ELECTENG 700A: Research Project

Sunlink II: Light-Based Wireless Communication Using Sunlight

Department of Electrical and Electronics Engineering

University of Auckland, Auckland, New Zealand

Vivek Chauhan

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Supervisor: Talia Xu

Project Partner: Ryan Farrell

Abstract

Acknowledgements

Table of Contents

1. Introduction

Light-based wireless communication has gained traction as a promising method for efficient and high-speed data transmission. However, many current systems rely on ambient or artificial light sources for development and testing, which introduces variability and limits their real-world effectiveness. These light sources, while convenient in controlled environments, often lack the consistency and intensity required for stable, scalable communication outdoors.

This project addresses these limitations by designing and implementing a wireless communication system that uses direct sunlight as the primary transmission medium. Sunlight offers a more robust and naturally available alternative, but requires dynamic tracking to maintain alignment and efficiency throughout the day. To achieve this, the system integrates a motor-driven sun-tracking mechanism capable of accurately following the sun's position. This allows the transmitter and receiver to maintain optimal alignment, maximising light collection and ensuring reliable signal transmission. Additionally, the system is developed to support multi-unit communication, enabling consistent and efficient data exchange between multiple devices using sunlight alone. Through this approach, the project aims to demonstrate a scalable, sunlight-based wireless communication system that overcomes the limitations of ambient-light-dependent models by enabling consistent, real-world performance through precise sun-tracking and robust system-to-system communication.

Project Objectives:

1. Conduct a review of existing and previous light-based wireless communication technologies, with a focus their dependence on ambient light, signal stability, and communication reliability.
2. Identify the key limitations of ambient light-based systems and establish criteria for performance improvement using direct sunlight.
3. Develop a sun-tracking subsystem using motor-electronics control components capable of accurately following the sun's position throughout the day.
4. Integrate the tracking subsystem with a light communication subsystem created to allow for real-life data transmission using sunlight as the carrier.
5. Design and test a prototype capable of system-to-system communication under varying environmental conditions, analysing factors such as data integrity, transmission range, and power efficiency.
6. Compare the performance of the developed system against ambient light-based alternatives, with a focus on signal stability, reliability, and practicality for real-world deployment.
7. Evaluate the scalability and feasibility of the system for broader applications, including potential use in remote or off-grid communication networks.

2. Literature Review

2.1. Introduction to Wireless Communication in the IoT Era

The Internet of Things (IoT) emerged as a transformative paradigm in the early 2010s'[1], embedding connectivity into everyday objects to enable real-time data exchange across distributed systems. With billions of devices projected to come online in the coming years, the demand for reliable, scalable, and energy-efficient wireless communication has intensified. Traditional radio frequency (RF) communication technologies—such as Wi-Fi, Bluetooth, and Zigbee—have served as the backbone of IoT networking. However, the exponential growth of connected devices has placed immense pressure on the RF spectrum, particularly within the overcrowded 2.4 GHz and 5 GHz bands [2]. Overcrowding is observable in national spectrum allocations, one source from New Zealand's 2024 Radio Spectrum Allocation Chart, maintained by the Ministry of Business, Innovation and Employment (MBIE), reveals that nearly the entire RF range—from Very Low Frequency (VLF) to Extremely High Frequency (EHF)—is already assigned for diverse applications such as broadcasting, mobile data, aviation, maritime services, satellite communication, and defence operations. Highly likely it will result in harder processes with implementation of new technologies in the future.

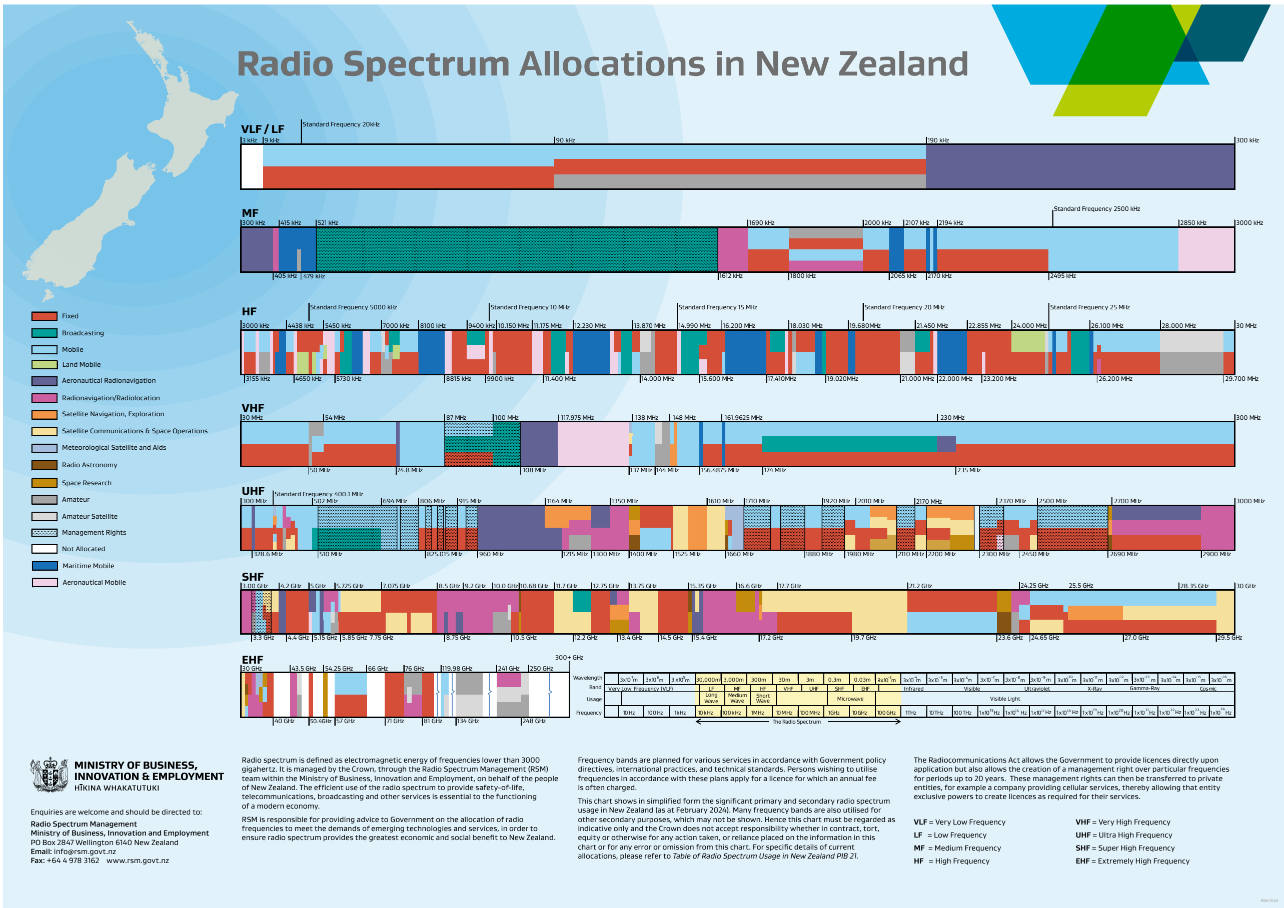

Figure 1: Radio spectrum usage across New Zealand, showing extensive allocation across most frequency bands as of March 2024 [3].

The growing constraints of the RF spectrum have led researchers to investigate alternative wireless communication methods. Visible Light Communication (VLC) has emerged as a promising candidate as a result, utilising the unlicensed and abundant visible spectrum to transmit data through light sources such as LEDs or natural sunlight. By operating outside conventional RF bands, VLC avoids spectral congestion while enabling dual-purpose functionality, such as combining illumination and data transmission. VLC aligns well with the energy constraints of IoT deployments, Especially in passive VLC systems, where no active light emission is required from the transmitter side, communication can be achieved at dramatically reduced energy costs. Resulting in VLC being a candidate for the next generation of scalable, low-power IoT communication technologies.

Building upon this premise, exploring VLC as an emerging solution to RF congestion, It progresses from foundational VLC concepts to cutting-edge research in sunlight-based, passive communication systems—with a research focus specifically on the feasibility of real-time, sun-tracked, system-to-system communication.

2.2. Fundamentals of Visible Light Communication (VLC) and Its Evolution

Visible Light Communication (VLC) offers a promising alternative to RF-based wireless systems, particularly for energy-constrained and spectrum-scarce IoT deployments as mentioned before. Operating within the unlicensed 400–700 nm range, VLC enables data transmission through light intensity modulation. Typically using LEDs, allowing it to leverage existing lighting infrastructure for secure and energy-efficient communication [4]. Conventional VLC relies on actively modulated LEDs for downlink communication, which, while supporting high throughput, which inturn incurs considerable energy consumption. Presenting a barrier for ultra-low-power IoT applications, especially those relying on energy harvesting, which is problematic. Additionally, uplink communication in such systems often reintroduces RF components, undermining VLC's spectral benefits.

Addressing these limitations, passive VLC systems have emerged as a prominent field, these architectures eliminate the need for active emitters by modulating ambient or incident light using low-power optical components such as LCD shutters and/or retroreflectors. Significantly, reducing power consumption while supporting uplink communication in resource-constrained environments [5].

Recent efforts have introduced more systematic design approaches to passive VLC. A researcher, Ghiasi et al. present ChromaLux, a framework that leverages the transient, non-monotonic switching behaviour of liquid crystal (LC) cells to enhance modulation depth and speed [6]. By stacking multiple LC layers, ChromaLux broadens the modulation spectrum and achieves communication distances of up to 50 meters with error rates below 1% with ambient lighting conditions. Their design incorporates a novel duty-cycled modulation strategy and explores trade-offs between contrast and bandwidth using birefringence, [7], theory and the Michel-Lévy chart. Developing a shift from ad hoc designs toward structured, physics-informed architectures capable of supporting scalable and passive VLC systems for the next generation of IoT connectivity.

2.3. Passive VLC Using Ambient Light

Recent research has explored the feasibility of passive visible light communication (VLC) systems that rely on ambient light—such as sunlight, fluorescent bulbs, or uncontrolled LED fixtures—as the carrier medium for data transmission. Systems of such, are a particular interest in ultra-low-power IoT contexts where eliminating the need for modulated light sources can yield significant energy savings and system simplicity. One of the earliest and foundational works in this space is Passive Communication with Ambient Light by Wang et al. [4], proposing a communication system in which mobile objects modulate data using reflective surface patterns, without controlling the light source itself. The authors demonstrated that by "wearing" sequences of high-contrast materials (e.g., aluminium tape and black paper), mobile devices could encode data that can be decoded by simple photodiode-based receivers. The system however, was highly sensitive to environmental parameters such as distance, angle of incidence, light source intensity, and field-of-view (FoV).

To improve robustness under fluctuating lighting conditions, LuxLink proposed a frequency-based modulation (FSK) scheme for passive VLC using ambient light and LCD shutters [8]. Unlike earlier approaches that relied on pulse or amplitude modulation—both of which introduced flickering or instability, LuxLink demonstrated that FSK provided flicker-free and interference-resistant communication. The system achieved data rates of up to 80 bps at distances up to 60 meters outdoors, significantly outperforming earlier systems, while consuming minimal energy.

Edge-Light further expanded the ambient VLC design space by addressing a fundamental limitation in passive systems. The inability to communicate laterally (i.e. perpendicular to the direction of light propagation) [9], by integrating luminescent solar concentrators (LSCs) with LC shutters and colour sensors, the authors demonstrated lateral passive VLC links under both indoor and outdoor ambient lighting. Although limited by the low optical conversion efficiency (5%) of commercial LSCs, the system introduced a critical new capability of non-directional communication that does not require mechanical realignment.

These works together illustrate the growing maturity of ambient light-based passive VLC systems. However, a consistent theme across all three is the dependency on light variability. As Ullah et al. summarised, such systems 'often face intensity variability and limited control over spectral consistency, which affects communication reliability' [5]. These limitations have motivated recent research to explore direct sunlight as a more stable, high-intensity, and directionally consistent source for passive communication.

2.4. Passive VLC with Direct Sunlight: Toward Solar-Driven Communication

Many studies have explored the potential of direct sunlight as a communication medium in passive VLC systems. While, unlike ambient or artificial light, sunlight provides a high-intensity, spectrally broad, and globally available source, making it an appealing candidate for energy-efficient and scalable outdoor communication. This section continues by reviewing three systems, Sol-Fi, Sunlight-Duo, and SpectraLux, which all exemplify current approaches to leveraging sunlight for passive communication.

Sol-Fi introduces a system that combines sunlight collectors with passive modulators to deliver both natural illumination and data transmission indoors [10]. The system explores liquid crystal (LC) and digital micro-mirror device (DMD) modulators, offering a comparative analysis of their trade-offs in terms of modulation speed, area, power, and cost. Impressively, Sol-Fi also proposes a multibandmodulation approach, dividing the visible spectrum into separate bands to increase data tthrough-put, achieving up to 80 kbps over 5 meters depending on configuration.

Sunlight-Duo extends passive VLC by using solar cells as dual-purpose receivers capable of simultaneous energy harvesting and data reception [11]. This system highlights the trade-off between maximising energy intake and decoding modulated data embedded in the same light stream. Through dynamic reconfiguration of solar cell parameters, the prototype maintains a bi-directional link up to 11 meters, supporting 1200 bps downlink and 800 bps uplink, powered by sunlight.

SpectraLux takes a different approach by shifting from spectrum-agnostic to spectrum-aware modulation using LC shutters and spectrometer-based receivers [12]. Rather than modulating light intensity alone, SpectraLux encodes data through spectral signatures generated by stacking and fine-tuning LC cells. This enables the use of multiple distinguishable symbols in the spectrum domain, increasing modulation quality even under the constraints of slow LC switching speeds.

Demonstrating growing maturity in sunlight-based passive VLC, each system addresses a unique aspect towards the area. Sol-Fi focuses on optical integration and multiband design, while Sunlight-Duo focuses on self-powered bidirectional links, and SpectraLux on advanced spectral modulation. These works collectively point toward the feasibility of robust and scalable communication systems that operate entirely on natural light.

2.5. System Implementation: Backscatter and Retro-reflective Designs

Passive visible light communication (VLC) relies on carefully engineered hardware and modulation schemes to enable energy-efficient communication without active emitters. Two implementations-PassiveVLC and RetroI2V, both demonstrate how backscatter communication can be achieved using retroreflectors and liquid crystal (LC) shutters, while being tailored to different application scenarios.

PassiveVLC presents a low-power, backscatter uplink system where a retroreflective fabric and a commercial LCD shutter are used to modulate incident light from overhead LEDs [13]. The system is powered entirely by harvested light through onboard solar cells, enabling fully battery-free operation. A key innovation is its trend-based modulation, which encodes data based on the direction of the LCD's transition state rather than waiting for complete on/off switching. This reduces latency and improves symbol rate. The use of Miller encoding further mitigates flicker and improves decoding robustness. The prototype achieves a 1 kbps uplink and operates under low light conditions with strong resilience to tag orientation.

RetroI2V, by contrast, targets long-range infrastructure-to-vehicle (I2V) communication by retrofitting road signs with transparent LCDs [14]. These "RetroSigns" maintain their original function while enabling data transmission via visible light backscatter. The system introduces a late-polarisation architecture, where the LCD's front polariser is moved to the vehicle-mounted receiver. This eliminates flickering and enables consistent light reflection regardless of LCD state. Additionally, polarisation-based differential reception (PDR) is employed to suppress ambient noise and improve signal quality. Paired photodiodes with orthogonal polariser extracted differential signals, resulting in an average 5.3 dB Signal-to-noise ratio (SNR) improvement. As RetroI2V supports ranges up to 101 meters and incorporates a decentralised MAC protocol for managing multi-device access without coordination infrastructure, this is slightly different from PassiveVLC.

Both systems illustrate distinct strategies for enabling practical backscatter communication: PassiveVLC focuses on compact, energy-autonomous indoor tags, while RetroI2V addresses mobile, long-range outdoor communication through physical-layer enhancements. Their combined insights underline the importance of optical design and modulation co-optimisation in advancing passive VLC systems.

2.6. Vision for Sun-tracking Light Communication Systems

Despite significant progress in passive VLC, current systems remain constrained by their reliance on static lighting conditions, limited modulation diversity, and narrow directional capabilities. While prior work has explored passive communication using both ambient light and direct sunlight, none have implemented real-time, sun-tracking subsystems designed for dynamic, directional system-to-system communication across distributed nodes. All this presents a unique opportunity to push the boundaries of passive VLC beyond static point-to-point setups.

Existing ambient-light-based systems are inherently limited by fluctuating intensity and spectral inconsistencies. While studies such as Edge-Light [9] and LuxLink [8] improve spatial adaptability, they are still reliant on uncontrolled lighting. Conversely, systems like Sol-Fi [10] and Sunlight-Duo [11] demonstrate the viability of direct-sunlight-based communication, but they either use fixed sunlight delivery methods or focus exclusively on single-node communication.

Our proposed direction introduces a sun-tracking light communication subsystem that mimics the behaviour of sunflowers—mechanically orienting a reflector or optical transmission system toward the sun in real time. Achieved primarily using a combination of electronic sensing, motor control, and closed-loop control systems, ensuring for continuous alignment with the sun's azimuth and elevation. The control architecture may incorporate feedback systems with light sensors or photodiode arrays to dynamically adjust orientation, using PID control or adaptive gain scheduling to ensure responsive and energy-efficient tracking.

In contrast to current systems that rely on fixed pairs or point-to-point communication, the proposed subsystem aims to support scalable, multi-node data exchange through a central sun-tracking emitter. This central node would broadcast to and receive data from distributed receivers, each located according to deployment needs. Achieving this requires communication protocols capable of handling spatial diversity, incorporating techniques such as time- or wavelength-division modulation alongside addressing and synchronisation schemes. This dual-function approach—combining sun tracking with dynamic, system-to-system communication—enables the formation of distributed networks of passive or semi-passive nodes. These nodes do not require direct line-of-sight to the sun, instead relying on modulated light directed via a form of control. By integrating mechanical sun tracking, electronic control, and spatially aware communication protocols, this research opens a new direction within the VLC domain: sunlight-tracked, system-to-system communication networks.

2.7. Summary and Research

The evolving domain of visible light communication (VLC) presents a promising alternative to congested and energy-intensive RF-based wireless systems. The discussion began with an overview of conventional VLC approaches, highlighting their reliance on active, power-consuming light sources. This was followed by an examination of recent advancements toward passive architectures that exploit ambient or incident light, enabling ultra-low-power communication suitable for IoT deployments. Foundational systems such as Passive Communication with Ambient Light [4], LuxLink [8], and Edge-Light [9] demonstrate early efforts to use uncontrolled lighting environments for low-power communication.

In response to these challenges, recent research has shifted toward systems that utilise direct sunlight as a stable and high-intensity light source. Sol-Fi [10], Sunlight-Duo [11], and SpectraLux [12] made significant strides in harnessing sunlight for communication, exploring advanced modulation schemes, energy harvesting, and bidirectional links. Yet, these systems largely assume static transmitter or receiver configurations, often limiting to one-to-one communication setups or indoor applications.

At the hardware level, efforts such as PassiveVLC [13] and RetroI2V [14] have shown how low-power, reflective hardware using LCD shutters and retroreflectors can enable practical backscatter communication. Reinforcing the importance of optical and modulation design in passive VLC systems but do not address directional sunlight capture or distributed system architectures, as common limitation across these works lies in their static design and narrow communication scope. While ambient-light and sunlight-driven VLC systems have advanced considerably, no existing research integrates real-time, sunflower-like sun tracking with dynamic, system-to-system communication between multiple nodes. Furthermore, the opportunity to leverage motorised tracking for both signal alignment and beam steering—while maintaining passive or semi-passive node operation—remains unexplored.

This project addresses that gap, proposing a sun-tracking VLC subsystem that autonomously aligns to the sun's position while facilitating scalable, multi-node communication utilising directional sunlight. And by combining principles of electronic control, spatial modulation, and retroreflective hardware, the system aims to provide consistent, low-power connectivity in environments where traditional lighting and RF infrastructure may be unreliable or unavailable.

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3. Gantt Charts

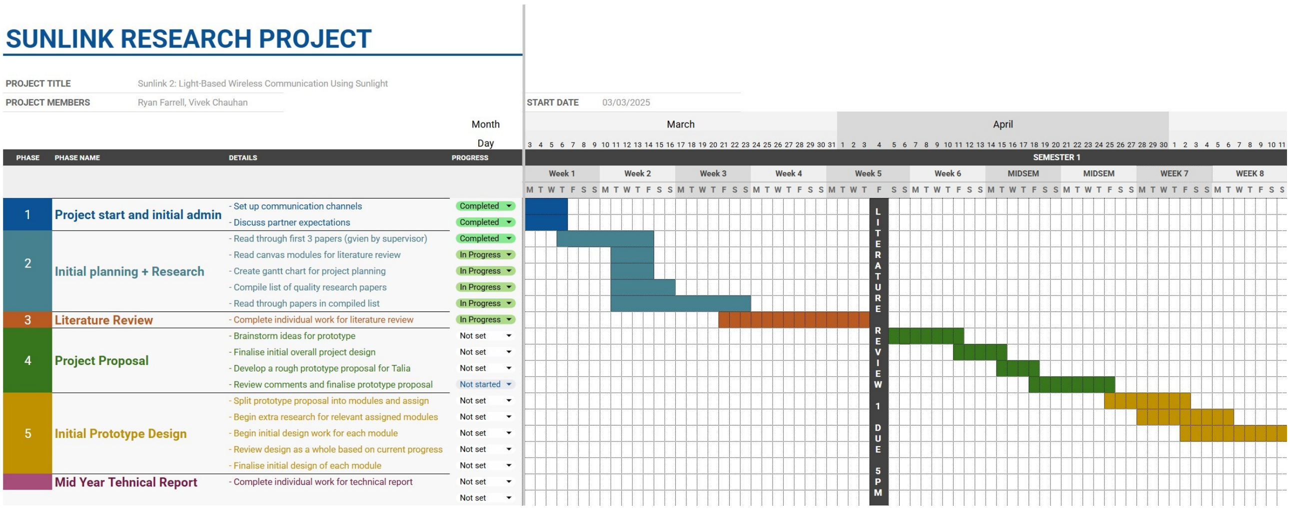

Figure 2: Gantt Chart – March to April Project Planning Timeline

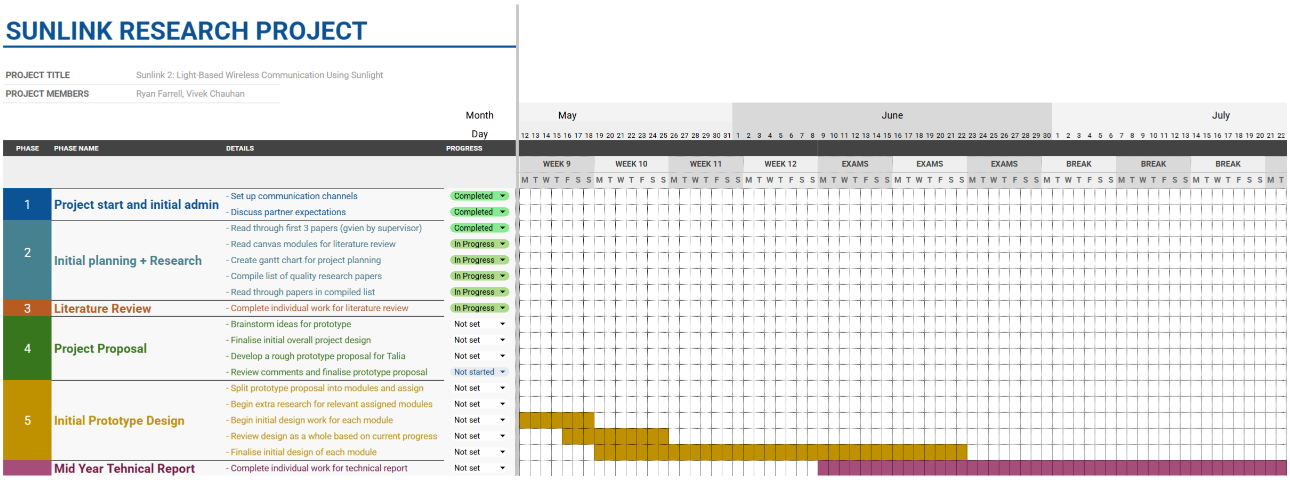

Figure 3: Gantt Chart – May to July Project Planning Timeline