

Enhancing Remote Conservation in Borneo: NVIS for Wildlife Monitoring and Protection using BearWave

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Biodiversity conservation in fragmented and remote ecosystems often requires labour-intensive, time-consuming fieldwork, placing staff at risk and limiting the scope of long-term monitoring. To address these challenges in a sustainable, locally adaptable manner, we present BearWave, a novel, place-based HF communication framework attuned to local infrastructure constraints and designed to support low-power sensing networks under severe radio-frequency (RF) conditions. By leveraging Near Vertical Incidence Skywave (NVIS) propagation and the FT8 digital modulation technique, BearWave achieves reliable, bidirectional data transfer—even in dense tropical rainforest conditions—while keeping costs under £200 per node and enabling extended battery-powered operation. A case study in UK woodlands, chosen as an environmental analogue to Borneo’s rainforest, demonstrated BearWave’s robustness and adaptability: despite dense vegetation and non-line-of-sight paths, the system maintained over 90% message reliability at distances of up to 25 km using only 1 W of RF power. Notably, the strongest signal propagation and best reception rates occurred during nighttime, reflecting diurnal ionospheric variations. These empirical results confirm that BearWave outperforms conventional technologies such as LoRaWAN or satellite systems in harsh, attenuating environments, offering a scalable, energy-efficient approach that lowers both ecological footprints and staff labor risks. This research advances conservation-focused communication by providing a universal, scientifically validated framework capable of supporting long-term ecological monitoring, poacher detection, and improved animal welfare. Crucially, BearWave’s low-cost, low-impact design broadens access for under-resourced organisations and community-driven conservation programs, where local knowledge and stakeholder insights help shape technology decisions on the ground. By embracing a socio-technical innovation model, BearWave exemplifies how computing can be sustainably embedded in remote ecosystems worldwide.

CCS Concepts: • **Networks** → *Physical links*; • **Hardware** → **Sensor applications and deployments; Signal processing systems; Radio frequency and wireless interconnect**; • **General and reference** → *Experimentation*; Empirical studies; • **Applied computing** → *Environmental sciences*.

Additional Key Words and Phrases: Near Vertical Incidence Skywave (NVIS), Wildlife Monitoring, Low-Power IoT Communication, Energy-efficient Rainforest

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1 Introduction

Borneo's Lower Kinabatangan region in Sabah, Malaysian Borneo, is home to the Danau Girang Field Centre (DGFC), a critical site for biodiversity research and conservation in one of Asia's most ecologically rich yet rapidly shrinking rainforests. Stretching approximately 25 km along the Kinabatangan River, this mosaic of tropical lowland forest harbors a remarkable diversity of fauna: critically endangered orangutans, pygmy elephants, proboscis monkeys, and the vulnerable Sun Bear (*Helarctos malayanus*). Despite the area's ecological importance, habitat fragmentation and rampant poaching threaten local wildlife populations, underscoring the urgency for effective monitoring and protection strategies.

Among DGFC's core activities are trap-based studies of species such as the Sun Bear, which remains highly susceptible to the illegal wildlife trade. While these traps adhere to strict ethical guidelines, they demand daily manual checks to ensure prompt animal release. The resulting fieldwork places staff at physical risk and incurs heavy labor demands, especially in dense rainforest terrain where thick canopies, high humidity, and rugged ground complicate travel. Advances in sensor networks and Internet of Things (IoT) technologies offer potential solutions: by automating data collection and alerting rangers in real-time, these systems can reduce the need for hazardous, time-intensive on-site visits. Yet, many current IoT implementations (from power-hungry Wi-Fi and cellular networks to low-power, long-range protocols like LoRaWAN or Sigfox) often falter in Borneo's humid, foliage-dense conditions. Severe radio-frequency (RF) attenuation in the canopy [14, 26, 37] and the absence of supporting infrastructure compound these obstacles. Satellite services (e.g., Argus, Iridium) bypass terrestrial barriers but remain costly, power-intensive, and contingent on clear line-of-sight. Comparable challenges surface in other extreme environments: Antarctica's hostile climate limits ground infrastructure [8], while mountainous North Wales experiences significant signal obstruction [31].

We propose that low-power, low-bandwidth high-frequency (HF) signals, specifically those harnessing *Near Vertical Incidence Skywave (NVIS)* propagation, can surmount the non-line-of-sight (NLOS) constraints and severe RF attenuation typical of thick-canopy rainforests. NVIS involves transmitting signals at steep angles so they reflect off the ionosphere back to Earth over short to medium distances, an approach well-suited for terrains where direct line-of-sight is untenable. To evaluate this hypothesis, we pose one primary research question:

- **Research Question:** Can an NVIS-based HF approach outperform established IoT technologies (e.g., LoRaWAN, satellite) in dense rainforest canopies?

Beyond raw signal transmission, any solution must also balance energy efficiency, especially where frequent battery changes or solar panels are impractical under heavy canopy cover; affordability, given the limited budgets of local NGOs and community-led conservation programs; and minimal ecological disturbance, to protect sensitive habitats from infrastructure footprints. These broader requirements align with the concept of "*computing in place*" that is, embedding technology in a manner that is socio-culturally, economically, and environmentally sustainable. In practice, our system's design has been guided by ongoing consultations with DGFC staff, who provided input on hardware trade-offs, data-reporting intervals, and training protocols. This collaborative process not only ensures local rangers can deploy and maintain the system independently, but also fosters a deeper sense of ownership that may extend the long-term viability of the technology.

In this paper, we present BearWave, a communication framework leveraging NVIS propagation and the FT8 digital modulation technique to establish reliable, low-power IoT sensor networks in remote rainforest settings. BearWave's lower-frequency HF signals are comparatively resilient to heavy vegetation and atmospheric moisture, making them particularly well-suited to challenging RF conditions in places like DGFC. By marrying HF communication with compact, lightweight IoT components, BearWave aims to overcome the connectivity gaps that undermine existing technologies in thick-canopy environments. Our field results demonstrate that BearWave not only achieves robust signal penetration but also rivals or surpasses alternative IoT solutions in terms of coverage, reliability, and power usage. Ultimately, BearWave exemplifies how a socio-technical approach to computing can be sustainably integrated in remote ecological contexts, bridging environmental and technological considerations to advance conservation outcomes. The contributions of this paper are as follows:

- (1) **NVIS Framework for Dense Rainforests:** We propose a novel communication framework built around Near Vertical Incidence Skywave (NVIS) propagation, explicitly tailored to confront the radio-frequency (RF) challenges of thick-canopy habitats.
- (2) **Development and Validation of BearWave:** We develop and thoroughly evaluate the BearWave system, demonstrating robust, low-power IoT communication under severe RF constraints. Our tests quantify key metrics such as message reliability, energy consumption, and feasible coverage ranges.
- (3) **FT8 Modulation for Remote Wildlife Monitoring:** We highlight how FT8's narrow bandwidth and error-correcting capabilities achieve high message reliability and long operational lifetimes in rainforest deployments. This supports near real-time data transfer for tasks like trap monitoring and poacher detection, reducing risky manual field checks.
- (4) **Insights into Tropical RF Attenuation:** We provide empirical data on the impact of dense rainforest vegetation on signal strength, offering guidelines for designing future low-bandwidth communication systems in similarly challenging environments.

By tackling core constraints, from thick canopy attenuation and limited power availability to the absence of substantial on-site infrastructure, this research outlines a pathway toward more efficient, ethically grounded, and scalable conservation technologies. In demonstrating how NVIS-based HF communication can outperform conventional IoT protocols in humid, vegetation-rich settings, our findings establish BearWave as a promising solution for sustainable IoT deployments across diverse ecological contexts. Consequently, we show that applying a place-based, socio-technical framework enables more resilient and culturally appropriate approaches to wildlife conservation, bridging the gap between cutting-edge computing and the on-the-ground realities of rainforest ecology.

2 Related Work

This section surveys the communication technologies and research most pertinent to our NVIS-based IoT solution in dense rainforest settings. We begin with an overview of mainstream options (LPWAN, satellite, VLF), then examine prior work on NVIS, and finally discuss long-range IoT research in harsh RF conditions. We conclude by highlighting how these insights converge in BearWave's design and relate to our overarching research question.

2.1 Overview of Communication Options in Remote Areas

In remote, resource-constrained environments like the DGFC, communication infrastructure is scarce, terrain is rugged, and vegetation is extremely dense. As shown in Table 1, several widely used technologies perform well in urban settings but falter under canopy-induced signal attenuation.

Very Low Frequency (VLF) systems (around 136 kHz) have been used for Through-The-Earth (TTE) communication in mines and similarly harsh scenarios [36], but they require large antennas and significant groundwork, rendering them impractical for DGFC [11]. Mainstream solutions such as Wi-Fi or cellular networks can deliver high bandwidth but depend on robust infrastructure and clear line-of-sight, which is unworkable under thick canopies. License-free LPWAN protocols (e.g., LoRaWAN, SigFox) and licensed IoT standards (NB-IoT, LTE-M) excel in urban or semi-urban areas but struggle in canopied habitats. Many “IoT as a service” models assume resilient mesh networks, which collapse in highly isolated regions. Meanwhile, satellite-based systems (Argus, Iridium, Globalstar, Starlink) circumvent local obstructions but require high power, incur elevated costs, and still need a clear view of the sky. Consequently, they often prove infeasible for budget-constrained conservation projects.

Table 1. Comparison of communication technologies in urban vs. rainforest environments, highlighting coverage, reliability, cost, and ease of use.

Technology	Criterion	Urban Settings	Rainforest Settings
LoRaWAN	Reliability	Moderate (up to 10–15 km)	Moderate (3–5 km in dense foliage)
	Coverage	10–15 km LOS	Reduced by canopy (3–5 km)
	Setup/Costs	Low setup	Requires extra nodes for coverage
	Ease of Use	Straightforward	Challenging in dense terrain
	Env. Impact	Low power	Low power, limited range
SigFox	Reliability	Moderate (urban)	Limited in dense forests
	Coverage	Up to 50 km (rural)	2–5 km under canopy
	Setup/Costs	Low	Low
	Ease of Use	Easy	Difficult in thick vegetation
	Env. Impact	Low	Low
NVIS	Reliability	Moderate NLOS	Excellent mid-range NLOS
	Coverage	300–500 km	Ideal for 100–300 km
	Setup/Costs	Moderate (antenna)	Moderate (antenna)
	Ease of Use	Radio expertise	Radio expertise
	Env. Impact	Low power	Low power
Cellular	Reliability	High	Not applicable
	Coverage	Wide	None in dense canopy
	Setup/Costs	High	Not feasible
	Ease of Use	Very easy in cities	Inapplicable
	Env. Impact	High	N/A
Satellite	Reliability	High, global	High, global
	Coverage	Global	Global
	Setup/Costs	High fees	High fees, power
	Ease of Use	Complex	Complex in thick canopy
	Env. Impact	Higher energy	Higher energy

2.2 NVIS Overview and Prior Applications

Near Vertical Incidence Skywave (NVIS) uses HF (3–10 MHz) signals transmitted at steep angles to reflect off the ionosphere and return to Earth [33]. By circumventing the need for direct line-of-sight, NVIS can provide mid-range coverage (up to a few hundred kilometers) even through rugged terrain or thick foliage [21]. Historically, the U.S. military employed NVIS in jungle warfare, while

disaster scenarios (e.g., Hurricane Katrina) relied on HF radios once cellular towers failed [27]. In Antarctica, NVIS has enabled remote sensor data collection under extreme cold and atmospheric conditions [8].

Early NVIS deployments often used high-power voice transmissions, but recent work suggests that low-power, narrow-band digital modes can also perform well. Witvliet et al. [34] explored ionospheric probing with low-power NVIS signals, hinting at the feasibility of more IoT-focused deployments.

2.3 Long-Range IoT Systems in Dense Canopies

Long-range IoT protocols (LoRaWAN, NB-IoT, SigFox) offer promising low-power operation, but they degrade sharply in non-line-of-sight (NLOS) scenarios, exactly the situation in dense tropical forests. For example, Bor et al. [3] and Zhang et al. [38] note the steep attenuation of sub-GHz signals in heavy foliage, often requiring multiple repeaters or gateways to maintain coverage. LoRaWAN usage in Malaysia's 919–923 MHz band is similarly hindered by canopy absorption [20, 24], restricting practical distances to under 860 m in extremely dense vegetation.

Satellite IoT (Iridium, Starlink) bypasses local obstructions but is expensive and power-intensive, as shown by Gomez et al. [15]. Some projects (e.g., "Wildsensing" [10]) adopt store-and-forward data collection, which cuts energy costs but sacrifices near-real-time alerts critical for poacher detection or trap monitoring.

Unlike LoRaWAN or satellite, NVIS requires neither line-of-sight nor orbital links. Operating in the HF range, it better resists moisture and vegetation attenuation, making it particularly attractive for sites like DGFC where cost, power, and LOS constraints converge.

2.4 Communications in Harsh RF Environments

Jungle communications research dates back to the Vietnam War, highlighting how dense foliage drastically reduces HF and VHF signal range [22]. Such military studies inform modern antenna designs and frequency selection in projects like BearWave. Similarly, polar research underscores that standard HF solutions demand specialized modulation to handle extreme noise or multipath [25]. Both tropical and polar environments face limited infrastructure and harsh conditions, favouring robust, low-power HF techniques.

Digital HF protocols like FT8 [12] excel in weak-signal scenarios, using an 8-FSK scheme and occupying roughly 50 Hz of bandwidth at around 6.25 baud. This design allows decodes at SNRs down to -20 dB. Table 2 contrasts FT8's strong error resilience with higher-throughput modulations like 4QAM, clarifying why FT8 suits energy-limited rainforest IoT. By harnessing NVIS propagation and FT8's weak-signal resilience, BearWave avoids costly high-power relays or satellite terminals, offering a low-cost path to near-real-time communication in rainforest terrains.

Table 2. Comparison of FT8's 8-FSK vs. 4QAM modulation for weak-signal vs. high-throughput use cases.

Characteristic	FT8 (8-FSK)	4QAM
Modulation Type	Frequency Shift Keying	Amplitude/Phase Modulation
Number of States	8 frequency tones	4 amplitude/phase combos
Symbol Bits	3 bits/symbol	2 bits/symbol
Error Resilience	Excellent	Moderate, needs higher SNR
Spectral Efficiency	Low	High
Data Rate	~6.25 baud	Higher, depends on bandwidth
Use Case	Weak-signal IoT	Wi-Fi, 4G, etc.

In summary, off-the-shelf IoT approaches (LoRaWAN, SigFox, satellite) often falter under severe canopy attenuation, while VLF imposes large-scale antenna requirements, and store-and-forward networks lack immediate data delivery. No current system, to our knowledge, has combined NVIS propagation with a low-power, weak-signal digital mode like FT8 to enable robust, near-real-time IoT data collection in thick-canopy tropical rainforests. By merging the lessons learned from military and disaster-relief NVIS usage with modern low-power digital protocols, BearWave addresses a clear gap in the literature.

In the next section, we detail BearWave's system design and implementation, showing how these foundational insights in NVIS, weak-signal digital modes, and remote IoT technology converge to form a practical solution for wildlife monitoring and poacher detection under dense rainforest conditions.

3 BearWave Overview and Design

3.1 Design Objectives

The BearWave solution is designed to deliver a robust, cost-effective platform for transmitting IoT messages within challenging RF environments. The development and construction of a proof-of-concept demonstrator for a low-cost, narrow-bandwidth NVIS messaging system forms the foundation of this work. Built to be fully open-source in both hardware and software, BearWave empowers researchers by providing modifiable, high-quality, and affordable tools. The project creates a scalable, open-source design that enables reliable, long-distance monitoring of IoT sensors in remote and inhospitable areas. By integrating existing open-source software and accessible, low-cost hardware components, BearWave supports ease of assembly, maintenance, and deployment, helping researchers overcome the environmental and logistical challenges inherent to field-based conservation efforts.

3.2 High-Level System Design

The hardware and software components integral to the BearWave project are designed to achieve a functional, low-cost, narrow-bandwidth NVIS messaging system. Extensive research identified Near Vertical Incidence Skywave (NVIS) propagation and the FT8 communication protocol as promising approaches for enabling reliable IoT communications in challenging environments. A prototype was constructed and evaluated to determine whether NVIS could deliver the necessary coverage and signal stability for the intended application.

Initial test results validate the effectiveness of FT8 in conjunction with NVIS, demonstrating robust performance and reliability over the required distances. However, challenges such as multipath interference were observed, impacting the accuracy of signal decoding. These findings highlight the need for further investigation and potential adjustments to optimise BearWave's performance in dense and complex RF environments. Detailed insights into the hardware and software choices, as well as an assessment of the prototype's efficacy in meeting the project's objectives, are provided.

The DGFC communication system scales to support at least 20 remote nodes. For the trap monitoring solution, FT8 operates at a 5.3366 MHz suppressed carrier using a transmitter offset of up to 3200 kHz. Dividing the offsets into 50 Hz steps provides 64 channels. Transmissions occur every 15 seconds (time synchronised), with 12.97 seconds for transmission (TX) and the remainder for reception (RX). The receiver decodes the full 3200 kHz band to generate the received messages. For DGFC, a single time slot suffices for data collection from all traps, with spare capacity. For larger wireless sensor networks (WSNs), remote nodes can be split into groups and assigned transmission

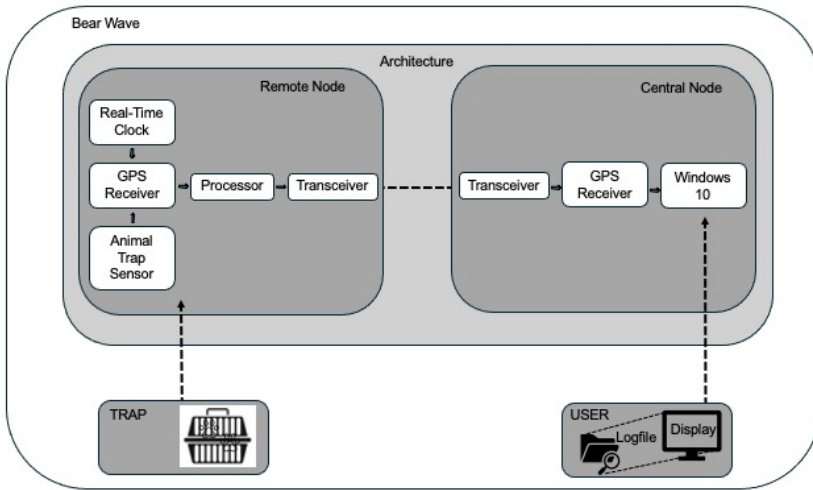


Fig. 1. Block diagram illustrating the high-level architecture of a remote node in the BearWave system. The diagram details the integration of sensors, a microcontroller, a radio module, and a power supply, highlighting the modular design tailored for low-power, scalable, and reliable IoT communications in remote and challenging RF environments.

time slots. To minimise cross-channel interference, the frequency spacing for each remote node transmission is set to 110 Hz.

The goal is to create a low cost, reliable, and scaleable system. The high-level system design is governed by a set of clearly defined requirements and critical research questions that shape both the functional objectives and the constraints of this endeavour. First, there is a need to minimise the amount of time and effort required for manual inspections, particularly in the context of animal traps deployed in remote, densely forested areas. By providing immediate, low-power wireless notification of trap activations, the system must expedite intervention and thereby improve animal welfare. Furthermore, these dense jungle environments are characterised by heavy attenuation of radio-frequency signals, an issue that necessitates the exploration of frequency bands and modulation techniques capable of sustaining reliable, non-line-of-sight communication over distances of up to twenty miles.

A parallel concern arises in the indirect detection of poachers or suspicious activities, where sensors must be discreetly integrated to provide early warnings without the need for direct interaction or line-of-sight monitoring. Achieving this requires a communication protocol that not only operates efficiently under challenging RF conditions but also adapts to event-driven data flows, enabling the system to remain largely dormant and conserve energy until triggered by a noteworthy incident.

Ensuring that the entire network remains operational in environments devoid of reliable external power sources introduces another layer of complexity. The design must incorporate energy-efficient components and strategies that extend operational life on exchangeable long-life batteries. It is therefore essential to evaluate duty cycles, sleep states, and data transfer intervals that strike an optimal balance between timely updates and prolonged battery life. Additionally, strict cost constraints influence every design decision; each node must be constructed economically, guiding

the selection of hardware, frequencies, and antenna configurations. The ultimate aim is to maintain high reliability and functional versatility at a cost low enough to facilitate large-scale deployment.

In addressing these concerns, the research also examines data integrity, message security, and parameter adaptability in the face of diurnal ionospheric variations and unpredictable environmental changes. Consequently, the high-level system design is driven by the imperative to deliver a scalable communication framework that meets the multifaceted demands of remote wildlife monitoring, balancing cost-effectiveness, technical feasibility, and ecological sensitivity.

To improve clarity and support the detailed narrative provided in the previous sections, the following decision flowchart outlines the key constraints, evaluation steps, and rationale that guided the selection of communication technologies and system components for BearWave.

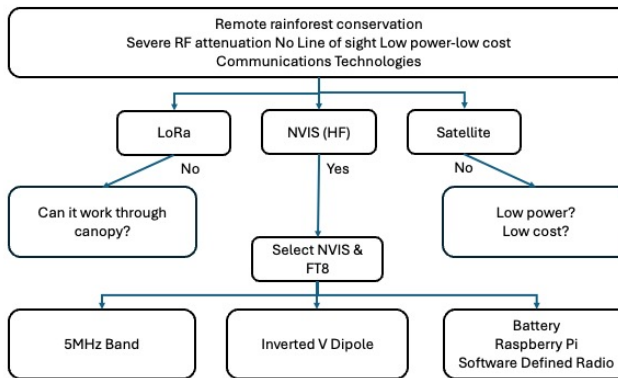
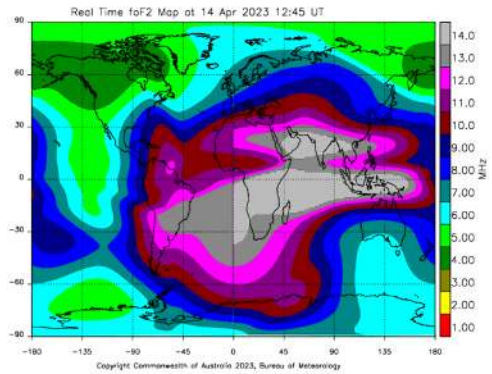
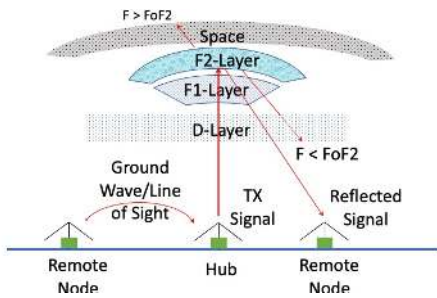


Fig. 2. Decision flowchart summarising the rationale behind BearWave’s design. Key constraints and environmental conditions are traced through a series of technology evaluations, leading to the selection of NVIS propagation, FT8 protocol, and supporting hardware.

3.3 Communications Techniques

Communication techniques are essential for enabling reliable data transmission, combining propagation methods, modulation, and transmission protocols to achieve efficient and accurate communication. Propagation focuses on how radio waves travel through different environments, such as direct line-of-sight or via reflection from the ionosphere, as seen in Near Vertical Incidence Skywave (NVIS) techniques. At the physical layer (Layer 1) of the OSI model, modulation transforms digital or analog data into a form suitable for transmission through a specific medium, such as radio waves or cables. Operating at higher layers, transmission protocols (Data Link or Network layers) structure, manage, and ensure the correct interpretation of these modulated signals between the sender and receiver. Together, these elements form the backbone of modern communication systems, enabling robust performance in diverse and challenging conditions.

3.3.1 *Propagation.* Near Vertical Incidence Skywave (NVIS) is a radio propagation technique that transmits signals nearly vertically, reflecting them off the ionosphere back to Earth. The coverage area of an NVIS signal is approximately 200 km in diameter, similar to the spot beam of an Iridium geostationary satellite [1]. The ionosphere is reflective only within certain frequency ranges, typically 1 MHz to 10 MHz. The optimal frequency for NVIS depends on atmospheric conditions, as solar activity alters the density of ionospheric layers. Frequencies are diurnal because sunlight ionises the D-layer, increasing attenuation for lower-frequency signals. The Maximum Usable Frequency (MUF) is determined by the critical frequency of the F-layer.



(a) An illustration of NVIS signal reflection off the ionosphere, highlighting its capability for short-range HF communication.

(b) A global real-time ionospheric foF2 map, showing frequency contours of the F2 layer and aiding frequency selection.

Fig. 3. Illustrations of NVIS signal propagation and ionospheric mapping, providing insights into short-range communication and frequency selection.

A literature search and technology horizon scan indicate that an off-the-shelf solution for jungle IoT sensor networks does not exist. Frequencies in the 3-10 MHz range can facilitate reliable NVIS signals, covering the DGFC. Using a frequency 15% below the Critical Frequency ensures reliable NVIS coverage. A global real-time ionospheric map (Figure 3b) from the Australian Bureau of Meteorology [23] helps determine suitable frequencies. For the DGFC, a high angle of reflection is necessary to minimise signal travel distances and reduce losses through the D-layer.

Three types of HF propagation exist: line-of-sight, ground-wave, and sky-wave:

- **Line-of-sight** propagation occurs directly between transmitter and receiver but is limited by obstacles and Earth’s curvature.
- **Ground-wave** propagation uses Earth’s surface conductivity to follow its curvature, dependent on frequency and surface characteristics [9].
- **Sky-wave** propagation reflects off the ionosphere, typically at low angles, for long-distance communication. NVIS, however, operates at near-vertical angles, making it suitable for environments where line-of-sight communication is infeasible.

While BearWave was designed as an alternative to LoRaWAN and satellite-based communication systems, the comparison presented in this work is based on expected performance constraints and analytical evaluation rather than empirical side-by-side trials. LoRaWAN’s susceptibility to attenuation in dense forest and the high power and cost requirements of satellite systems were key motivating factors in the selection of NVIS and FT8. However, future work may involve parallel

field deployments of these technologies under identical environmental conditions to provide more rigorous comparative performance data.

3.3.2 Frequency Selection. Research has identified a frequency with the best propagation characteristics for dense jungle environments. Multiple studies, including those commissioned during the Vietnam War, have examined jungle communications and the propagation of short-range radio waves at HF/VHF frequencies [2, 35]. These studies consistently demonstrate improved propagation performance at lower HF frequencies, providing valuable insights into the behaviour of the RF spectrum in dense vegetation. Antenna size is directly proportional to frequency. To ensure practicality, a careful assessment of antenna size versus usability is essential. This evaluation may necessitate a compromise in frequency selection to achieve a deployable system. For example, while Very Low Frequency (VLF) signals offer exceptional propagation characteristics, the antennas required are extremely large and challenging to deploy, making them unsuitable for this project [11].

With the most suitable frequency identified, a process of aligning the selection with the Malaysian Communications and Multimedia Commission (MCMC) band plan was undertaken to determine the nearest usable band. The MCMC oversees RF spectrum management in Malaysia, where unlicensed bands are not available. Instead, users can register for designated ‘free bands.’ In this case, the necessary licensing permitted the use of a range of frequencies under the International Telecommunication Union’s (ITU) Amateur and Amateur Satellite Service radio regulations. For the application of Near Vertical Incidence Skywave (NVIS) communication in this project, the 5 MHz band was selected for experiments. According to the MCMC band plan, the usable frequency range is 5.3515 – 5.3665 MHz [7]. Malaysia is located in ITU Region 3, where operating restrictions for this band specify a maximum radiated power of 15 W Effective Isotropic Radiated Power (EIRP). As this research focuses on low-power solutions, the system will operate with transmit powers ranging between 1 and 5 watts. The table below illustrates the UK 5 MHz frequency allocation, which was referenced for this study. The 5366 kHz band corresponds to the frequency selected for UK-based experiments [4].

Table 3. The UK 5 MHz frequency allocation table, detailing guidelines on current usage and suggested USB frequencies. This allocation provides a reference for experiments conducted as part of this research, ensuring compatibility with NVIS communication requirements and regulatory compliance.

Frequency Range (MHz)	Guidelines on Current Usage and Suggested USB Frequencies
5258.5 - 5264.0	CW activity
5276.0 - 5284.0	USB
5288.5 - 5292.0	Beacons (5290 kHz)
5298.0 - 5307.0	All Modes. USB: 5298.5 kHz, 5301 kHz, 5304 kHz
5313.0 - 5323.0	All Modes. AM: 5317 kHz. USB: 5320 kHz
5333.0 - 5338.0	USB: 5335 kHz
5354.0 - 5358.0	All Modes. USB: 5354 kHz
5362.0 - 5374.5	All Modes. USB: Weak Signal (5366.0 – 5366.5 kHz)
5378.0 - 5382.0	USB
5395.0 - 5401.5	USB
5403.5 - 5406.5	USB

This frequency selection ensures compliance with regulatory requirements while supporting efficient NVIS communication for the intended application. By operating in the 5 MHz band, this project aims to achieve reliable communication for IoT sensors in the challenging RF environment of the DGFC.

In the current implementation, frequency selection is static and fixed prior to deployment. For the field trials, all remote nodes operated at 5.3366 MHz, aligned with the MCMC-licensed 5 MHz band in Malaysia and the ITU amateur allocation. Although the central node's software-defined radio (SDR) is capable of frequency agility across the entire HF spectrum (130 kHz to 30 MHz), dynamic in-field frequency selection was not utilised in this study. This design decision was made to simplify antenna tuning and minimise deployment complexity, especially for the remote nodes. The inverted "V" dipoles used at remote sites were cut to resonate specifically at 5.3366 MHz; changing frequency significantly outside this range would require physical reconfiguration or the use of wideband matching networks. The central node employed a tri-band fan dipole covering 3.607 MHz, 5.350 MHz, and 7.070 MHz, allowing more flexibility. Future versions of BearWave may incorporate tunable or broadband antenna designs to enable dynamic frequency selection while maintaining efficient NVIS propagation.

3.3.3 Transmission Protocol. The selection of a transmission protocol is critically influenced by the chosen frequency and modulation technique. A protocol leveraging Digital Signal Processing (DSP) has been selected to ensure an optimal communication link margin, even under low signal-to-noise ratio (SNR) conditions. This decision prioritises efficient power usage and reliable data transfer, which are essential for operations in challenging RF environments. Several open-source projects offer robust foundations for the reliable transmission of small messages using low power and extremely narrow bandwidth transmissions. These protocols are designed to handle message sizes ranging from 50 to 79 bits, excluding error correction overhead. By building on these open-source foundations, the project ensures a robust and efficient communication protocol tailored to its specific requirements. The most suitable protocols available are weak signal communication packages FT8/FT4 [32], JSCALL [28], and WSPR [18]. These are open-source projects written and conceived by Joe Taylor from Princeton University and are subject to GNU public licensing.

Among the most suitable protocols identified for this purpose are FT8, JS8Call, and WSPR. FT8, short for 8-tone Frequency Shift Keying, is a highly efficient weak-signal communication protocol. It operates on a structured, time-synchronised cycle of 15 seconds for transmission and reception, with each transmission encoding 77 bits of data, including metadata, payload, and forward error correction (FEC). This structure makes FT8 an excellent choice for environments where concise, reliable messaging is required. FT4, a derivative of FT8, provides faster transmission cycles, making it suitable for higher data rates in more stable conditions. Both protocols excel in their ability to decode signals well below the noise floor, handling SNR levels as low as -20 dB, which is crucial for the dense jungle environment and during periods of high atmospheric noise or multipath interference. JS8Call, a protocol built on the FT8 foundation, extends its functionality by enabling free-form text messaging and message relaying. This added flexibility makes it suitable for applications requiring mesh networking or more complex communication scenarios. While its free-form nature introduces additional overhead compared to FT8, the robust FEC mechanisms ensure reliable performance in RF-challenged environments. JS8Call's capability to relay messages through intermediate nodes also opens possibilities for dynamic networking in future iterations of the system. The Weak Signal Propagation Reporter (WSPR) protocol offers another valuable tool in this context. Primarily designed for beaconing applications, WSPR excels at monitoring propagation conditions and identifying optimal frequencies for communication. Although it is not intended for general message-passing purposes, its low power consumption and narrow bandwidth characteristics make it an important ancillary tool for propagation analysis and system calibration.

For the BearWave system, FT8 has been selected as the primary protocol due to its balance of efficiency, reliability, and suitability for short, structured telemetry messages. Its ability to operate effectively in low SNR environments, combined with its robust DSP-based decoding, ensures

FT8 Transmission Components

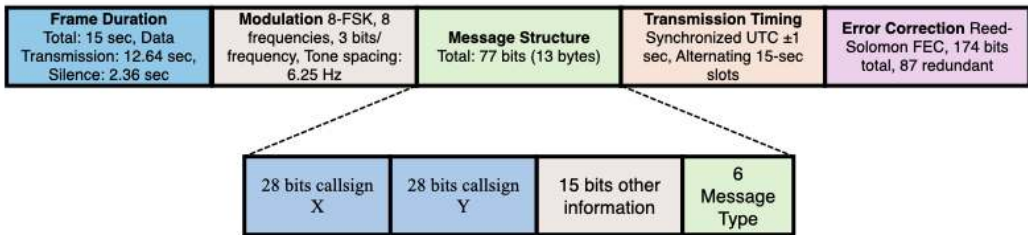


Fig. 4. The FT8 message structure, detailing its 77-bit composition, including metadata, payload, and forward error correction (FEC). This efficient design enables reliable communication in low signal-to-noise ratio (SNR) environments, making it a core component of the BearWave system for transmitting critical telemetry data.

dependable performance even in dense jungle terrains. The structured nature of FT8 makes it particularly effective for transmitting critical trap status updates and telemetry data. While FT8 serves as the backbone of the communication system, future iterations may integrate features of JS8Call to explore mesh networking and dynamic message relaying. Similarly, WSPR could be employed as a supplementary tool for evaluating propagation conditions and optimising the system’s frequency and timing parameters. By leveraging these established open-source protocols, the BearWave system benefits from a high degree of reliability, flexibility, and community support, ensuring effective communication in some of the most challenging RF environments.

3.3.4 Modulation. The choice of modulation is fundamentally influenced by the frequency selection and the need for reliable performance in weak signal and fading environments. Traditional modulation techniques, such as Amplitude Modulation (AM), Frequency Modulation (FM), and Single Side Band (SSB), can be readily discounted for this application due to their poor spectral efficiency. For the specific demands of this research task, a low-bandwidth digital modulation technique has been identified as the most appropriate. Among the available options, Princeton University’s FT8 protocol, utilising 8-Frequency Shift Keying (8-FSK), is particularly well-suited to the communication challenges of the dense jungle environment. Low-bandwidth digital modulation techniques, such as Weak Signal Propagation Reporter (WSPR) and Frankie Taylor 8 (FT8), are designed to perform effectively under conditions of high signal attenuation and significant noise. These protocols offer remarkable signal-to-noise ratio improvements compared to traditional communication methods, making them ideal for harsh RF environments. Specifically, FT8 achieves reliable communication at an SNR as low as -21 dB, while WSPR extends this capability to -31 dB. In contrast, conventional Single Side Band (SSB) Voice requires an SNR of at least +10 dB. The superior noise resilience of FT8 makes it the preferred modulation choice for this project, offering a practical balance of data throughput and environmental robustness. FT8 employs 8-frequency Gaussian Frequency Shift Keying (8-GFSK) modulation, occupying a narrow 50 Hz bandwidth. It encodes data into eight tones, each spaced at 6.25 Hz, and operates on a precisely time-synchronised 15-second transmission cycle [29]. The protocol incorporates a text compression and encoding mechanism, converting user-defined messages into a 77-bit word for transmission. This structure ensures efficient and reliable data encoding within the constraints of the available bandwidth.

For the purposes of this research, the standard FT8 protocol will be modified to support be-spoke messaging requirements. These modifications will include the encoding of essential trap information, such as trap ID, GPS location coordinates, and activation timestamps, into the FT8

data block. Additionally, the protocol will be adjusted to allow for automated communication, a feature not supported under the standard FT8 operational guidelines. The foundational work for these customisations draws on the functionalities already implemented in JS8Call, an extension of the FT8 protocol designed for more versatile messaging. By leveraging the capabilities of JS8Call and integrating the Tripnology API, this project enables seamless control of message composition, transmission, and decoding. These enhancements ensure that the BearWave system delivers the reliable, low-power communication needed to monitor and manage traps in the challenging RF environment of the DGFCX DGFCXX Field Centre.

3.3.5 Energy Efficiency Considerations. In the context of immediate improvements to energy usage, the system can benefit from incorporating advanced power management algorithms and optimising duty cycles. By intelligently scheduling sensor wake-up times and transmission intervals, overall power consumption can be reduced, thereby extending operational life without frequent battery replacements. Additionally, fine-tuning parameters such as transmit power levels, antenna orientation, and data compression can further conserve energy. These design considerations focus on adjustments that can be implemented with existing hardware and software, leveraging low-power modes and intermittent operation. Integrating stable energy sources suitable for the environment (e.g., exchangeable long-life batteries) and improving hardware efficiency through higher-quality DC-DC converters are also practical steps. These changes can be actioned immediately to enhance overall efficiency without requiring radical architectural modifications.

3.4 Hardware Components

The BearWave system employs a carefully designed hardware configuration to enable robust, low-power, and reliable communication for IoT applications in challenging environments. The hardware includes a transmitter, processor, timing modules, and power management components, all selected to ensure seamless operation under the demanding conditions of the DGFC. The design emphasises simplicity, cost-effectiveness, and scientific adaptability while providing the foundation for long-term deployment in remote and RF-challenging environments.

3.4.1 Transmitter. The transmitter is a critical component of the BearWave system, chosen for its compact design, efficiency, and frequency stability. The QRPGuys DSB Digital Transceiver II module forms the basis of the design, modified to operate within the 2–8 MHz range. Custom modules were developed to support 5 MHz operation, the frequency used for NVIS propagation experiments. The transceiver is configured to transmit at 1 watt, balancing power consumption with communication reliability. Its design includes a crystal-controlled oscillator for frequency stability, ensuring consistent operation in field conditions. For experimental purposes, a Variable Frequency Oscillator (VFO) based on the Si5351A Phase-Locked Loop integrated circuit has been added, allowing for flexible frequency adjustments during testing. Operating from a 12V supply, the transceiver draws 15mA in receive mode and 350mA during transmission, supporting energy-efficient, long-term use in remote deployments.

3.4.2 Processor and Control Unit. The Raspberry Pi 4 serves as the central processor for the system, providing a versatile and low-cost platform for managing communication protocols and processing tasks. The device is equipped with 4GB of RAM and a 16GB flash card, running the Raspbian OS to ensure compatibility with the project's software requirements. Given the absence of analogue audio input on the Raspberry Pi, an external USB sound card is employed to process baseband signals from the transceiver. To ensure precise time synchronisation, essential for protocols like FT8, the system integrates a VK-162 USB GPS receiver and a DS3231 Real-Time Clock (RTC) module. The GPS receiver provides accurate time and location data, even under dense canopy conditions,

while the RTC ensures timing accuracy during power interruptions. Thermal management is addressed through a passive aluminium heatsink case, which prevents thermal throttling under high ambient temperatures. The processor is powered by a 5V supply derived from a 12V battery via a high-efficiency DC-DC converter, ensuring stable and reliable operation.

3.4.3 Timing and Synchronisation. Accurate timing is fundamental to the system's operation, particularly for protocols requiring synchronised transmissions. The DS3231 RTC module offers ± 5 ppm accuracy, maintaining precise timekeeping with minimal drift. The VK-162 USB GPS receiver further enhances synchronisation, supporting rapid start times and maintaining accuracy under dense foliage, which is critical in the forested terrain of the DGFC. These components ensure the system operates reliably even in adverse conditions.

3.4.4 Power Management. The system employs a high-efficiency DC-DC converter to step down the 12V supply from the battery to 5V for the Raspberry Pi and other components. This converter achieves 96% efficiency and provides robust protections against overvoltage, overcurrent, overheating, and short circuits. Encased in waterproof housing, it ensures reliable performance in the humid and challenging conditions of the rainforest.

3.4.5 Central Node Transceiver. For the central node, the Hermes Lite 2 software-defined radio (SDR) transceiver has been selected for its frequency agility and ability to accommodate NVIS diurnal shifts. This open-source SDR covers a frequency range from 130 kHz to 30 MHz and provides a 5-watt output. Its capability to support up to seven virtual receivers allows simultaneous monitoring of multiple channels, enhancing the system's scalability. The Hermes Lite 2 connects to the control unit via Ethernet and operates on a 12V, 2A supply, ensuring compatibility with the overall power management system.

3.5 Antenna Design

An effective antenna is crucial for optimising NVIS communication. The performance of an NVIS system depends heavily on the antenna's ability to produce a high-angle radiation pattern, ensuring that signals are transmitted nearly vertically and received reliably within the intended coverage area. The design and deployment of the antenna significantly influence signal strength, efficiency, and overall reliability of the communication link.

An optimal NVIS antenna design must prioritise the following factors:

- **Radiation Pattern:** The antenna must generate a strong, vertically focused radiation pattern to ensure the signal reaches the ionosphere at the correct angle for reflection.
- **Height Above Ground:** NVIS antennas are typically placed relatively low to the ground, often between 0.1 and 0.25 wavelengths, to achieve the desired high-angle radiation.
- **Portability:** For use in rainforest environments, the antenna must be low-cost, portable, easy to carry, and simple to erect, ensuring rapid deployment in challenging conditions.
- **Impedance Matching:** Proper impedance matching between the antenna and the transmitter is critical to maximise power transfer and minimise signal loss during transmission and reception.

The most commonly used NVIS antenna is the inverted "V" dipole, known for its simplicity, ease of deployment, and effectiveness in generating the required high-angle radiation pattern. When positioned close to the ground, this antenna alters its gain and signal patterns, creating a vertically focused lobe. The slope of the "V" affects the angle of incidence for the transmitted signal. Adding a perpendicular dipole to form a turnstile antenna can improve performance by compensating for phase shifts in the received signal. These phase shifts occur as the wave reflects off the ionosphere, causing a 90-degree phase shift. Additionally, the planet's rotation introduces a Doppler effect,

further influencing the received signal. Both phenomena significantly impact the choice of antenna design. Despite its sensitivity benefits, a turnstile antenna was not selected for this application to minimise size and simplify the jungle deployment setup. Instead, an inverted "V" dipole is preferred due to its practicality and reliability. The angle of incidence is also critical, as it determines the footprint of the reflected wave. To minimise the skip zone, this angle typically ranges from 70° to 90°. For this experiment, a nearly vertical angle of 90° is chosen, as the remote and control nodes are less than 20 miles apart [16]. During the field trials, two different inverted "V" antennas will be employed. While both designs are based on the same principle, the jungle-deployed antenna will feature a simplified structure for easier erection and deployment in dense rainforest conditions.

The central control node at DGFC employs a tri-band fan dipole antenna, designed to efficiently operate at the three NVIS bands selected for this experiment: 3.607 MHz, 5.350 MHz, and 7.070 MHz. The fan dipole structure incorporates three resonant elements, each tuned to one of the target frequencies, enabling multi-band operation. The longest element, resonant at 3.607 MHz, measures approximately 19.605 metres, and the overall antenna span is around 42 metres when deployed. The antenna is supported at its centre by a telescopic aluminium pole, with the ends positioned 1.5 metres above the ground. A 50Ω feed line using RG56 coaxial cable connects the antenna array to the control node receiver. The antenna is designed to accommodate a frequency deviation of ±2%, providing flexibility to avoid interference during operation. This multi-band fan dipole offers low impedance at its resonant frequencies while maintaining high impedance out of band. This configuration ensures minimal mutual interference between elements. Construction follows the guidelines from the Stanford Research Institute's "A Field Guide to Simple HF Dipoles" [6].

- Lowest Frequency (3.607 MHz):

$$\text{Wavelength, } \lambda = \frac{C}{f} = \frac{299,792,458}{3,607,000} = 81.687 \text{ m}$$

$$\text{Element Length} = 0.96 \times \frac{\lambda}{4} = 19.605 \text{ m}$$

- Centre Frequency (5.350 MHz):

$$\text{Wavelength, } \lambda = \frac{C}{f} = \frac{299,792,458}{5,350,000} = 56.036 \text{ m}$$

$$\text{Element Length} = \frac{\lambda}{4} = 14.009 \text{ m}$$

- Highest Frequency (7.070 MHz):

$$\text{Wavelength, } \lambda = \frac{C}{f} = \frac{299,792,458}{7,070,000} = 42.404 \text{ m}$$

$$\text{Element Length} = 1.01 \times \frac{\lambda}{4} = 10.707 \text{ m}$$

In a field deployment, the aluminium pole used to support the dipole can be replaced with a tree branch, simplifying setup in forest environments. The ends of the antenna are positioned to maintain clearance from dense vegetation, minimising ground and foliage interference. The dipole design ensures resonance at 5.3366 MHz for this experiment. Each leg of the dipole measures 13.365 metres, with a span of approximately 25 metres and 1.5 metres above ground. These parameters optimise NVIS propagation while balancing portability and ease of deployment. While other antenna designs, such as magnetic loops or circularly polarised Yagi antennas, were considered, they were deemed impractical for this project due to their size and complexity. The fan dipole's simplicity, effectiveness, and suitability for the 5 MHz band made it the optimal choice for this application.



(a) Inverted “V” dipole antenna, designed for multi-frequency operation at 3.607MHz, 5.350MHz, and 7.070MHz.

(b) SWR plot of the multiband inverted “V” dipole, indicating resonance at 3.607MHz, 5.350MHz, and 7.070MHz for NVIS applications.

Fig. 5. The inverted “V” dipole antenna design and SWR performance, showcasing its efficiency and ease of deployment in jungle environments.

This configuration demonstrates an ideal balance of performance, cost, and practicality, making it highly suitable for the DGFC’s operational requirements.

The remote node antenna must balance efficiency, portability, and ease of deployment in the challenging jungle environment. Two design options were considered for this purpose:

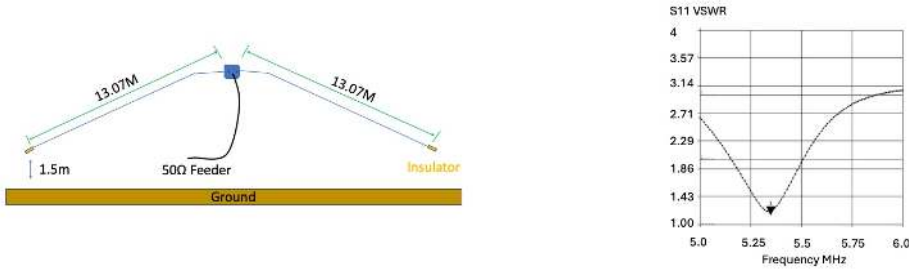
Option 1: Single-Frequency Inverted “V” Dipole. This design offers simplicity, compactness, and efficiency, making it a practical choice for the remote node. The antenna is resonant at 5.3366 MHz, with each leg measuring 13.365 metres. The ends of the dipole are positioned approximately 1.5 metres above the ground and span roughly 25 metres. A centre 50Ω RG56 coaxial cable connects the antenna to the transmitter. The inverted “V” configuration allows for easy support using a tree branch, removing the need for additional poles or complex structures. This approach ensures that the antenna is specifically tuned to its operating frequency, maximising its performance in a compact and portable form.

Option 2: Multi-Band Antenna. A fan-style dipole similar to the central node could be used, capable of covering all required frequencies. While efficient, this design is cumbersome to erect and requires significantly more space, posing logistical challenges in a dense jungle setting. Based on these considerations, the single-frequency inverted “V” dipole was selected for its balance of efficiency, portability, and adaptability to the jungle environment.

Impact of Inverted “V” Design: An inverted “V” configuration lowers the resonant frequency compared to a horizontal dipole of the same length, resulting in the radiator length being approximately 5% shorter than a traditional horizontal dipole at the same frequency [19]. This adjustment ensures optimal performance without requiring additional space or structural complexity.

Antenna Construction Parameters: The following table summarises the dimensions and setup requirements for dipoles resonant at three frequencies. These calculations account for the 5% reduction in length due to the inverted “V” configuration.

Tuning and Deployment: The antenna was tuned using a Vector Network Analyser (VNA) to ensure resonance at 5.3366 MHz. Deployment is straightforward, requiring only a suitable tree branch to support the apex. This practical setup minimises logistical challenges and ensures reliable operation in a dense forest environment. The combination of compact design, single-frequency tuning, and ease of deployment makes the inverted “V” dipole an ideal choice for the remote node antenna. While less flexible than multi-band designs, its simplicity and reliability are critical advantages in challenging jungle conditions.



(a) Inverted “V” dipole antenna, designed for single-frequency operation at 5.3366 MHz. (b) SWR plot of the inverted “V” dipole, indicating resonance at 5.3366 MHz for NVIS applications.

Fig. 6. The inverted “V” dipole antenna design and SWR performance, showcasing its efficiency and ease of deployment in jungle environments.

Table 4. A table summarising the construction parameters of NVIS dipole antennas across three frequencies. It includes radiator lengths, minimum central heights, and horizontal spreads for optimising NVIS communication.

Frequency (MHz)	Radiator Length (m)	Minimum Central Point Height (m)	Minimum Horizontal Spread (m)
3.6070	19.38	7.26	35.94
5.350	13.07	4.89	24.22
7.070	9.89	3.70	18.34

While the total length of the inverted "V" dipole used in BearWave is approximately 28–30 meters (tip to tip), this does not correspond to vertical height. The center of the antenna is typically hoisted into a tree branch at a height of only 4 to 7 meters above ground level, with the wire legs sloping downward and anchored to the forest floor. This setup operates well below the rainforest canopy, which at the DGFC typically ranges from 30 to 50 meters in height, with emergent trees reaching 60 meters or more. As such, mounting equipment above the canopy for satellite, WiFi, or LoRaWAN communication is not feasible and is not compatible with rapid, low-impact deployment in conservation contexts. The BearWave system was explicitly designed to avoid the need for line-of-sight or elevated infrastructure by leveraging NVIS propagation, which allows reliable long-range communication under dense canopy without breaching the forest structure.

3.6 Software Stack

The BearWave system leverages a suite of open-source software tools to provide a robust, reliable platform for weak-signal communication in challenging RF environments. These software solutions are designed to optimise communication performance, enhance signal integrity, and ensure precise time synchronisation. The chosen software also supports flexible message handling and automation, making it suitable for the unique demands of the DGFC.

3.6.1 Operating System and Software Framework. The processor runs on Raspberry Pi OS, a light-weight operating system derived from Debian Linux and optimised for Raspberry Pi hardware. Its support for Advanced Package Tool (APT) and GPIO interfaces ensures seamless integration

with the system's hardware components. The OS serves as a stable foundation for deploying the software tools critical to the system's operation.

3.6.2 SparkSDR for SDR Control. SparkSDR is the software chosen to control the central node's Hermes Lite 2 software-defined radio (SDR). This cross-platform application is specifically designed for Hermes Lite and Open HPSDR-compatible radios. SparkSDR offers advanced digital signal processing (DSP) capabilities, including noise reduction, automatic gain control, and power output level adjustment. Its ability to manage multiple virtual receivers simultaneously enhances the system's scalability and efficiency, allowing various communication channels to operate concurrently. Although SparkSDR supports numerous built-in modulation techniques, such as FT8 and WSPR, the BearWave system employs external tools for fine-grained modulation control. SparkSDR integrates seamlessly with JS8Call via virtual audio routing, facilitating efficient and automated message decoding.

3.6.3 FT8 and JS8Call for Digital Communication. The FT8 mode, developed by Joe Taylor and his team at Princeton University, is a digital communication protocol that excels in weak-signal environments. FT8 employs an 8-tone frequency shift keying (8-FSK) modulation scheme and occupies a narrow 50 Hz bandwidth. With a 15-second transmission cycle and robust forward error correction (FEC), FT8 decodes signals with signal-to-noise ratios as low as -20 dB. These characteristics make it ideal for the low-bandwidth, high-reliability requirements of the BearWave system. JS8Call, a fork of the WSJT-X software suite, builds upon FT8 to enable more flexible and detailed messaging. While FT8 prioritises concise telemetry, JS8Call supports free-form text messages, making it suitable for scenarios requiring more extensive communication. JS8Call also features strong FEC and mesh networking capabilities, enhancing its utility in disrupted and attenuated signal environments, such as dense rainforests. For the BearWave system, JS8Call is initially employed for testing and evaluation purposes, with plans to modify FT8 for optimised IoT communication. JS8Call is a derivative of the WSJT-X application, restructured and redesigned for message passing using a custom FT8 modulation technique called JS8. While the WSJT-X group maintains copyright over the original work and code, JS8Call is a derivative work licensed under and by the terms of the GPLv3 license. The source code modifications are public and can be found in the JS8call branch of the repository [17]. @trippnology-js8-cli v1.2.5 is a program that is a command line interface wrapper for lib-js8call. This allows messages to be sent and received using JS8Call's JSON API, allowing full automation for trap monitoring messages [30].

3.6.4 GPS2Time for Synchronisation. Precise time synchronisation is essential for the FT8 protocol and its derivatives. The GPS2Time software leverages GPS signals to synchronise system clocks with high accuracy, often within milliseconds. Regular synchronisation ensures that transmissions remain aligned with the 15-second FT8 cycle, maximising communication reliability in adverse RF conditions.

3.6.5 Audio Routing with VB-Audio. VB-Audio virtual cable software is used to route audio signals digitally between applications, eliminating the need for multiple physical audio interfaces. This capability simplifies the system architecture by enabling multiple virtual transceivers to connect with JS8Call instances. VB-Audio's efficient management of audio routing enhances the system's flexibility and scalability, crucial for handling complex communication tasks.

4 Methodology

4.1 Study setup

Experimental configuration in UK woodlands as a case study: The UK field trials are designed to rigorously test the hypothesis that a Near Vertical Incidence Skywave (NVIS) signal can reliably transmit trap status information across an area approximating a 200-kilometre radius, simulating the challenging conditions of the DGFC rainforest. These trials aim to evaluate the performance, reliability, and feasibility of the BearWave system, focusing on message propagation through dense canopy analogues, atmospheric reflection reliability, and centralised reception.

The experimental setup has been designed to assess the effectiveness of NVIS propagation under variable environmental conditions. Key factors, including diurnal atmospheric changes, ionospheric dynamics, and environmental moisture levels, will be closely monitored throughout the trials. These variables are critical in determining NVIS signal efficacy, as they directly influence reflection efficiency and signal attenuation. The trials employ a transmission frequency of 5 MHz, consistent with the NVIS band, with a low power output of 1 Watt per transmission. Messages will be transmitted every 15 minutes, ensuring a high-frequency dataset for comprehensive analysis while minimising energy consumption.

Each trial transmission consists of a controlled test signal, and data collection at the central node includes timestamped logs of signal strength, reception quality, and message integrity. Synchronisation of all units to GPS time ensures precise temporal alignment, enabling accurate correlation of data across test sites. The trial duration is set for seven consecutive days, capturing diurnal variations in atmospheric conditions and providing a robust dataset for statistical evaluation.

Three remote locations have been strategically selected to replicate geographical diversity and the absence of line-of-sight communication paths to the central node. These locations emulate the environmental and operational challenges of the DGFC, requiring exclusive reliance on NVIS propagation rather than ground wave transmission. The selected sites exhibit variations in canopy density, topographical features, and potential local interference sources, enabling the comprehensive evaluation of system performance across diverse conditions.

4.2 Health and Safety

The BearWave system adheres to the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines [13], which stipulate safe levels of RF electromagnetic field (EMF) exposure. The frequencies and power levels utilised in this experiment are well within these guidelines. Specifically, the average power in the frequency band being used does not exceed 10 W, with peak power limited to a maximum of 100 W EIRP. The transmitters employed in the system are designed with a maximum output of 5 W, ensuring that even in the event of system failure, the exposure levels remain compliant [39]. These measures reflect a commitment to ensuring the safety of both researchers and the surrounding environment during all phases of the project.

4.3 Remote Node Configuration

The remote site setup has been carefully designed to withstand the challenging conditions of forested environments, including exposure to rain and potential insect ingress. The remote trap module is securely housed within a ruggedised Peli 1400 case, providing a robust and reliable enclosure for its components. The interior contains a transceiver, a Raspberry Pi with an attached USB audio card, a real-time clock (RTC), a GPS module, and a battery equipped with a 12V-to-5V DC-DC converter for power regulation. To facilitate field testing, a screen is included within the setup, alongside a protected BNC antenna connection to ensure stable and uninterrupted signal transmission in adverse conditions.



Fig. 7. Remote node test setup housed in a ruggedised Peli 1400 case, featuring a transceiver, Raspberry Pi, GPS module, real-time clock, and 12V lead-acid battery. This configuration ensures durability and reliable operation in forested environments.

The remote nodes were configured to operate continuously during the trial period, omitting power-saving mechanisms to allow for a comprehensive mapping of ionospheric conditions and their impact on IoT message reliability. Each node transmitted a message every 15 minutes, enabling a detailed temporal analysis of signal reception patterns under varying environmental and atmospheric conditions. A large 12V lead-acid battery was employed to ensure uninterrupted operation of the remote nodes throughout the testing phase. While this choice was practical for these controlled trials, it is recognised that future deployments in the Bornean rainforest will necessitate the integration of advanced power-saving techniques and more portable energy solutions to align with the environmental and logistical constraints of fieldwork. This deliberate omission of power-saving measures in the trials was intended to isolate and evaluate the performance of the messaging system under optimal power conditions, providing baseline data for subsequent refinements.

4.4 Central Node Configuration

The central receiving station for the UK trials is strategically located in Skenfrith, chosen for its central position relative to the remote sites. This centralised location facilitates efficient data aggregation and automation of the experimental process. The receiving node mirrors the setup anticipated for the DGFC, including the benefit of continuous mains power. This eliminates energy constraints and ensures the system's reliability during prolonged testing periods. The core components of the receiving station include a Software-Defined Radio (SDR), a multiband antenna, and a laptop computer with sufficient processing power to handle data decoding and logging. The use of less energy-efficient but more powerful components enables continuous operation and provides the flexibility necessary for comprehensive testing. Additionally, the setup incorporates automatic logging of all incoming messages, mitigating the risk of data loss or human error.

To enhance system resilience, data received at the central node is automatically synchronised with a cloud storage solution, ensuring redundancy and accessibility. As precise timing is critical to the system's operation, the central node is equipped with a real-time clock (RTC) to maintain synchronisation during periods of GPS unavailability. This design ensures high levels of reliability and accuracy, even in the presence of environmental or technical disruptions. By addressing the unique requirements of both the remote and central nodes, this setup ensures a robust and scientifically rigorous framework for evaluating the BearWave system in conditions simulating the challenges of the DGFC environment.

The central node was strategically established in Skenfrith to provide an optimal location for signal reception and system testing (refer to Figure 1 for the geographical map). A multiband inverted 'V' antenna was deployed, adhering to the design specifications intended for the eventual jungle deployment. The antenna's central feed point was elevated approximately 10 metres above ground level, with the legs positioned at 1.5 metres above the surface to replicate the planned setup near the DGFC in Borneo. This setup was situated in a clearing adjacent to a small wooded area to simulate similar environmental conditions. The central node utilised the Hermes Lite Software-Defined Radio (SDR) system, operating in conjunction with JS8Call software for automated signal reception and logging. The system was powered by a reliable mains electricity supply, enabling continuous operation throughout the trial period. Upon successful receipt of a heartbeat signal from any remote node, the central node transmitted an acknowledgment using a 5-watt signal. The availability of a permanent power source at this location ensured that power constraints did not influence the experimental outcomes, allowing for uninterrupted logging of received signals and acknowledgments.

4.5 Analytical Methods

The analytical methods in this study focused on quantifying how ionospheric conditions and environmental variables affected NVIS communication performance. Using UK field-trial data, we compared received signal strength, message completion rates, and error-corrected integrity across different times of day, weather conditions, and vegetation densities.

Data processing involved logging timestamps, signal-to-noise ratios, and reception quality. Correlation analyses identified whether signal-strength variations matched diurnal ionospheric cycles, while statistical tests confirmed significant performance changes. Cross-referencing temperature and rainfall data revealed whether moisture and canopy wetness affected communication reliability. This approach isolated anomalous events, clarified persistent trends, and built a baseline of how the NVIS-based system coped with rainforest-like conditions.

Both quantitative and qualitative methods evaluated RF performance and network reliability, focusing on indicators like RSSI, bit error rates, and message completion percentages. Measurements were gathered over multiple days and sites to ensure system robustness under diverse environments. By mapping humidity, temperature, and rainfall against performance, thresholds emerged beyond which signal degradation rose. Prolonged rainfall and high atmospheric noise correlated with weaker reception, while clear nights often yielded stronger ionospheric reflection.

Reliability assessments examined raw message success rates and decoding errors to pinpoint conditions that predispose interference. Findings guided power-consumption strategies and duty-cycle optimisation, shaping a holistic view of real-world performance. Consequently, the analysis offers a rigorous foundation for improving frequency selection, protocol design, and energy management.

By linking performance metrics to physical and environmental factors, this study shows that NVIS can remain dependable under complex conditions. Ongoing refinements informed by these insights will further adapt the technology to demanding ecological scenarios, supporting long-term,

Table 5. Summary of the 1-week experimental setups across three locations: Belpa Farm, Clydach, and Brockweir Wood. Key attributes include location coordinates, distances, antenna configurations, and power sources, simulating field conditions for NVIS communication evaluation.

Attribute	Experiment 1	Experiment 2	Experiment 3
Location	Belpa Farm, Herefordshire 51.52141, -2.663536	Clydach, Welsh Valleys 51.80988, -3.11690	Brockweir Wood, Wye Valley 51.709262, -2.663536
Distance	12 km (as the crow flies)	19.7 km (as the crow flies)	22 km (as the crow flies)
Antenna Setup	Single-band 5 MHz antenna, supported by trees in dense wood	Single-band 5 MHz antenna, supported by trees in dense wood	Single-band 5 MHz antenna, supported by trees in dense wood
Power Source	12V lead-acid battery	12V lead-acid battery	12V lead-acid battery

sustainable communications. This analysis underpins a flexible communication framework capable of withstanding the unpredictable nature of remote field conditions.

4.6 Evaluations and Results

The field trials were conducted using the hardware and software configurations described in earlier sections. Each remote node was equipped with a QRPGuys Digital Sideband Transceiver configured to operate at 1 watt on the 5.3377 MHz frequency, along with a Raspberry Pi 4 running the JS8Call software. These components, described in the Hardware and Software Sections, were integrated into a robust setup designed for reliable field deployment.

The single-band 5 MHz antenna, used for all remote nodes, was installed in a dense wooded area and supported by tree branches to simulate the conditions expected in the Bornean rainforest. A large 12V lead-acid battery powered each remote node to ensure continuous operation throughout the trials. The central receiving station, located in Skenfrith, featured a multiband inverted "V" antenna with its centre elevated 10 metres above the ground. The antenna, described in Section Z, was situated in a clearing on the edge of a small wood to replicate its planned deployment near the DGFC. The Hermes Lite 2 Software-Defined Radio (SDR) was used as the central receiver, connected to a laptop running JS8Call software for continuous signal monitoring and automated logging.

Table 5 summarises the key attributes of the experimental setup across three distinct remote locations, selected for their varying distances and environmental conditions. These trials aimed to evaluate the reliability of the NVIS propagation phenomenon and the BearWave system's ability to transmit IoT messages over a 200-kilometre radius under conditions mimicking the target deployment environment.

The central node operated continuously, sending confirmation responses at 5 watts upon receipt of a heartbeat signal. Remote nodes transmitted a test message every 15 minutes to evaluate signal stability and reception reliability. This configuration ensured a rigorous assessment of the system's performance under varying diurnal and environmental conditions, reflecting the challenges anticipated in the DGFC deployment. Each experimental sequence began with a 24-hour trial period to establish baseline system functionality. This was followed by a continuous 7-day operational phase to evaluate the system's reliability under prolonged use. A test heartbeat message, consisting of a 5-character identifier and a 7-character message, was transmitted at 15-minute intervals. These messages were received by a central station equipped with automated logging capabilities. The data collected included parameters such as time of receipt, signal strength, identifier, location,

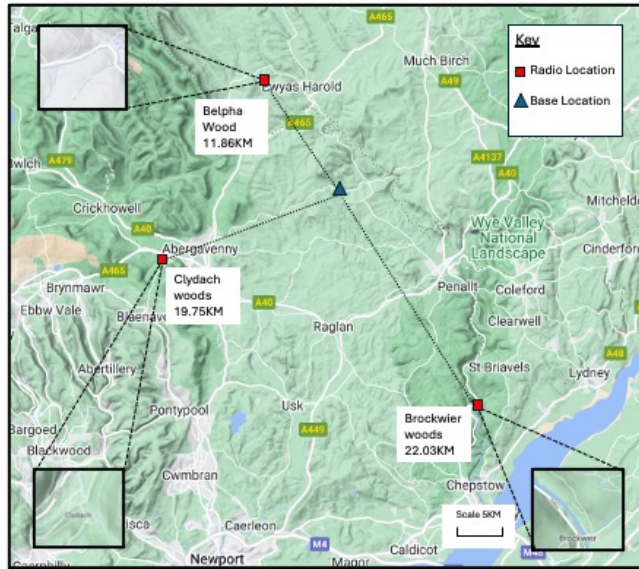


Fig. 8. Map showing the UK trial locations: Belpha Farm, Clydach, and Brockweir Wood. These sites were chosen for their varied distances and environmental conditions, providing a comprehensive evaluation of NVIS communication performance.

and message content. This systematic approach ensured that all relevant performance metrics were captured for subsequent analysis, providing a robust dataset to assess the BearWave system’s performance in conditions emulating those of the Bornean rainforest.

Data collection in this study centres on the periodic transmission of sensor-derived information from remote nodes to the central receiving station. Drawing upon the messaging protocols developed during the initial design phase, each sensor node generates and encodes data related to trap activity, environmental conditions, and system health. This approach was informed by earlier considerations regarding the most efficient means of transferring critical information—drawn partly from the future-focused messaging strategies discussed in the design and implementation stages—and guided by the technical constraints outlined in the hardware and software configurations.

At regular intervals determined during preliminary testing, the remote nodes activate and transmit compact data packets, ensuring that essential metrics are conveyed without unnecessarily consuming power. These intervals were chosen to strike a balance between timely updates and energy conservation, reflecting the operational duty cycles and low-power states refined throughout the development process. Depending on the sensor type and immediate conservation priorities, data messages may include indicators of trap status, battery voltage, and signal quality, as well as any relevant environmental parameters recorded by the deployed hardware. All data are received and logged automatically by the central node’s software stack, which records not only the content of the messages but also metadata such as signal strength, time of arrival, and decoding reliability. These details allow the research team to correlate environmental factors and network performance with actual data throughput, enabling subsequent assessment of robustness, responsiveness, and energy efficiency. Informed by initial setup trials and interim results, this iterative data collection scheme ensures that the communication framework remains closely aligned with the overarching research objectives while accommodating the evolving conditions of the field environment.

Table 6. Summary of experimental results across three locations: Belpa Farm, Clydach, and Brockweir Wood. The table highlights distances, weather conditions, and high message reliability rates, demonstrating the effectiveness of NVIS communication for IoT data transmission.

Attribute	Experiment 1	Experiment 2	Experiment 3
Location	Belpa Farm, Herefordshire (51.52141, -2.663536)	Clydach, Welsh Valleys (51.80988, -3.11690)	Brockweir Wood, Wye Valley (51.709262, -2.663536)
Distance	12 km	19.7 km	22 km
Duration	16–23 June	26 June–4 July	4–11 July
Weather	Temp: 7–27°C, Avg. rainfall: 4.8 mm (2 days)	Temp: 11–21°C, Avg. rainfall: 2.8 mm/day	Temp: 9–20°C, Avg. rainfall: 7.9 mm/day
Results	672 sent, 655 received (97%)	672 sent, 625 received (93%)	672 sent, 634 received (94%)

All measurements, data collection and analysis scripts used to compute message delivery statistics and SNR trends are available in our public GitHub repository [5]. This supports full transparency and reproducibility of the performance evaluation.

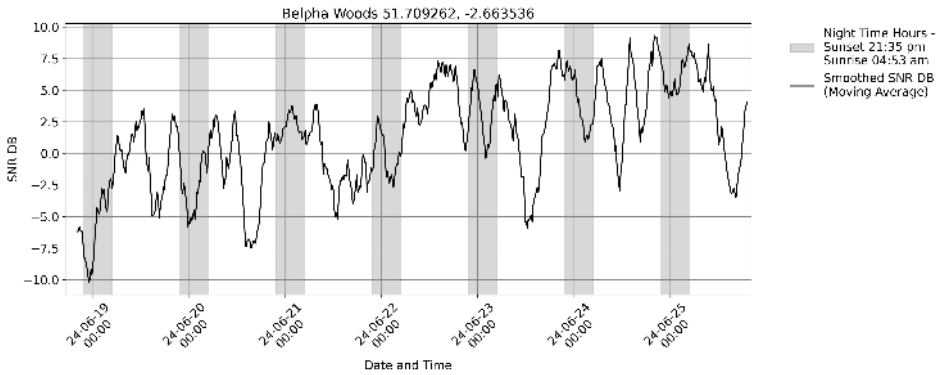
5 Results and Discussion

5.1 System Performance

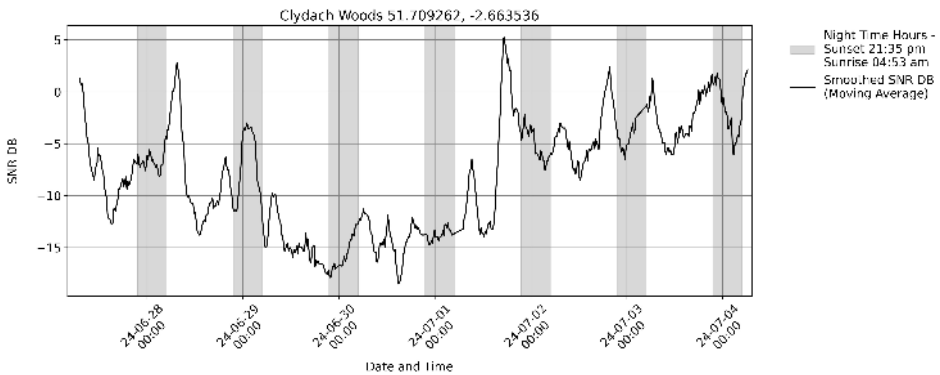
The UK trials successfully demonstrated the feasibility and effectiveness of the BearWave NVIS communication system for achieving reliable data transmission over substantial distances under simulated conditions akin to the Bornean rainforest. As summarised in Table 6, the experiments achieved high message reliability, with success rates of 97%, 93%, and 94% across the three remote locations. These results provide strong initial evidence that the NVIS-based communication setup can consistently convey trap status information across a wide area, even in challenging environments where traditional line-of-sight or ground-wave methods are impractical.

An analysis of signal strength over time revealed a consistent pattern influenced by diurnal variations in the ionosphere. During nighttime hours, signal strength peaked, corresponding to periods when the sun was absent and the ionosphere was cooler and less ionised. This reduction in ionospheric density during dark hours minimises signal attenuation, thereby improving signal propagation and enabling stronger and more reliable reception at the central node. Conversely, during daylight hours, increased solar radiation heats and ionises the ionosphere, leading to greater density and consequently higher attenuation. These fluctuations were clearly visible in the signal strength graphs, reinforcing the critical role of ionospheric conditions in NVIS signal propagation.

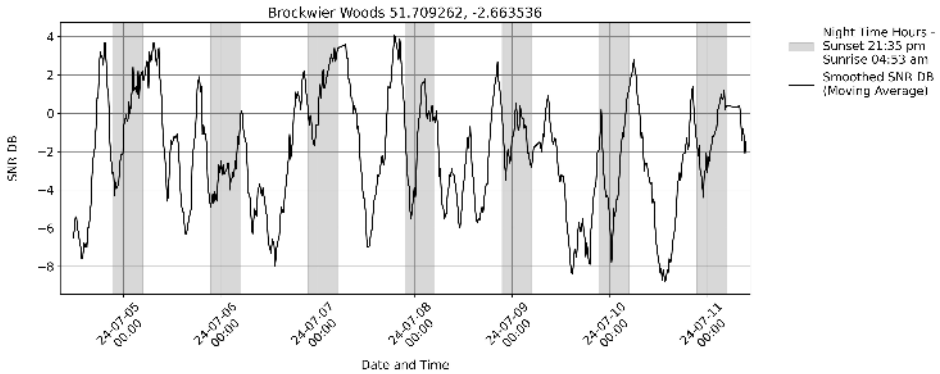
The graphs in Figures 9a, 9b, and 9c illustrate the diurnal fluctuations in signal strength throughout the 24-hour cycle, with distinct peaks during nighttime hours. These visual results, combined with the high message reliability percentages, confirm the robustness of the FT8/JS8 protocols in handling environmental signal variability. Such reliability is crucial for the BearWave system, ensuring that critical information related to trap statuses can be effectively communicated in dense, non-line-of-sight conditions similar to those in the Bornean rainforest. The results from these trials provide compelling evidence for the viability of the BearWave system's NVIS-based design. The combination of consistent message delivery rates and observable signal strength trends underpins the system's ability to operate effectively in variable RF propagation conditions characteristic of tropical rainforest environments. These findings lay a strong foundation for further refinements and field deployment in similarly challenging global environments.



(a) Belpha Farm 1-Week Trial Results



(b) Clydach Woods 1-Week Trial Results



(c) Brockweir Wood 1-Week Trial Results

Fig. 9. Signal performance graphs from the 1-week trials.

Fig. 10. Signal performance graphs from the 1-week trials at Belpha Farm, Clydach Woods, and Brockweir Wood. Each graph illustrates diurnal fluctuations in signal strength, highlighting the relationship between ionospheric conditions and message reliability across varied distances and environments.

The throughput and goodput metrics, derived from the three field deployments, range between 0.0619 and 0.0834 bits per second. These values, though low by conventional networking standards, reflect the intentional design choices that underpin BearWave's communication strategy.

Each FT8 message carries just 77 bits and is transmitted every 15 minutes. This infrequent duty cycle is a deliberate energy-saving measure, enabling long-term operation on battery power in remote and inaccessible locations. Furthermore, the FT8 protocol itself is designed for weak-signal environments, prioritising reliability and low signal-to-noise ratio (SNR) performance over data throughput. Operating at approximately 6.25 baud with a bandwidth of just 50 Hz, FT8 sacrifices speed in favour of robustness, allowing messages to be decoded even when the signal is 20 dB below the noise floor.

Given these parameters, the low throughput is not a limitation but an expected outcome aligned with the system's requirements. The BearWave framework is optimised to transmit short, critical telemetry, such as trap activation alerts or sensor health statuses, rather than bulk data. As such, these modest throughput values are sufficient to meet the application's needs while preserving power, minimising ecological disturbance, and maintaining reliable operation under harsh RF conditions.

In this context, goodput is effectively equal to throughput, as nearly all transmitted bits represent useful application-layer data, with minimal overhead or retransmission requirements. Future enhancements may explore adaptive duty cycling or compressed message formats to further optimise transmission efficiency, but the current figures reflect a strategic balance between power, cost, and communication resilience.

The UK field trials provided an extensive dataset for evaluating the BearWave system's operational capabilities under conditions designed to approximate those of the Bornean rainforest. Across the three remote sites, separated by distances of approximately 12 km, 20 km, and 22 km, the system maintained consistently high message reception rates, with success rates exceeding 90% in all cases. This robust performance not only confirmed the ability of NVIS propagation to overcome dense vegetation and uneven terrain but also validated the choice of FT8-based digital modulation as a method of reliably conveying data at low signal-to-noise ratios. In addition to gauging range and message integrity, these trials offered insights into the balance between data transmission frequency and energy consumption. Nodes configured to transmit at 15-minute intervals sustained reliable communication throughout the trial period without requiring significant battery capacity increases. Although power-saving modes were intentionally not implemented during these particular tests, the measured current draws and battery discharge profiles suggest that introducing periodic sleep states and adjusted duty cycles would yield further improvements in long-term energy efficiency. Such measures would be critical for extended deployments in remote habitats where logistical constraints make frequent battery replacements impractical.

From a reliability perspective, the results highlighted the system's resilience against diurnal variations in ionospheric conditions. While nighttime conditions generally provided slightly stronger signal propagation, daytime reception remained adequate for maintaining communication. This finding implies that scheduling more critical transmissions during nocturnal hours could enhance reliability and reduce power requirements, as less energy might be needed to ensure a successful message decode when ionospheric attenuation is lower. In essence, the UK trials demonstrated that the BearWave system could simultaneously achieve substantial transmission ranges, manage power consumption effectively, and maintain high levels of message reliability. These outcomes establish a solid foundation for future optimisation efforts, whether through refining antenna designs, implementing advanced power management strategies, or further tailoring the messaging protocol to match environmental conditions and sensor requirements.

While throughput and goodput were estimated based on successful FT8 message decodes, direct measurement of bit error rate (BER) and packet error rate (PER) was not feasible due to the constraints of the deployed decoding software. Future iterations of BearWave may integrate modified decoders or logging extensions to capture BER/PER directly in field deployments.

5.2 Environmental Adaptation

The BearWave system demonstrates that NVIS propagation can harness, rather than be hindered by, dense vegetation and variable terrain. Unlike line-of-sight techniques, which suffer significant signal loss in thick foliage or rugged landscapes, NVIS maintains consistent links over substantial distances. This capacity is especially valuable in environments resembling the Bornean rainforest, where moisture-laden air, high canopies, and abundant biodiversity create highly attenuative conditions for radio signals.

Although the UK field tests did not fully replicate rainforest conditions, they still provided a strong analogue. Changes in humidity and rainfall correlated with shifts in signal strength, yet overall communication reliability remained high. By operating at lower HF frequencies, the system experienced less attenuation than typical higher-frequency methods, ensuring stable, robust links and timely sensor data retrieval.

Fine-tuning of operational parameters emerged as a critical strategy for dealing with environmental variability. Adjusting transmission schedules to coincide with reduced ionospheric absorption and optimising antenna orientation to match local vegetation densities can substantially improve reliability. Adopting a flexible, dynamic approach to system configuration allows BearWave to evolve alongside changing environmental factors.

These adaptations underscore NVIS's usefulness for conservation. Selecting appropriate frequencies, hardware, and duty cycles permits sustained operation in tropical forests, forming a basis for long-term ecological monitoring. The field data also highlight how weather and terrain shape NVIS performance. Conditions typical of tropical jungles high humidity, dense foliage, and frequent rain, are known to increase RF attenuation. Even so, subtle dips in signal strength were temporary and did not undermine reliability.

Terrain features such as valleys, wooded slopes, and uneven surfaces introduced further complexity, but NVIS's flexible propagation paths ensured stable links. In contrast, line-of-sight alternatives would likely require extensive infrastructure or experience frequent outages in similar settings. These findings confirm that while weather and terrain do modulate NVIS-based communication, they are not insurmountable obstacles. Through scheduling adjustments, antenna refinements, and, when needed, frequency changes, the system can sustain reliable operation under challenging conditions. This adaptability is crucial for conservation contexts where dependable, low-impact monitoring in remote, dynamic habitats is integral to effective research and protection efforts.

Although BearWave was developed primarily to monitor wildlife traps and transmit activation alerts, its underlying design principles, extremely low data rate, energy efficiency, and resilience to nonline-of-sight conditions lend themselves to a wide range of conservation and environmental monitoring applications. Many remote sensing tasks require only brief, periodic, or event-driven messages that can be encoded into the 77-bit payloads supported by FT8.

Potential use cases include intrusion alerts from poaching sensors, intermittent GPS location pings from animal collars, microclimate data collection (e.g., temperature or humidity), and early warnings for forest fires or flooding. These applications share a common need for low-power reliable communication in infrastructure-poor and RF-challenged environments, conditions under which BearWave has already demonstrated high message delivery reliability. The modularity and open-source foundations of the system further support its adaptation to other conservation scenarios where traditional communication technologies are cost-prohibitive or technically unfeasible.

5.3 Deployment Considerations

The BearWave system was designed with rainforest deployment in mind, but all field trials to date were conducted in temperate UK woodlands, where logistical conditions are significantly less demanding. During these trials, inverted "V" dipole antennas were deployed by hoisting the center feedpoint into suitable tree branches, typically 4 to 7 meters high, using simple rope and pulley systems. The antenna legs, approximately 14–15 meters each, were tensioned and anchored to the forest floor. This method avoided the need for rigid poles or masts, making the system lightweight and highly portable.

In the UK woodland context, access was straightforward, vegetation was relatively sparse, and environmental conditions (e.g., humidity, biodiversity, terrain ruggedness) were manageable. The total material cost per antenna installation was approximately £30–£50, including wire, coaxial feedline, rope, waterproof enclosures, and anchoring equipment. Setups were typically completed in 1–2 hours by a team of two, and the installations left no permanent footprint.

The planned deployment at the Danau Girang Field Centre (DGFC) in Borneo will introduce additional challenges not encountered during the UK trials. These include denser vegetation, higher humidity, less predictable terrain, and greater biodiversity, including wildlife that may interfere with equipment. Tree selection may be more constrained by undergrowth and canopy structure, and navigating through the environment will likely require more careful planning and physical effort.

Nonetheless, the core design choices, such as reliance on natural supports, minimal infrastructure, and fully portable components, were made specifically with rainforest constraints in mind. While the UK trials have demonstrated the basic feasibility of rapid, low-cost deployments in wooded environments, further testing at DGFC will be necessary to validate and adapt these procedures for truly remote tropical conditions.

The central receiving node used in this study was located in the UK and relied on uninterrupted power and broadband connectivity for decoding and cloud integration. This setup was sufficient for validating the feasibility of low-power FT8 transmission from remote nodes, but does not yet reflect a fully autonomous rainforest-compatible deployment. In future iterations, the receiving node architecture will be redesigned for off-grid operation, incorporating solar power, local data buffering, and optional HF reverse-links to operators. This step is essential for true end-to-end BearWave deployments in infrastructure-free tropical environments such as the Bornean rainforest. While the UK woodland trials served as a proof-of-concept for BearWave's reliability and ease of deployment, long-term operation in rainforest environments will require additional considerations. Power autonomy is a key challenge; future implementations will incorporate solar charging systems with low-draw regulators to support indefinite operation, even under diffuse canopy light. All system enclosures will be upgraded for full weatherproofing and tamper resistance, with designs adapted to mitigate interference from wildlife such as macaques or elephants. Data transmission will continue to use low-duty-cycle FT8 messaging, and future iterations may include status beacons or heartbeat signals to monitor node health remotely. Maintenance rotations may be required at multi-month intervals, but the system is designed to minimise on-foot interventions. These upgrades will extend BearWave from a deployable experimental framework to a robust tool for long-term ecological monitoring in remote tropical forests.

5.4 Challenges and Limitations

Although the BearWave system performed well, the study revealed challenges that warrant attention. Chief among these is ionospheric variability: diurnal cycles, solar activity, and atmospheric conditions can alter NVIS propagation, sometimes requiring adjustments in transmission schedules,

frequency selection, or power levels. Field deployment also proved demanding. Erecting even simple inverted “V” dipoles under dense canopy can be time-consuming, and vegetation may disrupt antenna orientation. The humid, remote environment necessitates robust, weatherproof enclosures capable of resisting corrosion, moisture ingress, and potential wildlife damage, adding logistical complexity and elevating the risk of component failure over prolonged periods.

Technical and operational hurdles arose around maintaining precise frequency calibration and stable time synchronisation without reliable external references. Although GPS timing units generally provided accurate synchronisation, dense foliage sometimes obstructed satellite signals, forcing periodic manual checks or fallback measures. Additionally, transporting equipment into remote jungle sites and setting up antennas while minimising habitat disturbance demanded careful planning and fieldcraft. Ground conditions often made it difficult to achieve optimal antenna height or orientation, requiring rapid on-site adaptations.

Overall, while NVIS offers a promising communication solution for remote conservation monitoring, ionospheric variability, hardware durability, and field deployment logistics must be carefully managed. Ongoing improvements in antenna design, power management, and protocol responsiveness are essential to surmount these hurdles and maximise the efficacy and sustainability of NVIS-based systems.

5.5 Lessons Learnt

The development, testing, and evaluation of the BearWave system in harsh RF environments reveal several pivotal insights for future applications. First, the feasibility of Near Vertical Incidence Skywave (NVIS) as a cost-effective, energy-efficient solution in dense, non-line-of-sight settings was clearly demonstrated. NVIS requires minimal infrastructure compared with satellite or conventional high-frequency line-of-sight systems, proving especially resilient for remote conservation tasks. BearWave’s hardware design uses modular, low-cost components, capitalising on software-defined radios and precise time-synchronised protocols to investigate NVIS propagation under challenging conditions. Its integrated software stack (including SparkSDR for SDR control, FT8 for weak-signal transmission, and JS8Call for extended messaging) provides robust digital communication, timing accuracy, and flexible audio routing. This cohesive approach offers a scalable, field-ready platform for studying IoT communications in regions with limited connectivity. Frequency choice and protocol selection proved critical. Operating at lower HF bands and using narrow-band, error-corrected digital modes (e.g., FT8) helped counter severe signal attenuation. These adaptive protocols, accommodating varied message structures and robust error correction, ensured high reliability under fluctuating ionospheric conditions and heavy vegetation. Additionally, diurnal ionospheric shifts highlighted the value of temporal awareness: scheduling transmissions or adjusting power output at night could further boost reliability, while intelligent duty cycling optimises power use. Energy efficiency emerged as vital for prolonged remote deployments. Strategic power management—through intermittent operation and low-power standby modes—substantially extended battery life, a key advantage in tropical rainforests with limited solar or wind resources. Simple antenna solutions, such as inverted “V” dipoles, balanced practical deployment needs with robust performance, minimising setup time and reducing potential failures. Customising messaging protocols around specific conservation goals proved essential. Incorporating encryption, error correction, and integrity checks safeguarded sensitive data (e.g., trap triggers, animal locations) while preserving accuracy. These findings underscore the scalability and general relevance of NVIS-based systems: frequency planning, diurnal scheduling, energy optimisation, and tailored protocols can be adapted to other remote, infrastructure-limited scenarios, advancing sustainable, long-term ecosystem monitoring. Overall, these lessons affirm the viability of resilient, low-power networks in extreme environments. Building on these insights will refine technology choices,

enhance message handling, and improve operational methodologies to bolster both the longevity and impact of remote conservation monitoring.

6 Conclusions and Future Work

The UK trials confirm that low-power, low-bandwidth Near Vertical Incidence Skywave (NVIS) reliably transmits IoT sensor data across challenging terrains, achieving message reliability of 97%, 93%, and 94%. NVIS overcomes dense foliage and hilly terrain, with diurnal ionospheric variations, especially at night, guiding optimal transmission schedules. Compared to satellites and LoRaWAN, NVIS is both cost-effective and energy-efficient, eliminating the need for extensive infrastructure. Energy efficiency can be enhanced by incorporating power-management algorithms, optimising duty cycles, and refining parameters such as transmit power and data compression, which extend battery life. Employing long-life batteries combined with efficient power management techniques further boosts operational longevity. NVIS-based systems enable real-time data gathering with minimal environmental disruption, reduce human presence in fragile habitats, and scale to global contexts like climate observation and disaster response. This study advances computer science by adapting weak-signal protocols (FT8 and JS8) for robust error correction under extreme RF conditions. Future work should refine these protocols for scalability, investigate hybrid systems with LoRaWAN and satellites, and harness machine learning for adaptive optimisation. Lightweight security measures are crucial for IoT conservation networks, while NVIS-generated data offers fertile ground for advanced analytics and ecosystem innovations. In conclusion, NVIS is a dependable, scalable, and energy-efficient solution for remote conservation monitoring. Further improvements in error correction, energy harvesting, and secure protocols will strengthen ecological protection and drive technological progress.

Acknowledgments

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