with VLC and receiving patient data from sensors with IR communication. An example of this is seen in [4], in which authors simulate a hybrid MBSN to investigate the performance of such systems in terms of outage probability. The scenario considered for this study includes a mobile patient outfitted with VLC-enabled sensors and an IR transmitter, along with several VLC access points to connect to. Analysis of the system relies on channel modeling techniques to take into account the patient's position, movement, and even the shadowing effect of the patient's body on the connected transceiver. This is achieved through Monte-Carlo ray-tracing techniques, a method adopted by several VLC researchers. Through simulation, the authors find the proposed system promising, being able to provide reliable communication at moderate data rates. In terms of power consumption, which has long been a primary consideration for networks utilizing resource-limited wireless sensors, the authors find that hybrid MBSN have the potential to remain operable even at very low power levels. The results indicate that it's possible to establish VLC transmissions even at power levels that produce imperceptible amounts of light, which brings the highly desirable benefit of supporting adaptive lighting schemes that can maintain communication even when the patient is sleeping and the room must be dark.

In hybrid VLC/IR communication, IR is sometimes selected so as not to provide a visual disturbance. However, there are several options for providing uplink communication to a VLC device. VLC can also be employed for the uplink channel, sending patient data to receivers located on the ceiling. [5] investigates the feasibility of VLC based uplink data transmission in the patient monitoring scenario. Authors' were particularly interested in analyzing the effects of ambient lighting interference on VLC-uplink MBSN. In this study, an experimental VLC testbed is used featuring multiple receivers to help mitigate interference and provide a stable signal to interference and noise ration (SINR). By utilizing two separate receivers in parallel, the received signal is amplified and sources of interference local to one receiver can be tolerated. In future VLC research, the use of multiple receivers could also enable us to minimize transmission power and extend sensor lifespan as well as help maintain LoS in the mobile patient scenario.

2.1.1.3. Contactless patient monitoring. Visible light sensing (VLS), differs from VLC in that no data is encoded into the transmitted light signals and therefore no modulation scheme is necessary. We choose to include VLS-based studies in this survey because VLS often utilizes similar hardware configurations and can make use of VLC network infrastructure. In the patient monitoring scenario, VLS can be employed to perform contactless vital sign monitoring. In this application, light impulses are directed towards the patient and the reflected rays are received and interpreted to derive the patient's condition. This is desirable as it eliminates the need to administer and replace wearable sensors, further reducing cost and minimizing necessary patient-contact. Additionally, contactless monitoring offers a greater quality of living to patients, who may feel anxious or uncomfortable as a result of attached wires or sensors.

Traditional methods of contactless monitoring make use of RF-based radios or imaging-based cameras; however, these methods present concerns over continuous RF radiation exposure and patient privacy respectively. Recent studies have explored VLS-based contactless monitoring systems to address these concerns. In [6], authors implement and evaluate a VLS-based non-contact vital sign monitoring system. Additional contributions include signal processing algorithms that allowed for the capture of heart and respiration rates to an accuracy of 94% relative to contact-based monitoring devices. Authors note that these vitals serve as critical indicators for several medical conditions such as sleep apnea, SIDs, heart or respiratory failure, and more.

2.1.2. Positioning. Another example of how VLS can be applied in the hospital environment is through the use of an indoor positioning system (IPS). IPS serve the purpose of providing an estimation of the physical location of a human or device within the hospital. Some of the applications that these systems enable include navigation, tracking, and inventory in the indoor scenario where satellite-based positioning methods such as GPS suffer from greatly reduced power and coverage. Hospitals are a prime example of an environment with the potential to greatly benefit from these applications. Take for example an IPS-enabled navigational system to guide users around the hospital. In large hospitals, many staff members experience difficulties getting to unfamiliar areas of the building. [7] Even to experienced staff, navigational delays come in the form of time spent directing visitors and peers who cannot find their destination. These difficulties naturally extend to patients and visitors to a greater degree, increasing the likelihood that they may require assistance from medical staff or wander into a restricted area.

IPS have been well studied, and can employ a wide variety of mechanisms towards position estimation including VLC, WiFi, Bluetooth, magnetic, and even acoustic technologies. VLC-based IPS have been highly regarded among researchers for their ability to provide precise and accurate positioning at a low cost and high ease of implementation. For the hospital environment specifically, they offer an advantage over radio-based IPS in that the effective coverage area can be extended to include RF-restricted sectors as well as a reduction in energy consumption when multipurpose light fixtures are used for positioning.

[8] provides a design of a VLC IPS tailored to hospital environments. In this study, powerline communication is used to support a received-signal-strength (RSS) based IPS delivering centimeter positioning accuracy to the hospital environment. These results were demonstrated experimentally, and authors note that the proposed system has several uses beyond navigation such as the collection of data to drive development of user-hospital interaction models and smart hospital operations.

2.1.3. Robotics. The final application we explore in this survey is the use of VLC-assisted robotics in the hospital environment. Robotic agents have long been envisioned as an important application for reducing the burden placed on medical staff in future smart hospitals. By performing basic yet time-consuming tasks, robotic assistants allow medical professionals to place a greater focus on patient well-being and provide a higher standard of care. The importance of reducing staff workload and improving operational efficiency has been highlighted in recent years with the onset of the COVID-19 pandemic, during which the world saw firsthand the immense strain placed on healthcare workers in caring for the affected. VLC offers enhance the performance of robotic agents by providing control signals and localization capabilities while avoiding the issues that arise from the use of RF-communication in hospitals. As early as 2012, VLC-guided mobile assistance robots have been deployed in real world hospital environments for testing. [9] This paper describes the operation of the developed HOSPI transportation robot. HOSPI utilizes VLC to perform position recognition, hazard avoidance, and to receive control signals. A total of four HOSPI were successfully operated to perform daily transportation tasks at Matsushita Memorial hospital. Authors describe the systems implemented that allowed for a practical demonstration and safe operation of the VLC-guided robot with minimal human intervention.

Aside from performing general tasks, the use of robotics in the hospital has also gained attention for its potential to improve the treatment of infectious diseases. In cases where a patient's condition can be easily spread to hospital staff, it becomes imperative to minimize the level of patient-to-physician contact as much as possible. A robotic agent can enable this, interacting with the patient while remaining easily disinfectable and easily tracked to record instances of exposure and prevent the spread of diseases. In [10], authors propose a novel VLC-based teleoperation system designed for the control of mobile robots in infectious disease hospitals. Their approach utilizes an array of LEDs as a transmitter, and a camera as a receiver. Control signals are displayed as blinking patterns on the LED array, which are in turn received and processed by a wheeled robot. Contributions include improved methods for discovery and tracking of the transmitter and pattern recognition for the receiver.

2.2. VLC EXPERIMENTAL TESTBEDS

The applications discussed above play an important role in motivating further research and real-world adoption of VLC-based networks into hospital environments, as well as identifying challenges and directions for the the development of VLC technology as a whole. It is equally important, however, to consider the design of the VLC network infrastructure that will support these applications and gain an understanding of their performance in comparison to traditional wireless communication technologies. To this end, we conduct a review of VLC network testbeds proposed by the scientific community.

2.2.1. Simulation Testbeds. Many of the studies on the performance of VLC networks and the development of new VLC networking protocols make use of bespoke, closed-source simulators designed for a specific network scenario. These systems often lack the reproducibility of results as well as the efficiency when applied to large-scale network environments that is offered by general-purpose network simulators supported by a community of developers.

ns-3 is an open-source network simulator that is widely adopted by researchers and developers for its active and growing community of users and maintainers, deep library of natively-available modules providing the ability to simulate common network technologies, and the potential to integrate simulated networks with real-world devices. Though ns-3 officially supports many communication technologies and network protocols, making it very popular among researchers, it does not natively include the ability to simulate VLC. Despite this, a number of VLC modules have been developed as an extension to the capabilities of ns-3 and made open source to the benefit of the wireless communication research community. One such module was introduced in [11], demonstrating the ability to simulate hybrid WiFi/VLC networks in ns-3 alongside validation of the results via a real testbed. While this module provided many useful features for experimenting with hybrid and large-scale VLC networks, it has not been maintained in recent years and has fallen out of direct compatibility with the latest versions of ns-3. A new ns-3 module for the creation of simulated VLC testbeds has been proposed by the authors of [12]. This module also focuses on hybrid WiFi/VLC networks, extending previous work by providing a comprehensive simulation framework that is capable of managing common networking tasks such as user-handover between APs as a result of unmet communication requirements.

2.2.2. Physical Testbeds. To the best of our knowledge, off-the-shelf VLC network components are not currently widely available commercially. This presents a challenge to researchers who wish to implement physical VLC networks to test their performance. There have been some attempts by researchers to develop a standard platform for VLC research, a well known example of which being OpenVLC [13]. With the latest version being capable of transmission distances of 6-19m and peak transport layer throughput of 400 kbps [14], OpenVLC provides a low-cost and fully open-source option to those wishing to study basic VLC networks.

Many researchers, however, opt to construct their own testbeds in order to utilize the resources available to them and improve the performance of their networks. Low-cost micro-controllers are often employed as network nodes equipped with LEDs for transmission, photo-diodes (PD) for receiving, and signal processing software such as GNUradio. The performance of these testbeds can be extended in several ways. In [15], a commercial software-defined radio (SDR) from Ettus Research allows to enable faster signal processing, increasing achievable data-rates. Furthermore, optical lenses can be placed at either the transmitter LED or receiver PD to focus the emitted light and extend the range of communication between nodes, as in [16].

3. PRIORITY-AWARE TDMA PROTOCOL

When designing VLC networks for healthcare environments, network throughput is not the only performance indicator to consider. The fast delivery of data that flows through hospital networks could be paramount in the successful treatment of a patient. Such considerations change the way that we must approach quality-of-service (QoS) in hospital networks. There is a need for health-oriented QoS assurances in our network protocols in order to prevent an overwhelmed network from affecting patient outcomes. With this in mind, we formulate QoS classifications tailored to the hospital environment, we design a novel MAC-layer network protocol utilizing these QoS classes, and finally we evaluate the performance of the protocol on a simulated VLC network environment.

3.1. PRIORITY-AWARE MAC PROTOCOL

While most protocols provide QoS based on the type of application that an individual packet is serving, such as *real-time* voice or video applications versus *best-effort* traffic like general browsing, hospital networks should always consider the health and safety of patients above interruption of real-time services. Priority should be given to traffic carrying health-critical information to ensure that it can arrive at its destination with a low latency.

Therefore, we define three different health-oriented access categories (AC) by which QoS requirements are assigned:

- *Type I data:* Data in this category is considered *health-critical* and is thus given the highest level of priority to ensure its low-latency transmission through the network. Examples of Type I data in a healthcare environment may include patient vital signs or alerts pertaining to patient condition

- *Type II data:* Data in this category is considered *operations-critical* and is given a moderate level of priority to encourage a low-latency transmission through the network. Examples of Type II data in a healthcare environment may include sensor data from monitoring systems or data supporting real-time applications such as positioning systems

- *Type III data:* Data in this category is not particularly important for healthcare-operations or to the health and safety of patients and is thus given a low level of priority. Examples of Type III data in a healthcare environment may include non-urgent email or web-browsing.

To apply these QoS requirements in a VLC network, we propose a modification to a widely-adopted protocol for sharing channel resources, time-division multiple access (TDMA). In TDMA, a single communication channel can be shared by multiple users by allocating to each user a number of time slots during which they can transmit their data without interruption. To create a priority-aware MAC protocol that can satisfy the QoS requirements defined above, we modify the method by which time slots are assigned to each user. If S_T represents the total number of time slots in a given TDMA data frame, a pre-configured number of low priority slots are set aside for Type III data (S_{III}) and the remaining slots are reserved for Type I and Type II data following equations 3.1 and 3.2, respectively.

$$S_I = C_I * (S_T - S_{III}) \tag{3.1}$$

$$S_{II} = C_{II} * (S_T - S_{III}) \tag{3.2}$$

Where S_T is the total number of transmission slots available and C_I, C_{II} are tunable parameters subject to the following constraints:

$$C_{II} \leq C_I < 1 \tag{3.3}$$

$$C_I + C_{II} = 1 \tag{3.4}$$

Once the number of slots for each access category are assigned, these slots are offered to users proportionally based on the number of users currently being served by the network. The number of slots offered to a user is calculated using the following equations.

$$A_I = \frac{S_I}{n_I} \tag{3.5}$$

$$A_{II} = \frac{S_{II}}{n_{II}} \tag{3.6}$$

$$A_{III} = \left\{ \begin{array}{ll} \frac{S_{III}}{n_{III}} & \text{if } n_{III} \leq S_{III} \\ 1 & \text{otherwise} \end{array} \right\} \tag{3.7}$$

Where n_I, n_{II}, n_{III} are the number of Type I, Type II, and Type III users, respectively.

Aside from the distribution of time slots to users, the rest of the protocol follows a similar process as the standard TDMA protocol as described in algorithm 1. Due to the limited number of low-priority slots, users requesting access for Type III data may not be assigned any slots in a given data frame and will instead be deferred to the next frame. This may result in an increase in latency for Type III data while Type I or Type II data rarely experiences a delay as a result of scheduling.

3.2. SIMULATION TESTBED DESIGN

Our simulation testbed is built using the popular open-source network simulator *ns-3*. In section 2.2.1, we discuss some openly available options to extend *ns-3* capabilities to include VLC support. For our purposes, we borrow the physical layer VLC modeling from [12] and add to it an implementation of the priority-aware TDMA protocol described in section 3.1. The rest of the higher layer protocols in the simulated network make use of the built-in *ns-3* library of modules.

Algorithm 1 Modified TDMA protocol

```
Parameters: slot time t, guard time G, inter-frame spacing I, total slots $T_s$
Start TDMA Frame
Initialize transmission array, low priority slots $LPS = S_{III}$
for (User associated with AP) do
    if User AC == Type I then
        Offer transmission slots based on equation 3.5
    else if User AC == Type II then
        Offer transmission slots based on equation 3.6
    else
        if $LPS \neq 0$ then
            Offer $A_{III}$ transmission slots based on equation 3.7
            LPS = LPS - $A_{III}$
        else
            Defer user to next frame
        end if
    end if
end for
Broadcast synchronization packet
for (Index in transmission array) do
    Select transmission unit $TU$
    Transmit data $TU$
    Wait for guard time G
end for
Wait for inter-frame spacing I
Advertise AP with beacon packet
for (Beacon response) do
    if Respondent not associated with AP then
        Associate new user
    end if
    Assign user AC based on traffic type
end for
Remove associations with non-respondent users
```

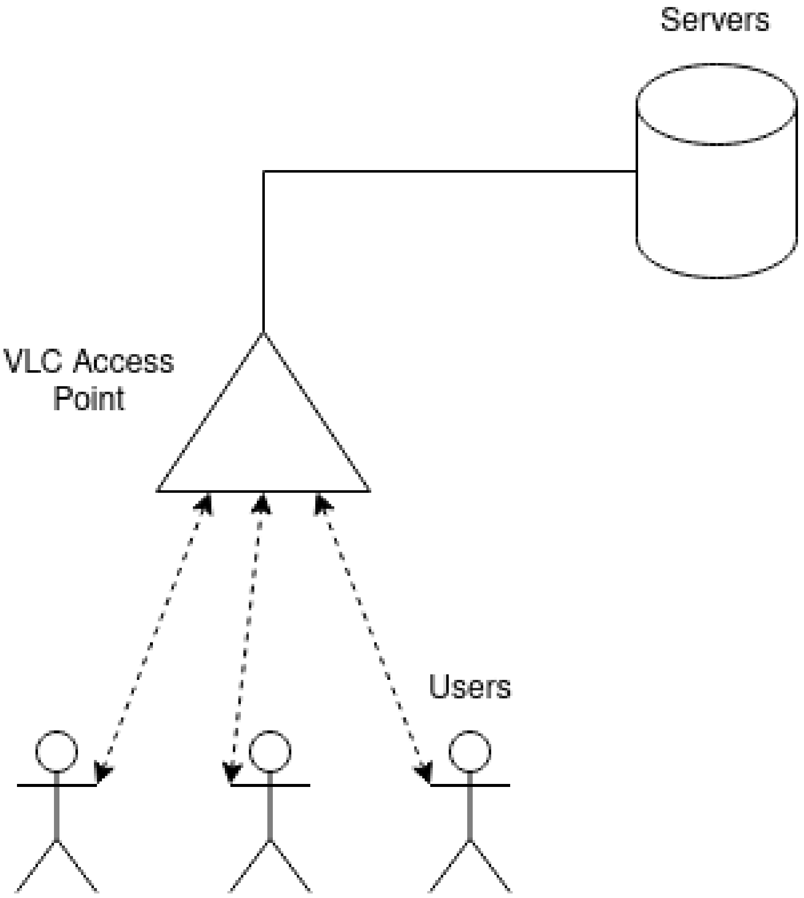

Figure 3.1. Simulated Network Topology

3.2.1. Simulation Setup. To evaluate the proposed protocol, we perform a comparison of two simulated networks. In one network, a standard TDMA protocol is used with no QoS enabled. In this network, time slots are distributed equally amongst all users regardless of the priority level of their data. In the second network, we apply the priority-aware TDMA protocol to satisfy the QoS requirements of the users. In both of these simulated networks, we consider the single VLC access point to multiple users scenario. To isolate the impact of the MAC protocol, we place all users within the LoS of the AP and do not consider their mobility. The topology of the simulated network can be found in Figure 3.1. In the simulation, we keep the number of user requesting access for Type I and Type II data

Table 3.1. System Parameters

Simulation Parameters	Value
Type I users	3
Type II users	3
User datarates	2.0Mbps
Simulation time	60 s
TDMA Parameters	**Value**
Total slots	50
Low-priority slots	10
Slot time	30 μs
Guard time	3 μs

fixed and gradually increase the number of users requesting access for low priority Type III data. In the results, we track the average latency experienced by each QoS category over the course of the simulation.

$$AverageLatency = \frac{TotalDelay}{P_{Rx}} \tag{3.8}$$

Where *Total Delay* is a combination of time spent waiting for channel resources from TDMA scheduling and time spent propagating individual packets. P_{Rx} is the total number of packets received.

3.2.2. Results. The results of the simulation show the resiliency of the network operating with the proposed priority-aware TDMA protocol. In Figure 3.2, the latency experienced by users of the network using the standard TDMA protocol. As expected, the average latency increases steadily as the number of low priority users in the network increases. In Figure 3.3, we see how in the network operating with the modified TDMA protocol the average latency experienced is dependent on the access category of the data. Even as the network becomes inundated with low priority traffic, users requesting access for Type I and Type II data experience a relatively stable average latency.

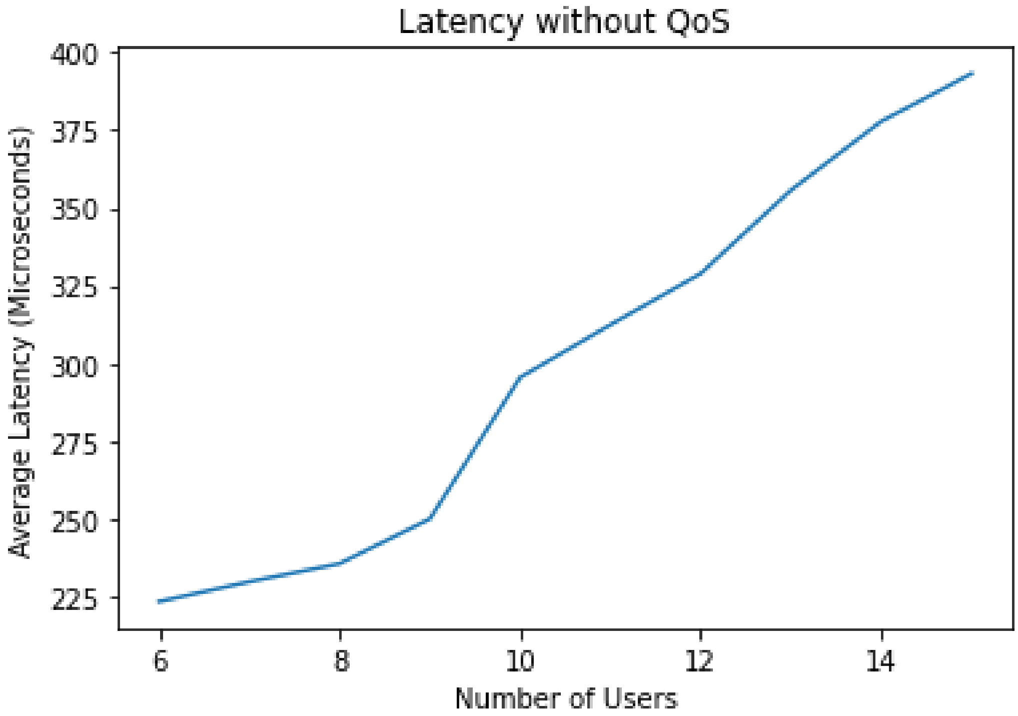

Figure 3.2. Average user latency with no QoS

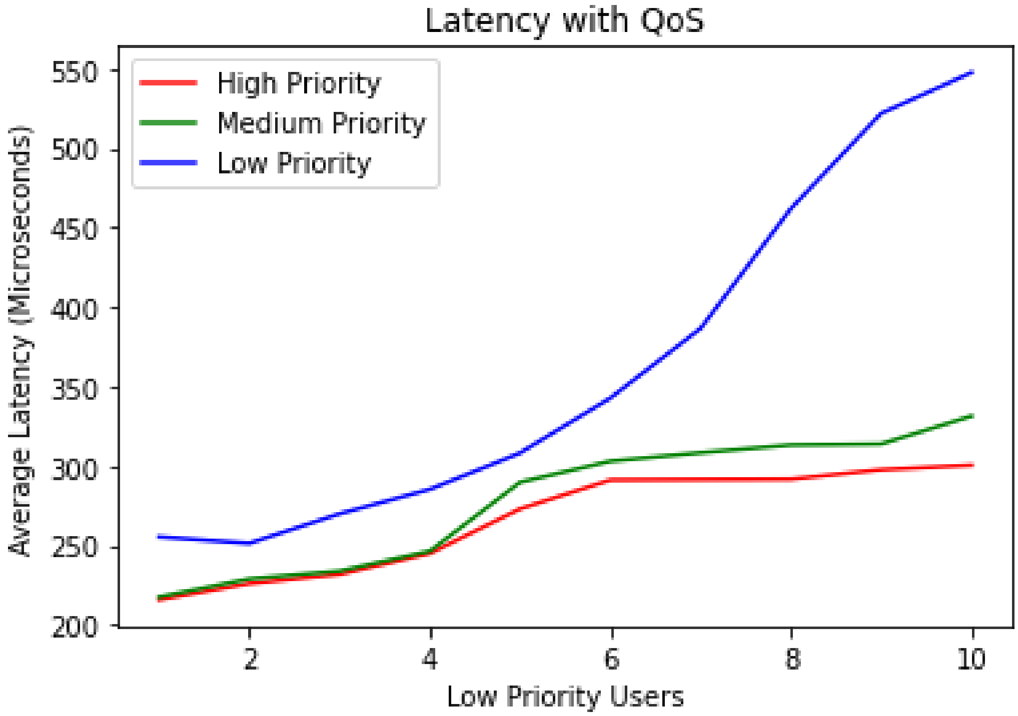

Figure 3.3. Average user latency with QoS

These simulations give a promising result for a real-world implementation of a health-oriented, priority-aware TDMA protocol as they demonstrate how hospital networks can be designed and optimized to protect the quality of care for patients and meet the unique challenges of healthcare environments.

4. INDOOR ENVIRONMENTAL MONITORING WITH D2D VLC NETWORKS

4.1. PHYSICAL TESTBED DESIGN

To complement the results of our simulated testbed, we design and develop a physical testbed to obtain empirical data regarding VLC network performance. The experimental scenario we choose to validate our testbed is indoor environmental monitoring, an important application for hospital environments that is envisioned to benefit greatly from the adoption of VLC networks.

Many of the existing studies aimed at performing environmental monitoring with VLC do not make use of fully networked communication, but rather focus on simple point-to-point connections or relay systems. The reason for this may be related to the characteristics of VLC that make supporting a full network with multiple access and MAC protocols difficult, namely the rapid attenuation of visible light limiting the number of supportable neighbors in range of a given node in addition to the loss of received power as a result of misalignment between the transmitter and receiver. Despite these challenges, the development of efficient MAC protocols tailored to VLC is an important enabler of this technology in real-world scenarios. With this in mind, our testbed focuses on shared-channel VLC communication between multiple nodes to validate the operation of existing MAC protocols and serve as a platform for the development of future protocols.

4.1.1. Node Architecture. Our hardware architecture is shown in Figure 4.1. The Host device is responsible for data packaging, modulation and demodulation, and unpacking. The SDR handles baseband signal processing for the data. Afterward, the transmission path is connected to an LED driver composed of a signal amplifier and a bias tee, which amplifies the physical signal generated by the SDR, eventually superimposing it with an external power supply on the bias tee and illuminating the LED. In the receiving path, the photoelectric

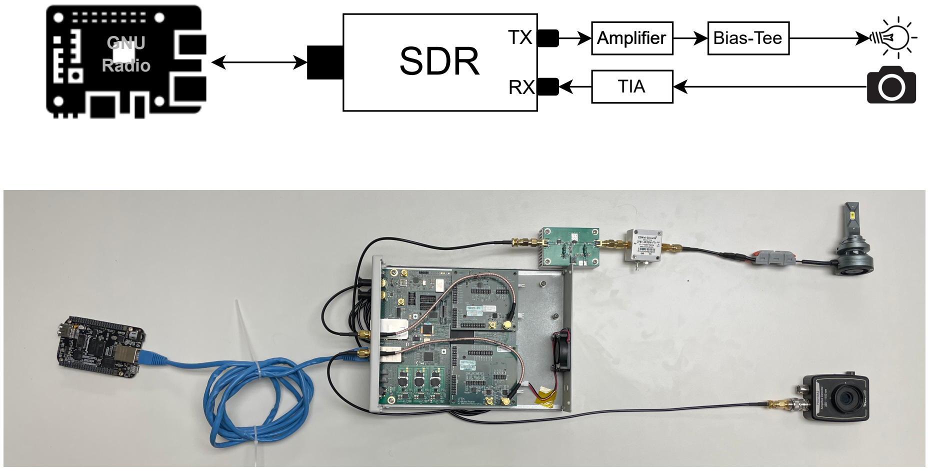

Figure 4.1. VLC node's Structure and VLC frontends

sensor detects changes in LED brightness and converts them into current signals. Then, the TIA reconverts the current signal into a voltage signal and amplifies it before feeding it back to the SDR for baseband signal processing.

Based on our designed hardware structure, we implemented the frontend as shown in Figure 4.1. Specifically, for the Host device, we used the BeagleBone Black (BBB) development platform. For the SDR, we utilized the widely used USRP from Ettus Research for wireless communication research. The LED driver was implemented with a 30 dB signal amplifier and a bias tee from Mini-Circuits. For the photoelectric sensor, we used Thorlabs' PDA100A2, which comes with a built-in TIA.

4.1.2. Network Architecture. Due to limitations in the amount of available hardware, we consider a simple network architecture between only two participating nodes. In order to overcome this limitation and apply the proposed physical testbed to the study of contention-based VLC MAC protocols, we simulate contention for channel resources using a third node equipped only with an LED. This network could easily be extended to a full-scale D2D VLC network once hardware resources become available. The network topology used is shown in the Figure 4.2. In the network, Node 0 acts as a sink, Node 1 collects and

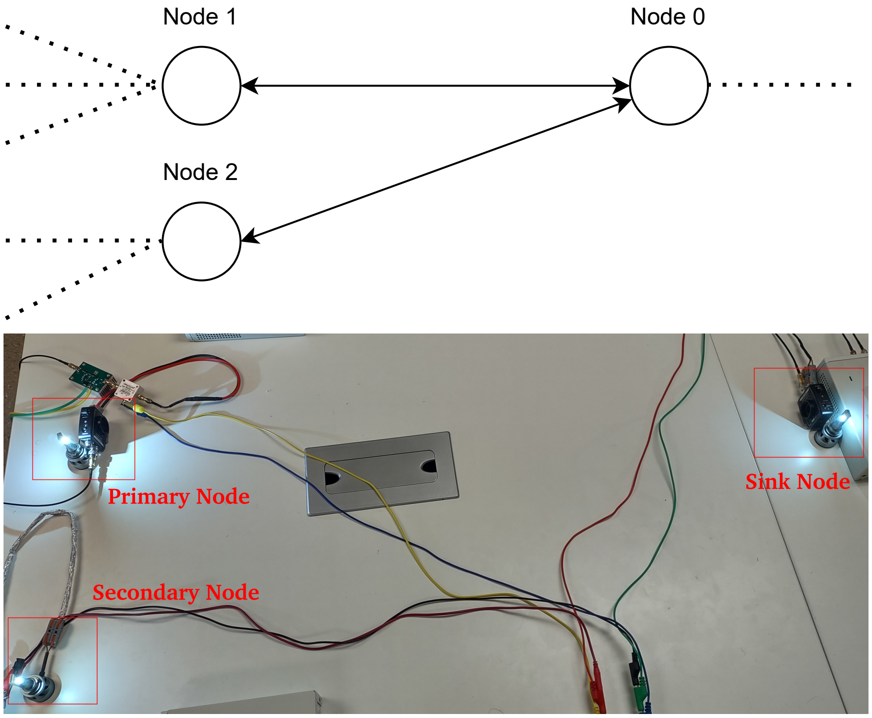

Figure 4.2. Network Structure

transmits data from an attached sensor, and Node 2 simulates the existence of neighboring nodes competing for access to the sink. We refer to Node 1 as the primary source node and Node 2 as the secondary source node. The specific behaviors of the primary and secondary source nodes will be explained in more detail in section 4.2.

4.1.3. MAC Protocol. The MAC protocol that we chose to implement for this testbed is the ALOHA protocol. ALOHA protocol is a very straightforward, contention-based MAC protocol, the core principle of which being that every time a transmitter sends a packet, the receiver replies with an acknowledgment packet. If the transmitter successfully receives the acknowledgment, it considers the packet successfully received and begins transmitting the next packet. If the transmitter does not receive the acknowledgment, it assumes that the packet has collided with another node's packet, and the transmitter waits

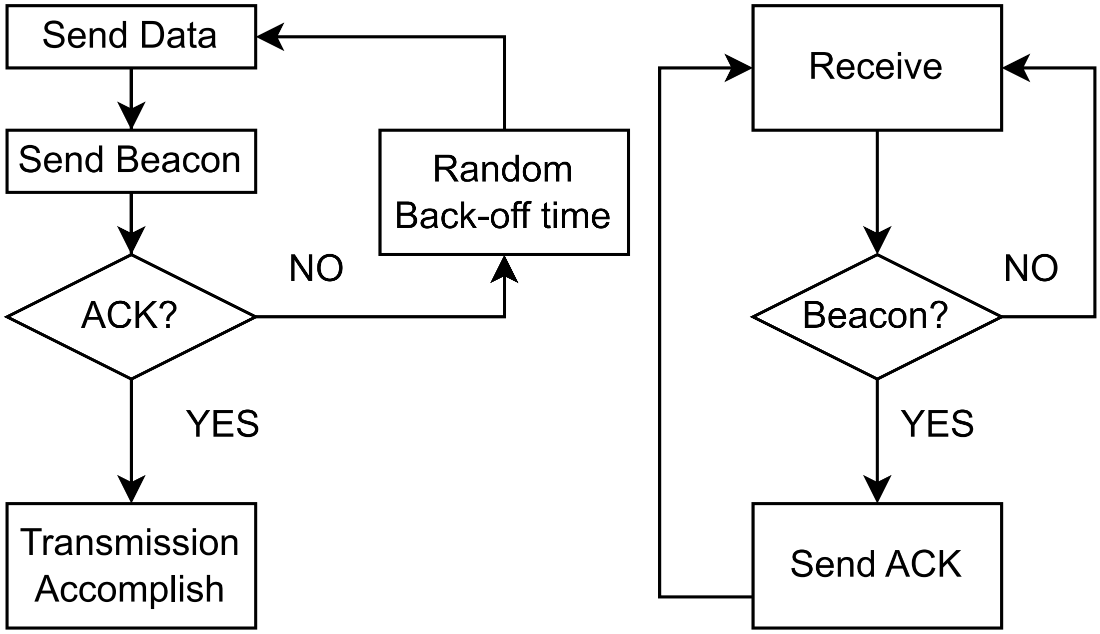

Figure 4.3. ALOHA Structure

for a random back-off time before re-transmitting the packet. Thanks to the straightforward transmission and acknowledgment mechanism mentioned above, the ALOHA protocol is widely used in both wireless and wired network systems.

When using standard ALOHA, the protocol requires the receiver to stop transmitting packets for a reasonable amount of time to accept the acknowledgment packet each time a packet is transmitted, typically an RTT interval. The advantage of this approach is that it ensures every packet is successfully acknowledged. However, when using ALOHA in visible light communication systems, due to the rapid fading characteristics of visible light, the number of VLC transmitters within the coverage range of a VLC receiver is generally limited. As a result, compared to RF channels, VLC channels are more prone to idleness. However, even when the channel is idle, the traditional ALOHA protocol still requires the transmitter to frequently listen for acknowledgment packets, increasing the time required to transmit data packets and, in turn, reducing the data rate.

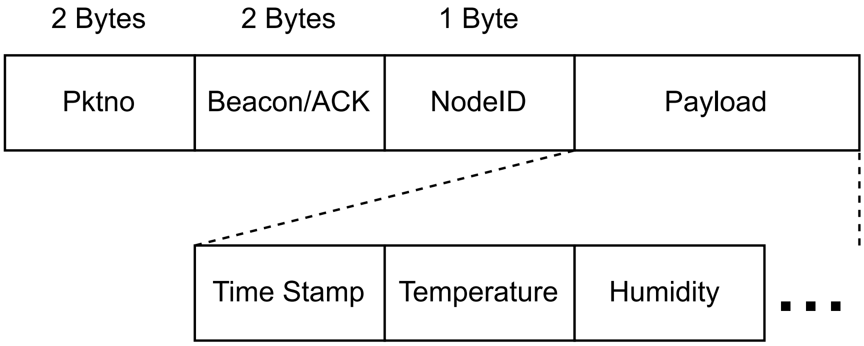

Figure 4.4. Packet Structure

To address this issue, we made slight modifications to the pure ALOHA protocol as illustrated in Figure 4.3. After transmitting a data packet, the transmitter sends an additional beacon. If the receiver successfully receives both the data packet and the beacon, it replies with an acknowledgment packet. The size of this beacon is much smaller than that of the actual data, so it does not significantly reduce data efficiency. Furthermore, the transmitter predicts channel idleness based on the number of acknowledgment packets successfully received per unit of time. When the channel is relatively idle, the transmitter sends multiple data packets in a row, followed by a final beacon. The transmitter then acknowledges all data packets in one instance upon receiving the beacon. If the transmitter successfully receives the acknowledgment packet, it proceeds with the next data transmission. If the acknowledgment is not successfully received, the transmitter re-transmits the aforementioned data packets separately.

4.1.4. Packet Structure. Our packet structure is illustrated in Figure 4.4, where Pktno is a 2-byte binary data ranging from 0x00 to 0xff. On the transmitter side, if the acknowledgment packet from the receiver is successfully received, Pktno is incremented; otherwise, Pktno is not updated. Pktno helps to resolve the redundancy at the receiver side caused by the re-transmission of the data packet when the receiver has already received the data and sent an acknowledgment packet, but the acknowledgment packet was not successfully received by the transmitter.

Beacon/ACK is a 2-byte string data. Beacon/ACK has three values, namely 'N', indicating that the packet is normal data; 'B', indicating that the packet is a beacon packet sent after the data transmission ends; and 'A', indicating that the packet is an acknowledgment packet sent from the receiver. NodeID is a 1-byte string data, and each node has a unique NodeID. NodeID is used at the receiver end to distinguish the data source. Lastly, the data field includes the environmental data collected from the sensors, which includes information on temperature, humidity, node status, and time of measurement.

4.2. VALIDATION

4.2.1. ALOHA Protocol Operation. A series of experiments were conducted to evaluate the performance of the VLC test bed. The initial set of experiments were conducted to characterize the behavior of the VLC channel without the use of a MAC protocol. In these experiments the primary and secondary nodes sent packets through the VLC channel at regular intervals over the span of three minutes. During the experiment, the sink node logged the data it received. This was used to find the Packet Error Rate (PER), which was computed as

$$\text{PER} = \frac{\text{Packets not received}}{\text{Total packets sent}} \tag{4.1}$$

Three experiments were performed without a MAC protocol to measure the effect that transmission frequency had on the VLC channel. The experiments were performed with data transmission frequencies of 10 packets per second, 50 packets per second and 100 packets per second. The results of the experiments are shown in Figure 4.5. The steady state PER for 10 packets per second, 50 packets per second and 100 packets per second was 0.094, 0.546 and 0.748, respectively. It was seen that the VLC channel was sufficiently saturated at a frequency of at least 50 packets per second and required additional logic to reliably use the channel.

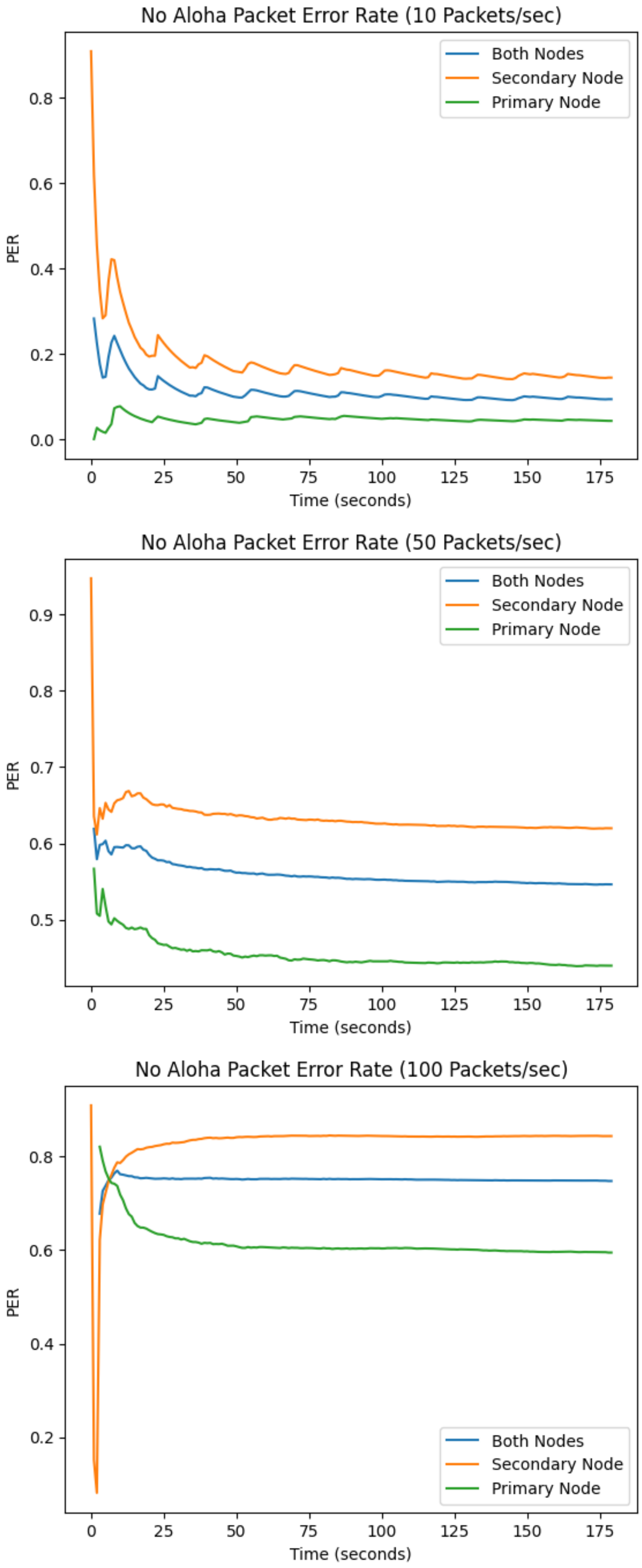

Figure 4.5. Packet Error Rate (PER) without using a MAC protocol

The next experiment conducted was to quantify the behavior of the ALOHA protocol by using the network under channel conditions that were shown to be unreliable without a MAC protocol. In this experiment the sink node and the primary node were configured to use the ALOHA MAC protocol and were fully equipped with hardware to send and receive on the VLC channel. Due to limited access to hardware, the secondary node was not equipped with a photodetector and therefore could not receive an acknowledgement from the acknowledgement from the sink node. To simulate network traffic, the secondary node was configured to send bursts of network traffic, emulating the presence of other nodes connected to the network. The bursts of randomly generated data from the secondary node had a 10% chance to happen every second, and a burst would last for 1 second. The purpose of these periodic bursts of traffic is to evaluate the ability of the protocol to detect and recover from collisions at the sink node, which is a defining feature of contention-based protocols. Due to the small packet sizes and short transmission windows for the primary node, such collisions were unlikely to occur among two nodes operating according to the application scenario. Another advantage to this method of modeling contention is that by increasing the frequency at which bursts would occur, we can investigate the effects of having an increasing number of nodes contending for the channel. Every second of network operation, the secondary node uses the *channel load factor* to determine whether or not the next second will be dedicated to sending a burst of traffic to force a collision to occur. The channel load factor (CLF) is tunable parameter subject to $0 \leq CLF < 1$ that gives the probability that a burst will occur in the next second. This is done to better model the random nature of genuine network traffic.

The experiment was run by collecting temperature, humidity and timing data on the primary node and sending the data to the sink node over a three minute interval. The temperature and humidity readings were done with a DHT-11 sensor, polling at a rate of 2 packets per second. The frequency of 2 packets per second was used as that was the maximum poll rate possible when using the Python library associated with the sensor.

During the experiment the primary node logged the acknowledgements from the sink node, which was used to calculate the PER. The result of the experiment was that the primary node achieved a PER of approximately 0.05 when ALOHA was enabled. The PER from this experiment can be seen in Figure 4.6.

The result from this experiment align closely with what would be found in an ideal case of using ALOHA as a MAC protocol. Over a span of 10 seconds, we expect 1 burst of transmissions from the secondary node. If the primary node is transmitting at 2 packets per second, we would expect 20 packets to be sent during this time. Without ALOHA, we would expect 2 of these messages to collide, giving a PER of 0.10. However with ALOHA enabled we would expect the primary node to back off after the first collision giving, therefore preventing a second collision. In this case we would expect a PER of approximately 0.05, which is exactly what was observed in the experiment. To complement this result, we show the effects of higher levels of contention by repeating the experiment with a gradually increasing CLF. The results of which are shown in Figure 4.7.

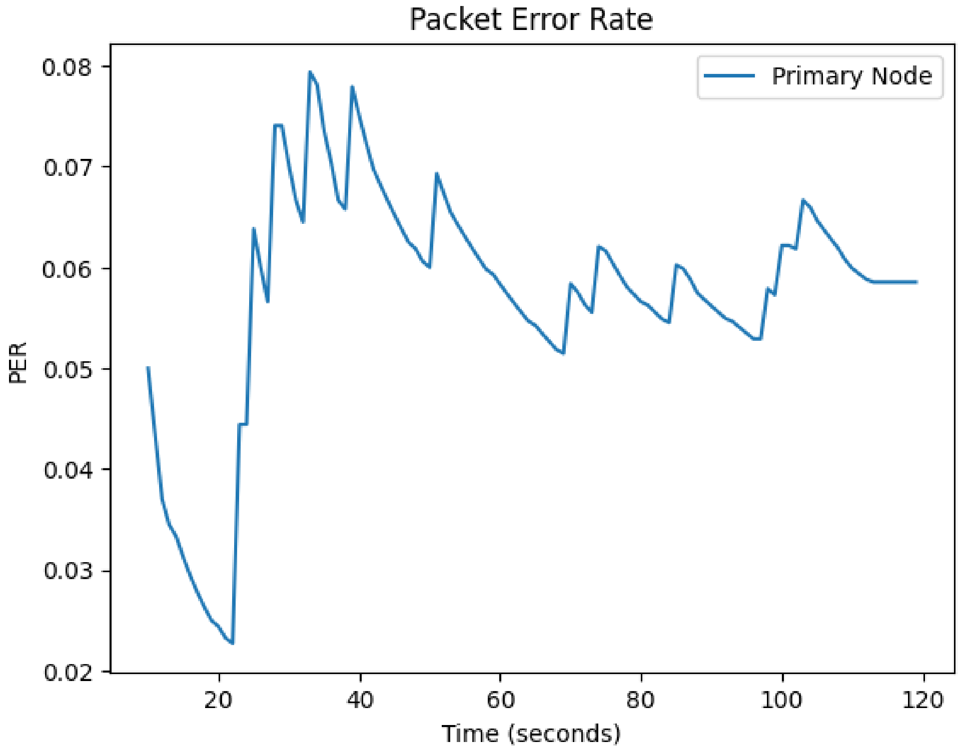

Figure 4.6. Packet Error Rate with ALOHA enabled

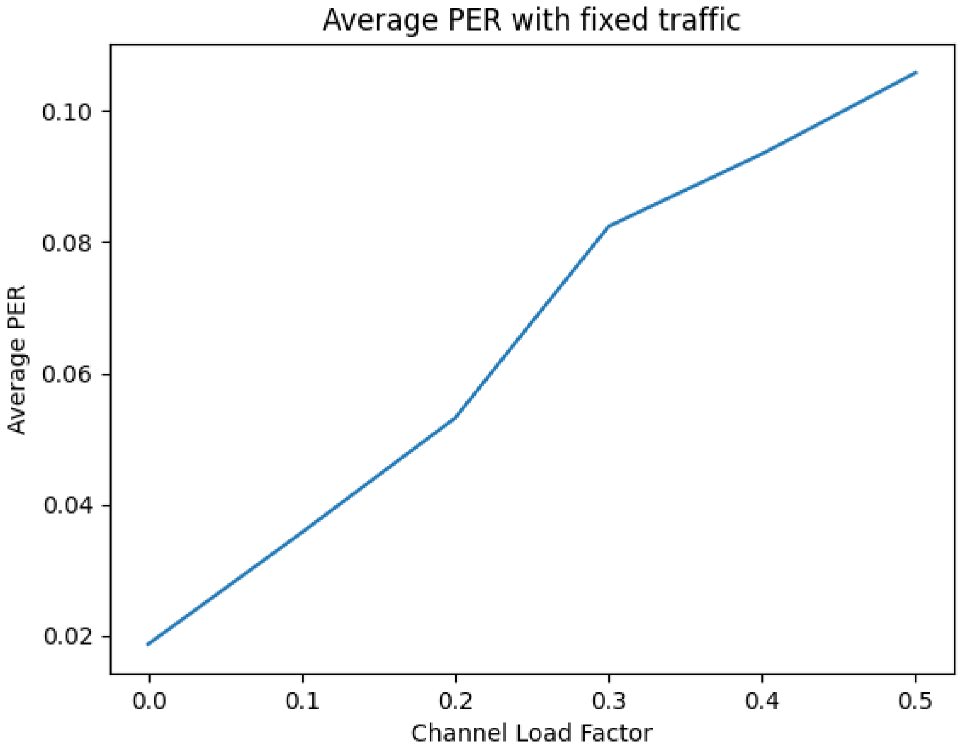

Figure 4.7. Effect of channel load factor

5. CONCLUSIONS

5.1. FUTURE WORK

The validation of our simulation testbed in section 3.2 opens the door to future research into new VLC network protocols. To continue our work into enabling future smart healthcare applications, we plan to use this testbed to investigate the use of visible light ad-hoc networks (LANETs) in hospital environments. In comparison to traditional VLC networks, LANETs offer a greater degree of robustness and scalability [17]. This makes them ideal for applications requiring rapid deployment and flexible placement of a VLC networks. For example, a monitoring system deployed in response to a time-critical incident such as an outbreak of infectious disease. While there has been some recent work on the development of specialized network protocols for LANETs [18], the research in this area is still developing. Our simulation testbed would enable us to study these protocols as the time and cost of implementing a real-world, large-scale LANET with many nodes would be a barrier to progress.

To extend the work in section 4.1 and gain a greater understanding of the empirical performance of VLC networks in real-world application scenarios, we plan to scale our physical testbed to include full networking capabilities. As part of this process, we plan to miniaturize the node architecture using components that are more portable, cost-effective, and readily available. Having the ability to construct basic D2D VLC networks will allow us to get a more thorough evaluation of overall network performance as well as enable validation of simulated results on new network protocols.

5.2. CONCLUSION

For the purpose of enabling future smart-healthcare applications, we have contributed to the growing body of research surrounding the use of VLC networks in hospital environments. We began by identifying the unique challenges regarding the use of wireless communication technology in hospitals, as well as observing the trend of communication requirements as a result of advancing healthcare operations. From these we propose the use of VLC networks as a solution to these challenges. As a precursor to our work, we conducted an extensive literature review into indoor VLC networks and the specific applications that they are envisioned to enable. From this we identified some necessary contributions in the development of new network protocols and the evaluation of said protocols in a full VLC network environment. With this in mind, we designed a novel MAC layer protocol for VLC networks tailored to healthcare environments and constructed a simulation testbed to evaluate the performance of our proposed protocol. In addition to our simulation testbed, we also constructed and validated a real-world D2D VLC network testbed for the development of network protocols.

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VITA

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