ACKNOWLEDGEMENT

ABSTRACT

List of Abbreviations & Acronyms

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CHAPTER 1:
Introduction to FalconResQ

1.1 Background and Context

1.1.1 Evolution of disaster communication systems:

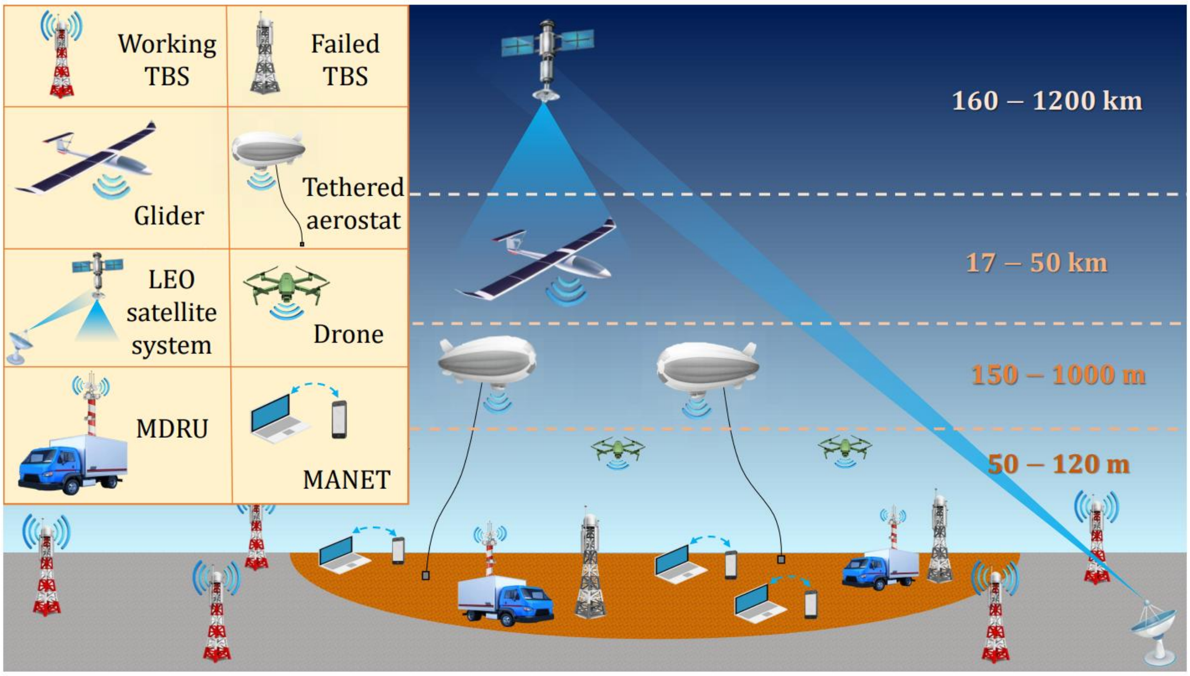
Pre-cellular era (telegraph → voice radio):
Early emergency coordination relied on wired telegraph/telephone (when lines survived) and then land-mobile radio (LMR aka Walkie-Talkie) for voice (police/fire dispatch). The big strength was independence from public networks, so they often kept working even when cities were in chaos; the big weakness was limited data + interoperability issues across agencies/bands.[1]

Satellite + digital messaging (late 20th century):
As disasters routinely damaged terrestrial lines, satellite (voice + low-rate data) became a standard fallback for relief/coordination, plus early warning systems.[2]

Cellular data & Internet era (2G/3G/4G):
Emergency response increasingly needed data (location, images, mapping, medical info). This pushed evolution from narrowband voice toward broadband IP networks - often still riding on commercial infrastructure, which is efficient but vulnerable to congestion/outages.[3]

Mission-critical broadband (LTE/5G PPDR):
Standards and national programs now emphasize LTE/5G “mission-critical” services (priority, pre-emption, group communications, push-to-talk/data/video), integrating with or complementing legacy LMR. India’s regulator has also recommended LTE as the long-term direction for Public Protection and Disaster Relief (PPDR) mobile broadband networks.[4]

Resilient/rapid-deploy networks (recent research & deployments):
Focus is now on portable base stations i.e. “network in a box”, portable cells, UAVs/balloons, mesh networks, and satellite backhaul to restore coverage quickly after infrastructure collapse, an active research area.[5] The below is an image showing a few “network in a box” approaches used during disasters today.



1.1.2 Current state of emergency response infrastructure

Modern emergency communication uses a hybrid approach, reliable radio systems for critical voice, broadband networks for data and video, guided by global standards, but still vulnerable to power loss and infrastructure damage, which makes offline backups essential.

a. P25, TETRA, and DMR are all digital two-way radio systems used by police, fire, and emergency services for reliable voice communication. They work on dedicated radio frequencies, not the public mobile internet, which makes them dependable during disasters. P25 is mainly used in North America, TETRA is common in Europe and many parts of Asia, and DMR is widely used because it is simpler and cheaper. All three are designed for push-to-talk group calls, fast call setup, and operation even when cellular networks fail, but they are narrowband systems, meaning they are mainly for voice and cannot support high-data services like video or large file sharing. These LMRs still dominates mission-critical voice in many places because it's proven and operates in dedicated spectrum.
b. Broadband public safety networks are expanding to support data/video and modern apps. A flagship example is the U.S. FirstNet nationwide public safety broadband network; it's a nationwide LTE-based network just for first responders where emergency users get priority access and normal users can be pushed aside if the network is busy.

Policy + standardization backbone: The ITU frames "emergency telecommunications" as a core global need (resilience, early warning, disaster relief), and The 3rd Generation Partnership Project (3GGP), the body that defines LTE/5G) has been pushing mission-critical broadband capabilities that can run on commercial or dedicated infrastructure.

Known fragilities (even in advanced regions): Major disasters still cause long-duration power loss + telecom infrastructure damage, and governments increasingly warn about "over-reliance" on online-only warning/coordination without offline continuity options.

1.1.3 Gap in remote/disaster-hit area communication

1. Infrastructure dependency:
   Cell towers need power + backhaul (fiber/microwave). Disasters break both, so coverage can vanish even if users have phones.
2. Congestion & priority:
   Public networks overload fast (voice/data). Without strong priority/pre-emption and public-safety mechanisms, responders compete with civilians for access.
3. Interoperability gaps:
   Different agencies often use incompatible systems/frequencies/protocols, especially across jurisdictions which is still a documented challenge.
4. Last-mile in remote areas:
   Sparse tower density + difficult terrain means baseline coverage is weak; a disaster pushes it to zero. Research and case studies repeatedly flag rural/remote telecom as a resilience bottleneck.
5. Backhaul is the Achilles' heel:
   Even if you restore local radio coverage (e.g., a portable cell), backhaul to the core network/internet is often the limiting factor; satellite backhaul is common but has latency/capacity constraints.

1.2 Motivation

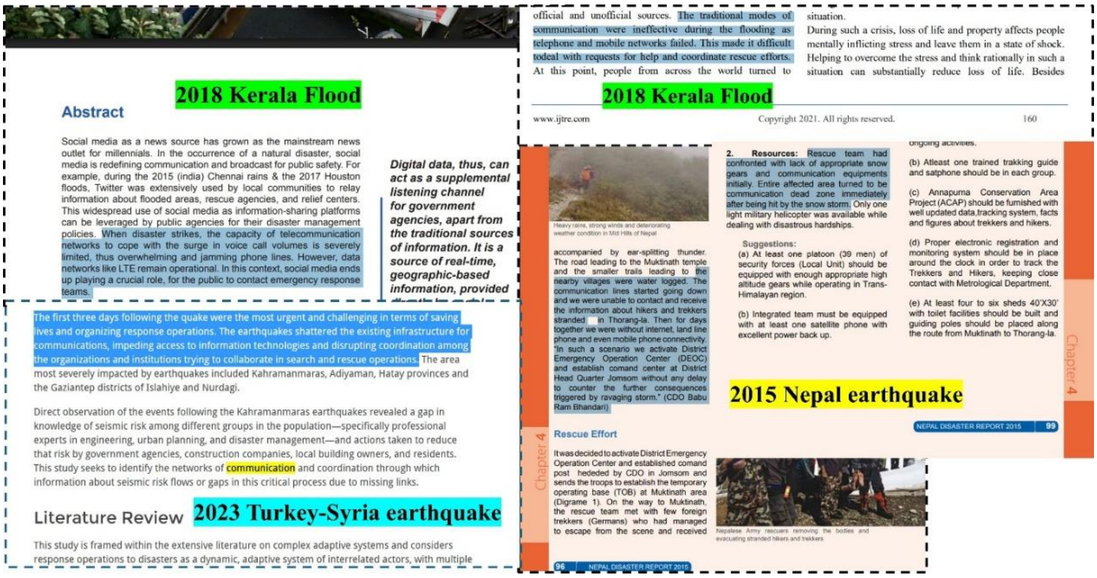
1.2.1 Why the problem matters

Reliable communication is one of the most basic requirement in disaster response. When communication systems fail, victims become isolated, and emergency responders lack the information needed to locate and prioritize rescue efforts. This problem is particularly severe in rural, mountainous, or island regions where alternative infrastructure is limited. Current emergency alert systems are often centralized, infrastructure-dependent, and costly to deploy at scale. One example being, SMS-based emergency alert systems rely on mobile network towers and internet gateways to function. During the 2015 Nepal earthquake, most cellular infrastructure was damaged, rendering such centralized alerts ineffective and inaccessible to those in urgent need. There is a pressing need for a decentralized, low-cost, and infrastructure-independent solution that allows affected individuals to send out SOS alerts even during complete network blackouts. A centralized emergency alert system relies on infrastructure like cell towers or internet to send alerts from a central authority to the public, which can fail during disasters. In contrast, a decentralized system allows individuals to transmit distress signals directly (e.g., via LoRa), making it more resilient in areas with damaged or no infrastructure.

1.2.2 Real world relevance

Historical data from disasters like the 2015 Nepal earthquake, the 2018 Kerala floods, and more recently, the 2023 Turkey-Syria earthquake reveal that thousands of victims were unreachable for hours or even days due to the collapse of communication systems. During Hurricane Maria in Puerto Rico (2017), 95% of cell towers went offline. In such cases, rescue operations were severely hampered by the inability to locate survivors.

The following statistical data, drawn from official post-disaster reports, show the critical role of communication during natural disasters. These findings reveal how communication breakdowns and network outages significantly hinder emergency response efforts, delay aid distribution, and escalate the overall impact of disasters. These findings hence prove that the loss of communication infrastructure is a serious and recurring real-world challenge during disasters.



1.3 Project Objectives

1.3.1 Primary objectives

The primary objectives define the core outcomes that this project aims to achieve. FalconResQ's primary objectives include:

1. Design and implement a reliable emergency communication prototype capable of transmitting critical radio and GNSS data from remote or disaster-hit areas where terrestrial infrastructure is unavailable or damaged.

    i. This means the system should demonstrate communication continuity even when cellular or wired infrastructure is down.

2. Validate long-range, low-power data link performance using LoRa (or similar LPWAN technology) over distances representative of rural/disaster coverage needs.

3. Integrate GPS/GNSS reporting with minimal latency so that location information of responders or assets can be communicated accurately.

4. Develop and document a complete communication stack, including hardware design, firmware logic, and protocol flow for reliable delivery and acknowledgment of messages.

1.3.2 Secondary objectives

The secondary objectives support the primary ones. They are not the main goals but enhance performance, usability, or preparedness for future work:

1. Optimize power consumption to extend operational time of nodes deployed in field conditions (e.g., battery-powered devices).
2. Benchmark communication in different topographic conditions, such as line-of-sight vs. non-line-of-sight environments.
3. Evaluate ease of deployment and scalability to support rapid setup by first responders or volunteers with minimal technical training.
4. Document integration pathways for future enhancements (e.g., adding mesh routing, priority traffic, or alternative backhaul) so FalconResQ can be evolved into larger resilience systems.

Secondary objectives provide context for quality, readiness, and potential expansion beyond the core feature set. They help clarify the value added and usability aspects of the project outcomes.

1.4 Scope & Limitations

1.4.1 What the project covers

1. Design and implementation of a prototype emergency communication system that uses low-power wide-area technologies (such as LoRa) to send critical text and positioning data from remote/disaster-affected areas where conventional cellular or wired infrastructure is unavailable or damaged.
2. Deployment of firmware and protocols necessary to enable reliable transmission, acknowledgment, and basic error handling of telemetry and GNSS data between field units and base stations.
3. Field testing and evaluation of communication performance (range, reliability, and energy efficiency) under controlled conditions that approximate disaster scenarios.
4. Documentation of system architecture, hardware components, communication flow, and test results, providing a reproducible framework for future research or expansion.
5. Develop a comprehensive ground station website to support the entire project and to act as a bridge between the hardware and the end user

1.4.2 What it doesn't cover

The prototype is intentionally designed to operate independently of existing telecom providers and therefore does not include full integration with commercial cellular or satellite networks for backhaul connectivity. Similarly, mission-critical broadband services such as LTE or 5G public safety networks

with priority, pre-emption, and quality-of-service guarantees, are outside the scope of this work, as these capabilities fall under large-scale national telecom infrastructure planning rather than a deployable prototype. In addition, advanced security hardening mechanisms, including sophisticated encryption key management and cryptographic authentication frameworks required for industrial or government security certification, are not implemented; the primary emphasis of the project is on establishing reliable and functional communication in disaster scenarios before addressing certification-grade security enhancements.

Given the critical nature of disaster communication, what solutions already exist in the market? How do they address these challenges, and where do they fall short? Are there any technologies we can leverage or gaps we can fill?

CHAPTER 2:
Literature Review & Existing Solutions

2.1 Existing Solutions Analysis

My proposed solution might have 5 potential competitors i.e., Catastrophe-Tolerant Telecom Network (CTTN) by Dr. Duong, Drone mesh system by A.F.M. Shahen Shah, Verizon/Spooky Action, JOUAV & HAM Radios. The core differentiating factors between my proposed solution and other competitors are as show below:

Criteria	FalconResQ	Dr. Duong (CTTN)	A.F.M. Shahen Shah	Verizon/Spooky Action	JOUAV	HAM Radio
Communication Type	LoRa (Low-power WAN)	Wi-Fi / Wireless mesh	Mesh + Cellular	Cellular (LTE/5G)	Mesh + Cellular	Analog/Digital Radio (VHF/UHF/HF bands) , manual radio communication
Drone Role	Passive receiver + mapper *(Drones fly overhead and listen for SOS signals sent by people on the ground (using LoRa beacons). The drones don't send messages or scan visually, they just receive the signals and map the GPS locations of the distress beacons.)*	Telecom relay + weather sensor *(Their drones act as temporary communication relays (like a mobile signal tower) and also collect weather data. So, the drone helps users connect by relaying Wi-Fi or signals, and also measures weather.)*	Base station substitute *(The drones form a mesh network, meaning multiple drones connect to each other to act like a temporary mobile network (base station). This allows people to make calls or send texts in areas where ground towers are down.)*	Temporary flying cell tower *(Their drones are like mobile telecom towers in the sky. They provide LTE or 5G signals, so users with smartphones can make calls or access the internet even when ground towers are gone.)*	Relay & network extender *(Their drones are used by rescue teams to extend communication in tough terrain. For example, one drone in the air can relay messages or video feeds between a rescue team in a valley and a command base.)*	None , ground-based communication only
Hardware Cost	Extremely low (LoRa + ESP32 + GPS)	Moderate	High	Very high	Very high	Moderate to high (licensed transceivers, large antennas, backup power)
User Dependency	Low , user presses a single SOS button	Moderate	Moderate	High (smartphones or radios needed)	High (team coordination)	Very high , requires skilled operators and licensed radio users
Autonomy	Manual drone ops or	Extended drone endurance	Future plan: AI-enabled	Fully deployable tethered/untethered	Self-organizing UAV mesh	None , entirely human-operated

	preplanned flight paths					communication system
Power Needs	Ultra-low (for beacons)	Moderate	High	High (requires generators or tethers)	High	High (HF radios, repeaters, and backup power sources like batteries/gens)
SOS Delivery Mechanism	LoRa-based beacon to drone	Signal relay	Direct communication via created drone mesh network	Voice/data over LTE	Voice/data relayed via UAVs	Manual voice communication , distress messages relayed via operators

2.1.1 Dr. Duong Catastrophe-Tolerant Telecom Network (CTTN)

Their Strengths:

- **Longer drone endurance (3–5× commercial drones).**
- **Real-time weather monitoring + telecom coverage.**
- **Low cost compared to professional drones.**

My project's strengths in comparison:

- **No reliance on infrastructure and has minimal user interaction i.e., just pressing a button on the beacon**
- **Lower cost, power consumption and beacon complexity.**
- **Pure SOS detection: My system functions even when users can't operate phones.**

2.1.2 A.F.M. Shahen Shah – UAV Mesh Base Stations

Their Strengths:

- **Mesh network of drones acting as backup base stations which helps restore full telecom capabilities (calls, messaging).**
- **AI integration for future autonomy & for automated drone routing.**
- **Enables users to connect via phones in network outages.**

My project's strengths in comparison:

- **No reliance on infrastructure and has minimal user interaction i.e., just pressing a button on the beacon**
- **Lower cost, power consumption and beacon complexity.**
- **Pure SOS detection: My system functions even when users can't operate phones.**

2.1.3 Verizon / Spooky Action – Flying Cell Towers

Their Strengths:

- Massive area coverage (~32–64 km).
- High-performance LTE/5G services, provides full voice/data capabilities.
- Industry-grade reliability.

My project's strengths in comparison:

- Ultra low-cost, ideal for local NGOs or disaster relief teams.
- Lower cost, power consumption and beacon complexity.
- Users don't need phones, only a beacon with an SOS button.

2.1.4 JOUAV

Their Strengths:

- Advanced UAV mesh network for military/rescue ops.
- High-bandwidth data and command relay.
- Real-time communication between drone-drone, drone-ground station in rough terrain.

My project's strengths in comparison:

- Fraction of the cost
- Designed for immediate geolocation of distressed individuals.
- Users don't need phones, only a beacon with an SOS button.

2.1.5 HAM Radios

Their Strengths:

- Proven reliability – HAM radio has been used for decades during disasters when modern networks fail.
- No dependency on modern electronics or drones – Purely ground-based, with experienced human operators.

- Long-range communication – HF/VHF/UHF radios can cover hundreds of kilometers with repeaters.
- Independence from internet or cellular networks – Works even if all modern infrastructure is down.
- Instant voice communication – Distress calls can be sent and received in real-time by operators.
- Continuous operation – As long as operators and power are available, the network can remain active 24/7.

My project's strengths in comparison:

- Minimal human dependency – Users simply press an SOS button; no need for licensed radio operators.
- Automatic mapping – Drones autonomously map distress beacon locations, giving exact GPS coordinates of victims.
- Ultra-low cost – LoRa beacons (ESP32 + GPS) are cheaper than building/maintaining HAM repeater stations.
- Scalable & mobile – Drones can cover large or remote areas quickly without relying on fixed infrastructure.
- Faster search capability – Drones collect data from multiple beacons during a single flight, reducing time-to-locate.
- Easier to use for civilians – People in distress don't need radios or technical skills, just a push-button beacon.
- Terrain-independent – Drones fly above mountains, forests, and valleys, eliminating the line-of-sight issues faced by ground-based HAM radios.

2.2 Why is FalconResQ superior

FalconResQ is designed in response to well-documented shortcomings in existing disaster communication systems, particularly in infrastructure-compromised, remote, and congestion-prone environments, and positions itself as a resilient complement to, not a replacement for, large-scale public safety networks. Among current emergency communication approaches, ranging from HAM radios and drone-based LTE towers to mesh networks and Wi-Fi relays, FalconResQ's LoRa-enabled, drone-assisted SOS mapping architecture offers a uniquely cost-

effective, scalable, and terrain-resilient solution. Unlike telecom drones that depend on expensive hardware, high power consumption, and smartphone access, or HAM radio systems that require trained operators and fixed infrastructure vulnerable to terrain constraints, FalconResQ enables civilians to trigger distress signals through a simple, ultra-low-power beacon with a single button press. Autonomous drones fly overhead to receive and geolocate GPS-encoded SOS packets, mapping distress points without relying on voice communication, ground infrastructure, or internet connectivity. By exploiting altitude-enabled line-of-sight propagation, the system maintains coverage in mountainous, forested, or otherwise obstructed terrains where conventional systems often fail. With minimal human intervention, rapid deployment, and wide-area coverage at a fraction of the cost of broadband or satellite-based solutions, FalconResQ is particularly well suited for disaster response, rural emergencies, and large-scale humanitarian operations.

2.2.1 Innovation highlights

1. **Infrastructure-independent emergency communication:**
   Unlike cellular-based emergency systems that depend on towers, backhaul, and grid power, FalconResQ operates independently of terrestrial infrastructure, addressing a critical vulnerability repeatedly highlighted by ITU and disaster-response studies.
2. **Protocol-level resilience instead of brute-force bandwidth:**
   Most modern public safety communication research focuses on high-bandwidth solutions (LTE/5G, UAV relays). FalconResQ innovates by emphasizing contention-aware, low-power protocol behavior (e.g., channel activity detection, controlled access, randomized transmission) , an area identified as underexplored in LPWAN disaster research.
3. **Long-range GNSS-enabled distress signaling at ultra-low power:**
   Research consistently notes that position information is the single most valuable data element in disaster response, yet many systems either assume smartphones or continuous connectivity. FalconResQ integrates GNSS with LPWAN transmission, enabling location reporting even when smartphones or networks fail.
4. **Rapid deploy-ability and simplicity:**
   Studies on post-disaster networks emphasize that time-to-deploy is as critical as throughput. FalconResQ's beacon-style architecture avoids complex network setup, aligning with recommendations for fast, ad-hoc emergency systems.

2.2.2 Unique selling propositions (USPs)

FalconResQ distinguishes itself through the following unique selling propositions, grounded in documented needs and gaps:

1. Operates where cellular and broadband PPDR systems cannot:
   Even advanced public-safety broadband networks fail when power and backhaul are lost. FalconResQ is built for the communication gap that appears immediately after a disaster, when phones and broadband simply don't work.

2. Low cost, low complexity, and scalable:
   Large PPDR networks (LTE/5G) require national-level investment and coordination. FalconResQ uses commercial off-the-shelf components, making it suitable for NGOs, volunteers, and local agencies, a scalability gap highlighted in disaster-communication literature.

3. Designed specifically for congestion and interference scenarios:
   Research shows that emergency networks fail not only due to damage but also due to sudden traffic surges. FalconResQ's design philosophy explicitly accounts for channel contention (uses Slotted ALOHA and CSMA P-Persistent Techniques) rather than assuming continuous availability.

4. Complements, not competes with, existing systems:
   FalconResQ is not positioned as a replacement for P25, or LTE-based PPDR systems. Instead, it fills the last-mile and fallback communication gap, a strategy recommended by ITU and IFRC guidance on layered emergency communication.

2.2.3 Competitive Advantages

When compared against existing disaster communication approaches, FalconResQ offers clear competitive advantages within its operational niche:

Aspect	Conventional Systems	FalconResQ Advantage
Infrastructure dependency	High (towers, backhaul, power)	None required
Power consumption	High (smartphones, base stations)	Ultra-low power LPWAN
Deployment time	Hours to days	Minutes
Congestion handling	Priority mechanisms but still overload-prone	Slotted ALOHA & CSMA P-Persistent

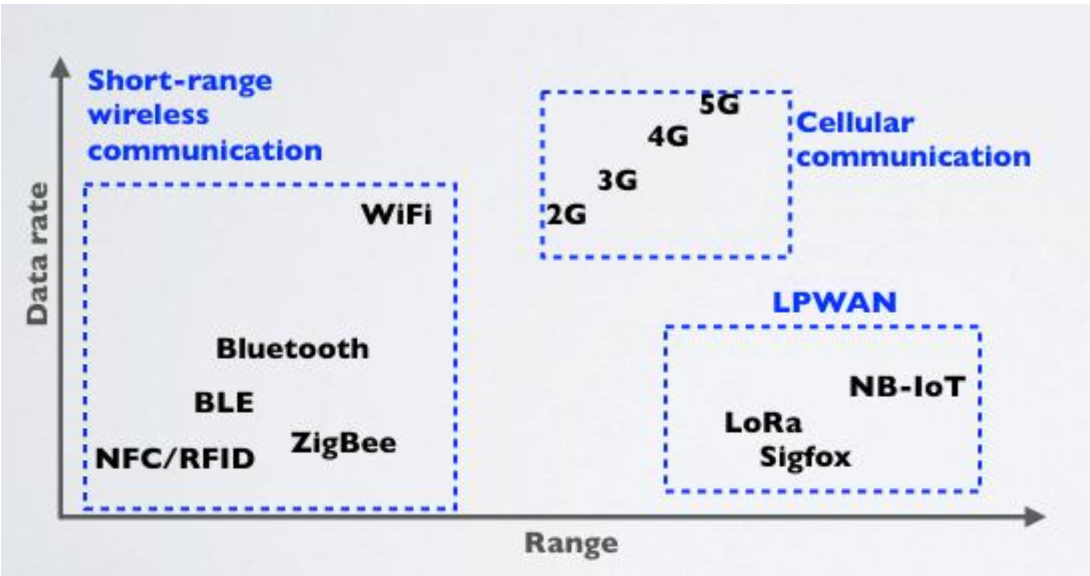
Cost & accessibility	**High, centralized**	**Low, decentralized**
Suitability for remote areas	**Limited**	**High**

We've identified that LoRa technology offers the best balance of range, power consumption, and cost for our application. But what exactly IS LoRa? How does it achieve such long-range communication? What are the underlying principles, regulations, and technical specifications we need to understand before implementing it? What about GPS technology and embedded systems that will form the backbone of our beacons?

CHAPTER 3:
Theoretical Foundations[3a][3b]

To properly design and implement FalconResQ, we must first understand the fundamental technologies involved. This chapter provides an exhaustive exploration of LoRa wireless communication, RF engineering principles, GPS technology, and embedded systems……

3.1 Introduction to Wireless Communication Technologies



Wireless communication refers to the transmission of information between devices without the use of physical cables, relying instead on electromagnetic waves, most commonly radio frequency (RF) signals, to convey data through free space. In wireless systems, information such as text, voice, or sensor data is encoded onto electromagnetic waves at a transmitter, propagated through the air, and decoded at a receiver that operates on the same frequency or channel, enabling connectivity across distances ranging from a few centimeters to several kilometers or more.[3.1a][3.1b]

Fundamentally, wireless communication exploits the electromagnetic spectrum, a continuous range of frequencies over which signals can be modulated. Varying portions of this spectrum are standardized for different applications, and signal

modulation techniques (such as frequency-shift keying or phase-shift keying) are employed to represent digital data on carrier waves efficiently and robustly.[3.1c]

Modern wireless technologies can be broadly classified based on their range, data rate, power consumption, and application domain. Short-range technologies such as Bluetooth and Wi-Fi facilitate connectivity among nearby devices, for example, connecting a smartphone to peripherals or providing local network access, typically within tens to hundreds of meters.[3.1d][3.1e] Wireless Personal Area Networks (WPAN) and local area networks like Wi-Fi enable high-throughput communication suitable for multimedia and internet access, while Bluetooth Low Energy (BLE) and Zigbee trade off data rate for lower power consumption in sensor or control applications.[3.1f][3.1g]

At larger spatial scales, cellular networks (e.g., 3G, 4G, 5G) provide wide-area broadband connectivity, supporting mobile telephony and high-speed data services across cities and regions by coordinating many base stations under standardized protocols.[3.1h] In the Internet of Things (IoT) context, Low-Power Wide-Area Networks (LPWAN) such as LoRa and Sigfox have emerged to enable long-range, low-power communication between distributed sensors and gateways, making them highly suitable for energy-constrained devices in remote or industrial settings.[3.1i]

Each class of wireless technology embodies specific trade-offs between range, bandwidth, energy use, and complexity. For example, Wi-Fi offers high data rates but higher energy consumption, whereas LPWAN solutions like LoRa provide extended coverage and long battery life at the expense of lower throughput. [3.1j] These diverse technologies together form the backbone of modern connected systems, enabling everything from everyday personal communications to large-scale sensor networks in smart cities and remote monitoring applications.

Feature	LoRaWAN	Wi-fi	Zigbee	Bluetooth	Cellular networks	RFID-IoT
Range	Very long range: up to 15 km in rural areas, 2–5 km in cities	Short range, usually ≤100 m indoors	Short range, typically ≤100 m	Short range: 10–100 m depending on type	Wide coverage, roughly 1–30 km	Very short range, usually <10 m
Data rate	Very low data rate (0.3–50 kbps)	Very high data rate	Moderate data rate	Low to moderate	High data rates (4G/5G: 100	Very low data rate (10–424 kbps)

		(up to 1 Gbps)	(20–250 kbps)	(up to 2 Mbps)	Mbps–20 Gbps)	
Power consumption	Very low, ideal for long-life battery devices	High, needs constant power	Low, good for battery devices	Low to moderate	Moderate to high	Very low, passive tags need no battery
Cost	Low cost devices and infrastructure	Moderate to high	Low cost	Low cost	High infrastructure and operating cost	Very low for passive tags, moderate for active tags
Scalability	Highly scalable, supports thousands of devices	Limited scalability	Moderate scalability	Limited scalability	Highly scalable, supports millions	Highly scalable for inventory and tracking
Network topology	Star (devices connect to gateway)	Star or mesh	Mesh network	Star	Cellular hierarchy (cells + base stations)	Star (reader ↔ tags)
Security	Strong end-to-end encryption	Strong (WPA3), setup can be complex	AES encryption, limited features	AES encryption, limited features	Very strong authentication and encryption	Minimal for passive tags, better for active tags
Use cases	IoT, smart cities, agriculture, disaster comm.	Internet access, streaming, file transfer	Home automation, industrial control	Wearables, audio devices, personal electronics	Mobile internet, voice, emergency services	Asset tracking, inventory, supply chain
Interference	Low interference (sub-GHz: 868/915 MHz)	High interference (2.4 & 5 GHz)	Moderate interference (2.4 GHz)	High interference (2.4 GHz)	Possible interference within cellular bands	Low interference

3.2 LoRa Technology - Comprehensive Overview

3.2.1 What is LoRa?

LoRa stands for Long Range. It's a wireless modulation technique specifically engineered for long-distance, low-power communication in IoT systems. At its core, LoRa uses a spread spectrum method called Chirp Spread Spectrum (CSS), this is how it encodes and transmits information over the air in a way that helps it reach much farther than many conventional radios while using minimal energy.

The technology was developed commercially by Semtech (originating from technology work by Cycleo in France) and is used in devices that operate in unlicensed ISM frequency bands such as 865-867 MHz (India), 868 MHz (Europe) and 915 MHz (Americas) - this makes it useful across many regions worldwide without needing licensed spectrum.

LoRaWAN stands for Long Range Wide Area Network. Unlike LoRa, which is just the modulation method at the physical layer, LoRaWAN is a communication protocol and network architecture designed to work on top of LoRa radios. It defines how devices join a network, how gateways and servers exchange messages, device classes, security, and more. The LoRaWAN specification was first released in 2015 and is maintained by the LoRa Alliance.

LoRa vs LoRaWAN - Key Distinction

A useful way to think about it:

- LoRa is the physical radio technology.
  It defines how bits are turned into radio signals and back again using special modulation.
- LoRaWAN is the network protocol that runs on LoRa radios.
  It defines who talks when, how messages are formatted, how devices authenticate, how network servers manage traffic, etc.

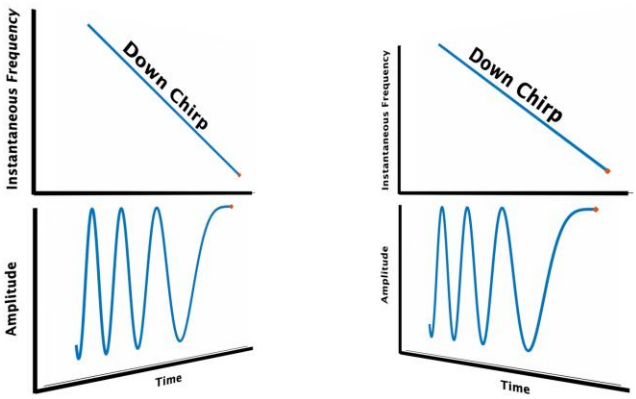
Put another way:

- LoRa is the modulation / PHY layer - the underlying way of sending signals.
- LoRaWAN is the protocol and system structure - the rules for organizing many LoRa devices on a wide-area network.

This distinction matters because you can use LoRa alone for simple point-to-point communication without any LoRaWAN network, as long as both ends agree on how to talk. LoRaWAN adds structure that scales to many distributed devices with gateways and network servers.

How Does LoRa Modulate Signals Differently from Traditional Radios?

Most traditional low-power radios (e.g., simple FSK or ASK transmitters used in basic RF links) modulate by altering amplitude or frequency in straightforward ways. LoRa instead uses Chirp Spread Spectrum (CSS) - a spread spectrum technique that sweeps the signal (assume sine wave) frequency up or down over time (a *chirp*) for each symbol transmitted. The information is encoded in how these chirps are shifted in time and frequency.



1. Spread Spectrum Modulation
   LoRa deliberately spreads the energy of each transmission across a wider bandwidth than the raw data rate would normally require. This reduces the impact of interference and makes the signal easier to recover at very low signal strengths.

2. Chirp Signals
   Instead of just sending a fixed frequency or switching between two frequencies (as in FSK), LoRa's chirps continuously sweep from lower to higher frequency (or vice-versa). The exact timing and shift of these chirps carry the data.

3. Resilience
   Because the signal sweeps across frequencies, it is more robust against narrowband interference and fading than many traditional modulation schemes. This allows LoRa receivers to decode signals that are far weaker relative to noise — which translates into very long communication ranges at low power.

So, fundamentally, LoRa's modulation is different because it uses wideband chirps instead of narrowband frequency or amplitude shifts. This gives it excellent range and interference resistance compared to many older, simpler radio modulation methods.

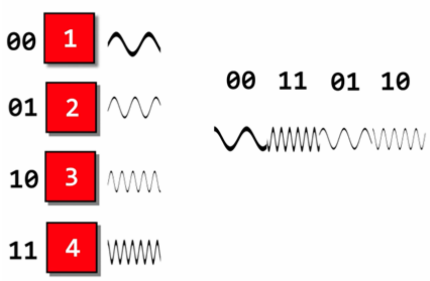
3.2.2 LoRa physical layer

3.2.2.1 Chirp Spread Spectrum (CSS)

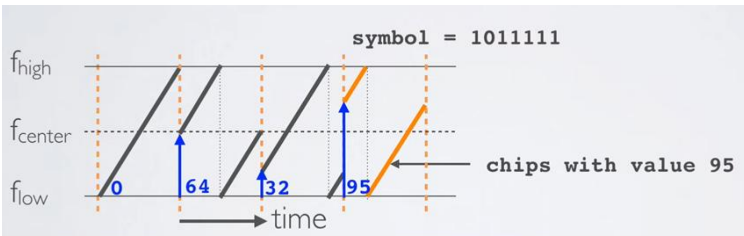
LoRa uses Chirp Spread Spectrum (CSS) as its fundamental modulation technique. In CSS, information is transmitted using signals called chirps, where the instantaneous frequency of the signal continuously sweeps across the entire channel bandwidth over a fixed symbol duration. Instead of representing data by changing amplitude or hopping between discrete frequencies, LoRa encodes information in the relative timing and frequency shift of these chirps. This approach deliberately spreads the signal energy over a wider bandwidth than the raw data rate requires, which is a defining characteristic of spread spectrum systems and is central to LoRa's long-range and low-power behaviour.

FSK vs CSS comparison

When comparing FSK and CSS, the difference lies mainly in how information is encoded and how the signal behaves in noise. In Frequency Shift Keying (FSK), data is represented by switching between distinct frequencies, each corresponding to a symbol or bit pattern. This makes FSK relatively simple and spectrally efficient, but it also means the receiver relies on detecting precise frequency differences, which becomes difficult when signals are weak or heavily interfered with. CSS, on the other hand, uses continuous frequency sweeps that occupy the full channel bandwidth for every symbol. Even if parts of the spectrum are affected by noise or interference, the receiver can still correlate the chirp pattern and recover the data. As a result, CSS can successfully demodulate signals at much lower signal-to-noise ratios than typical narrowband FSK systems.



Frequency Shift Keying



Chirp Diagram
Symbol: 1011111 (decimal value = 95)
@ Spreading Factors (SF=7)
Each Sweep is divided into 2^7 = 128 Chips

CSS is particularly well suited for long-range communication because of its high sensitivity and robustness. The spreading of the signal allows the receiver to process signals that are below the noise floor, something that is extremely difficult with conventional narrowband modulation schemes. Additionally, CSS is resilient to multipath fading and narrowband interferers, both of which are common in real-world environments such as urban disaster zones or cluttered RF spectra. This robustness directly translates into longer communication distances while maintaining very low transmit power, which is a core requirement for battery-powered and emergency-deployed devices.

What exactly are these 'chirps' and how do spreading factors affect them?
ans) A chirp in LoRa is a signal whose frequency increases or decreases linearly over time across the full channel bandwidth. Each LoRa symbol consists of one such chirp. The **spreading factor (SF)** determines how many distinct chirp patterns, or symbols, can be represented and how long each chirp lasts. A higher spreading factor means the chirp takes longer to sweep across the bandwidth, increasing the symbol duration. This increases processing gain, improves receiver sensitivity, and allows communication over longer distances, but at the cost of lower data rate. Conversely, a lower spreading factor produces shorter chirps, higher data rates, and reduced range. In practical terms, spreading factors allow LoRa systems to trade data rate for range and robustness, adapting the same modulation technique to very different link conditions without changing the underlying radio hardware.

3.2.2.2 Symbol, Spreading Factor, and Chip

In LoRa modulation, transmission is organized hierarchically using chips, symbols, and the spreading factor. A *chip* is the smallest time-frequency unit in the LoRa waveform and represents a single step in the chirp's frequency sweep across the channel bandwidth. A *symbol* is formed by a sequence of chips that together make up one complete chirp. The number of chips used to represent one symbol is determined by the spreading factor, mathematically given as,

$$\textbf{Number of chips per symbol} = \mathbf{2^{SF}}$$

This means that as the spreading factor increases, the symbol contains

exponentially more chips, and therefore takes longer to transmit. The symbol duration is directly related to this and is expressed as,

$$\text{Symbol duration (Ts)} = \frac{2^{SF}}{BW}, \text{ where BW is the channel bandwidth}$$

This relationship is central to understanding both data rate and range in LoRa systems.

The spreading factor range from SF7 to SF12 represents different operating points of the same modulation scheme. At SF7, each symbol consists of $2^7 = 128$ chips, resulting in the shortest symbol duration and the highest data rate among LoRa configurations. As the spreading factor increases step by step to SF12, the number of chips per symbol rises to 4096. This dramatically increases the symbol duration, allowing the receiver more time to correlate and detect the chirp, even when the received signal is extremely weak. Practically, SF7 is suited for short-range, higher-throughput links, while SF12 is optimized for maximum range and robustness, often used when devices are far from the gateway or operating in highly obstructed environments.

This leads directly to the trade-off between range and data rate, which is a defining characteristic of LoRa. Higher spreading factors increase processing gain, improve receiver sensitivity, and extend communication range, but they reduce the effective data rate because each symbol takes longer to transmit. Lower spreading factors reduce symbol duration and increase throughput, but require stronger received signals and therefore limit range. In networked systems, this trade-off also affects capacity, since higher spreading factors occupy the channel for longer durations, increasing airtime and reducing the number of devices that can be served simultaneously. As a result, selecting an appropriate spreading factor is not just a link-level decision but a system-level optimization balancing coverage, reliability, and network scalability.

SF7 to SF12 Comparative Overview

Spreading Factor	Symbol Duration	Data Rate	Receiver Sensitivity	Typical Use Case
SF7	Shortest	Highest	Lowest	Short range, good link quality

SF8	Short	High	Low	Moderate range
SF9	Medium	Medium	Medium	Balanced range and reliability
SF10	Long	Low	High	Long range, weaker signals
SF11	Longer	Very Low	Very High	Very long range
SF12	Longest	Lowest	Highest	Maximum range, extreme conditions

3.2.2.3 Bandwidth and Data Rates

In LoRa systems, bandwidth (BW) defines how wide the frequency range of each transmission is, and it directly influences symbol duration, data rate, and robustness. Commonly used bandwidth options are 125 kHz, 250 kHz, and 500 kHz. A narrower bandwidth such as 125 kHz results in longer symbol durations, which improves receiver sensitivity and extends range, making it the most widely used option for long-range communication. Increasing the bandwidth to 250 kHz or 500 kHz shortens symbol duration, enabling higher data rates but reducing sensitivity and therefore limiting range. As a result, wider bandwidths are typically used only when higher throughput is required and link conditions are good.

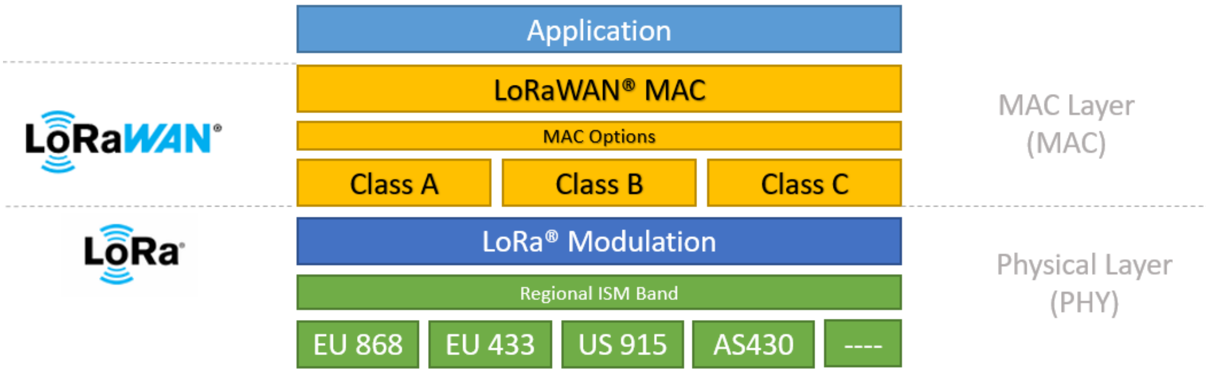
The data rate in LoRa is determined jointly by bandwidth, spreading factor, and coding rate. Conceptually, increasing bandwidth allows chirps to sweep faster across the frequency range, which reduces symbol time and increases the number of symbols transmitted per second. Lower spreading factors further increase data rate by reducing how long each symbol lasts, while higher spreading factors slow down transmission to improve robustness. Coding rate adds redundancy for error correction, improving reliability but slightly reducing the effective payload rate. Together, these parameters define the achievable data rate rather than bandwidth alone.

How does LoRa organize data from the chip level to the network level?'
ans) At the lowest level, data is represented as chips that form chirps, which combine to create symbols according to the chosen spreading factor and bandwidth. These symbols are assembled into frames at the physical layer and transmitted over the air using LoRa modulation. Above this, the LoRaWAN protocol structures these frames

into packets with headers, device addressing, and security features, and manages how devices access the network through gateways and network servers. In essence, LoRa handles how bits become radio signals, while LoRaWAN organizes those signals into a scalable, managed network that can support many devices simultaneously.

3.2.3 LoRa Protocol Stack

The LoRa protocol stack is structured in layers, where each layer has a clearly defined responsibility, allowing long-range radio communication to scale into a managed network.



Physical Layer (Complete FalconResQ project sits here)

The physical layer is responsible for the actual radio transmission and reception of data. It defines how bits are converted into radio signals using Chirp Spread Spectrum modulation, along with parameters such as bandwidth, spreading factor, coding rate, transmit power, and frequency channels. This layer handles signal robustness, range, and sensitivity, but it has no awareness of networking concepts like device identity or security. Its role is strictly to move raw data reliably over the air.

MAC Layer

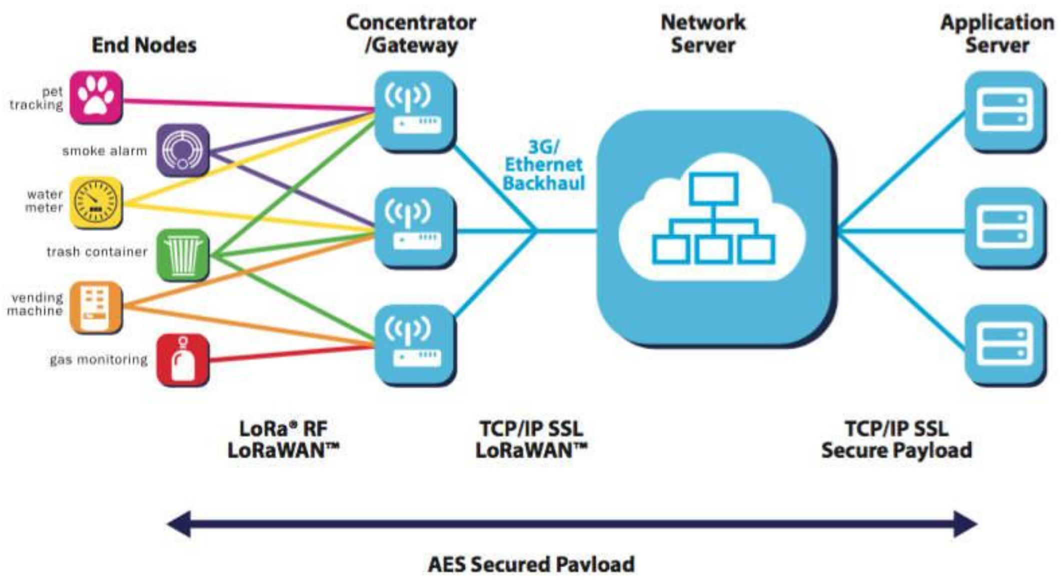
The MAC layer is where LoRaWAN logic begins. It controls how devices access the shared radio medium and how messages are formatted and managed. This layer defines frame structure, device addressing, message types, acknowledgements, adaptive data rate behaviour, and security mechanisms such as message integrity and encryption. It also manages uplink and downlink scheduling to ensure devices can communicate efficiently while respecting duty-cycle and power constraints. The MAC layer is essential for coordinating many devices over the same radio channels without centralized timing.

Application Layer

The application layer carries the actual user data, often called the payload. This layer is independent of the radio and network mechanics and focuses purely on application-specific information, such as sensor readings or emergency messages. Payload formatting, interpretation, and higher-level logic are handled here, allowing applications to evolve without changing the underlying communication system.

3.2.3.1 LoRaWAN Network Architecture

The LoRaWAN network follows a star-of-stars architecture, where end devices communicate with gateways, and intelligence is centralized in backend servers.



End Devices

End devices are low-power nodes such as sensors or emergency beacons. They transmit data using LoRa modulation and do not connect directly to each other. End devices are designed to be energy efficient, often spending most of their time in sleep mode and waking only to transmit or receive data. They are typically unaware of which gateway receives their message.

Gateway

Gateways act as transparent bridges between end devices and the network backend. They receive LoRa radio packets from end devices and forward them to the network server over IP-based backhaul such as Ethernet, cellular, or satellite links. Gateways do not make decisions about security, routing, or device management, their role is to provide wide-area radio coverage.

Network Server

The network server is the core intelligence of the LoRaWAN network. It manages device authentication, removes duplicate packets received by multiple gateways, enforces network policies, controls adaptive data rate, and schedules downlink messages. It ensures efficient use of spectrum and coordinates communication across the entire network.

Application Server

The application server handles the decrypted application payload and delivers it to end-user applications. It is responsible for interpreting data, triggering alerts, storing information, and integrating with external systems. This separation ensures that network operation and application logic remain independent, improving scalability and security.

Together, this layered protocol stack and centralized network architecture allow LoRaWAN to support long-range, low-power communication for a large number of devices, which aligns well with use cases requiring resilience, scalability, and minimal infrastructure.

3.2.4 LoRaWAN Device Classes

LoRaWAN defines different device classes to balance power consumption, downlink latency, and network responsiveness. These classes apply when operating within a LoRaWAN MAC and network context, and they describe when and how an end device can receive downlink messages relative to its uplink transmissions.

Class A (FalconResQ uses this)

Class A devices are bi-directional end devices and represent the baseline, mandatory mode of operation in LoRaWAN. Communication is primarily uplink-driven, meaning the end device initiates communication whenever it has data to send. After each uplink transmission, the device opens two short receive windows at predefined time offsets, during which downlink messages can be received. Outside of these windows, the device remains in a low-power sleep state.

This model results in very low power consumption, making Class A the most energy-efficient device class. The trade-off is that downlink latency is unpredictable, since the network can only send data immediately after an uplink. For systems like FalconResQ, this behavior aligns well with emergency or event-driven messaging, where the device primarily sends information outward and only occasionally needs to receive commands or acknowledgements.

Class B

Class B devices extend Class A behavior by introducing scheduled receive windows. In addition to the receive windows following uplinks, Class B devices periodically open extra receive slots at known times. These slots are synchronized using network beacons, which allow the device to maintain a shared time reference with the network.

This predictable scheduling enables the network to initiate downlinks with bounded latency, which is not possible in pure Class A operation. However, maintaining synchronization and opening additional receive windows increases power consumption compared to Class A. Class B is typically used in applications where devices need occasional but time-bounded downlink communication, such as periodic control updates.

Class C

Class C devices keep their receiver open almost continuously, except when transmitting uplinks. This allows the network to send downlink messages at virtually any time, resulting in minimum downlink latency.

The advantage of Class C is responsiveness, but the cost is high power consumption, making it unsuitable for battery-powered or energy-constrained devices. Class C devices are usually mains-powered actuators or control nodes where power availability is not a limiting factor.

Device Class	Receive Window Behavior	Downlink Latency	Power Consumption	Typical Use Case
Class A	Only after uplink transmissions	Highest, uplink-dependent	Lowest	Battery-powered sensors, emergency beacons
Class B	Scheduled receive windows plus Class A behavior	Bounded and predictable	Medium	Devices needing periodic downlink control
Class C	Continuous listening except during TX	Lowest	Highest	Mains-powered actuators, real-time control

NOTE: Since FalconResQ operates solely at the LoRa physical layer and does not implement LoRaWAN MAC functionality, these device classes are not applicable to the beacon, drone module, or ground receiver which we will be talking about shortly!

3.2.5 LoRa Physical Layer Packet Format

LoRa uses two types of physical layer packet formats for data transmission — explicit mode and implicit mode. These relate to how packet headers and synchronization information are included in LoRa radio packets.

3.2.5.1 Explicit Mode (Primary for FalconResQ)

In explicit mode, the LoRa packet includes fields that help the receiver understand the structure and contents of the incoming packet before decoding the payload. This mode is the typical mode used in point-to-point LoRa communication because it enables flexible payload lengths and error checking without requiring fixed packet sizes, which is helpful for the diverse message sizes used in FalconResQ.

The major elements of a LoRa packet in explicit mode are:

- Preamble
  This is a sequence of symbols used to synchronize the receiver with the transmitter. In LoRa modulation, the preamble field must have 8 symbols, and most radio implementations (including the Heltec modules used in FalconResQ) automatically add extra symbols, resulting in a total preamble length of about 13 symbols on air. This ensures the receiver can lock onto the signal before the data arrives.
- Physical Header (PHDR)
  This optional header contains information about the upcoming payload, such as its size and whether CRC (error detection) is used. It allows the receiver to prepare for the correct payload length and decoding parameters.
- Header CRC (PHDR_CRC)
  When present, this is a small error-checking code that helps detect errors in the header. The header and its CRC are encoded using a low coding rate (4/8) to improve robustness against noise and interference.

- **PHY Payload**
  This is the actual data being transmitted by the application It consists of the user payload and may include an optional CRC to detect errors in the payload data. The physical payload and the optional CRC are encoded using one of the allowed coding rates (e.g., 4/5, 4/7, etc.), and the whole packet is sent using a selected spreading factor (SF7 to SF12).

The following figure shows the physical layer structure of uplink and downlink packets that uses explicit mode.

Preamble	PHDR	PHDR_CRC	PHYPayload	CRC

a. Physical structure of an uplink packet

Preamble	PHDR	PHDR_CRC	PHYPayload

b. Physical structure of an uplink packet

3.3 Radio Frequency (RF) Fundamentals

Now that we understand LoRa's modulation, what about the radio frequency regulations, power measurements, and propagation characteristics we need to consider?

3.3.1 Frequency Bands and Regulations

LoRa operates in unlicensed ISM frequency bands, which allows devices to communicate without requiring individual spectrum licenses. The exact frequency band depends on the geographic region. Commonly used bands include 433 MHz, 865 MHz, and 915 MHz, with each region enforcing its own regulatory limits.

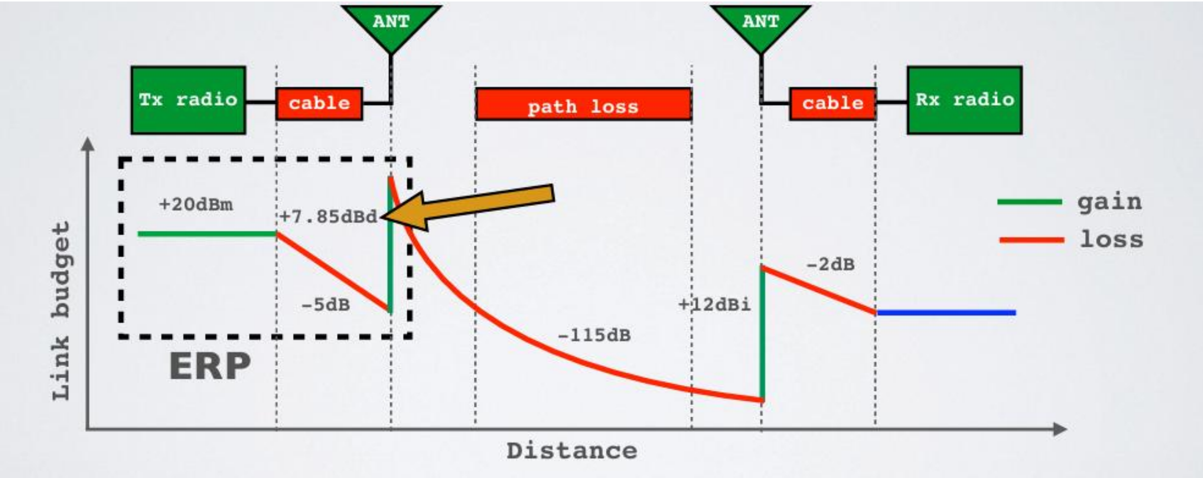
Regulations typically restrict maximum transmit power, duty cycle, and channel bandwidth to ensure fair spectrum usage and reduce interference between users. Devices must comply with these limits to operate legally. These constraints influence system design choices such as data rate, transmission interval, and range, especially for long-range, low-power applications like FalconResQ.

3.3.1.1 Indian Regulations for LoRa (865-867 MHz)

In India LoRa systems must operate within the licensed-exempt ISM band from 865 MHz to 867 MHz, which is reserved for low-power wide-area communications without requiring individual radio spectrum licenses. This band is officially designated as unlicensed under national rules, meaning devices can legally transmit in this range without paying for a spectrum allocation, provided they meet the equipment and usage conditions set by the government. The Wireless Planning & Coordination (WPC) wing under the Department of Telecommunications (DoT) oversees these regulations and issues the rules that define how low-power devices can operate in this band. The 865–867 MHz range is narrower than Europe's unlicensed band, so LoRa modules must be configured so that all transmit frequencies lie within this legal window to avoid out-of-band operation.[3.3a][3.3b]

Within this band, Indian regulations allow unlicensed usage for industrial, scientific and medical communication equipment including LoRa and other short-range devices, as long as they adhere to defined limits on transmission characteristics. Because this spectrum is unlicensed, equipment is not required to obtain an individual license before use, but manufacturers and deployers must ensure the hardware complies with national standards for electromagnetic emissions and interference. This enables widespread deployment of IoT and low-power systems while protecting the overall spectrum environment.[3.3c]

Regarding power limits, India permits low-power transmissions in the 865–867 MHz band with constraints on the effective radiated power (ERP). Typical implementations and local guidelines suggest that devices operating in this band may use up to about 30 dBm ERP*, which is equivalent to 1 W of transmit power accounting for antenna gain. Higher power levels can increase communication range but must remain within regulatory limits to prevent interference with other users of the unlicensed spectrum. Indian rules also define duty-cycle or similar time-on-air parameters to ensure fair use of the band across multiple devices; although specific duty-cycle restrictions vary by region, most broadcasters aim to stay within practical transmit limits (such as around 1 % for continuous uplinks) to comply with general unlicensed usage norms.[3.3d]



***The Effective Radiated Power (ERP) is the total power radiated by an actual antenna relative to a half-wave dipole rather than a theoretical isotropic antenna.**

3.3.2 Duty Cycle and Time on Air (ToA)

Duty cycle and Time on Air are closely related concepts used to control how long a radio occupies the shared spectrum. They are especially important in unlicensed bands to reduce interference and ensure fair coexistence between multiple users.

3.3.2.1 Duty Cycle Concept

Duty cycle is defined as the percentage of time a device is actively transmitting compared to the total observation time. In simple terms, it limits how often a radio is allowed to transmit so that no single device monopolizes the channel.

In many regions, especially Europe, a 1% duty cycle rule is enforced in specific sub-bands. This means a device is allowed to transmit for only 1% of the time and must remain silent for the remaining 99%. For example, if a transmission occupies the channel for 1 second, the device must wait approximately 99 seconds before transmitting again on the same sub-band. This rule is regulatory in nature and is designed to protect other users operating in the same unlicensed spectrum.

The duty cycle is commonly expressed using the relationship:

$$\text{Duty Cycle} = \frac{\textbf{ToA}}{(\textbf{ToA} + \textbf{Wait Time})}$$

Where:

- Time on Air (ToA) is the actual duration for which a LoRa packet is present on the air, from the start of the preamble to the end of the payload

- Wait Time is the mandatory silent period after transmission required to meet duty-cycle limits

3.3.2.1 Time on Air (ToA) Concept

Time on Air (ToA) is the total duration for which a LoRa packet occupies the radio channel, measured from the start of the preamble to the end of the payload. It is a critical parameter because it directly affects collision probability, power consumption, and regulatory compliance. ToA depends on spreading factor (SF), bandwidth (BW), coding rate (CR), and payload size.

General ToA calculation:
LoRa ToA is computed in two main parts, preamble time and payload time.

1. Symbol duration (T_{sym})

   $$T_{\text{sym}} = \frac{2^{\text{SF}}}{\text{BW}}$$

   This shows that symbol duration grows exponentially with spreading factor and decreases with bandwidth.

2. Preamble duration ($T_{preamble}$)

   $$T_{\text{preamble}} = \left(N_{\text{preamble}} + 4.25\right) T_{\text{sym}}$$

   For LoRa, the configured preamble is typically 8 symbols, with the radio adding 4.25 symbols internally.

3. Payload symbol calculation
   The number of payload symbols depends on SF, CR, payload length, header mode, and CRC enable. In simplified form, the payload symbol count increases when:
   - Payload size increases
   - Spreading factor increases
   - Coding rate adds more redundancy

4. Total Time on Air
   This total duration represents how long the channel is occupied by one packet.

   $$T_{\text{packet}} = T_{\text{preamble}} + T_{\text{payload}}$$

Calculations custom to FalconResQ:
The following are the parameters used for demonstration purpose:

Parameter	Value

Channel Frequency	866.1 MHz
Transmit Power	17 dBm
Spreading Factor (SF)	SF7
Bandwidth (BW)	125 kHz
Coding Rate (CR)	4/5
Payload Size	66 bytes
Header Mode	Explicit
CRC	Enabled
Preamble Length	8 symbols
Transmission Interval	5 seconds

Step 1: Symbol duration

The LoRa symbol duration depends only on spreading factor and bandwidth.

$$T_{\text{sym}} = \frac{2^{\text{SF}}}{\text{BW}}$$

$$T_{\text{sym}} = \frac{2^7}{125000} = \frac{128}{125000}$$

$$T_{\text{sym}} \approx 1.024 \text{ ms}$$

Step 2: Preamble duration

LoRa radios add 4.25 symbols internally to the programmed preamble.

$$T_{\text{preamble}} = (8 + 4.25) \times 1.024$$

$$T_{\text{preamble}} \approx 12.25 \times 1.024 \approx 12.54 \text{ ms}$$

Step 3: Payload symbol calculation

For explicit header mode with CRC enabled, the payload symbol count is determined by payload length, spreading factor, and coding rate.

Using the standard LoRa payload symbol formulation:

- **Payload = 66 bytes**
- **SF = 7**
- **CRC = enabled**

- Header = explicit
- Coding rate = 4/5

The resulting payload symbol count is 103 symbols.

(This value is typically obtained using the standard LoRa payload symbol equation)

Step 4: Payload duration

$$T_{\text{payload}} = 103 \times 1.024 \approx 105.5 \text{ ms}$$

Step 5: Total Time on Air

$$T_{packet} = T_{preamble} + T_{payload}$$

$$T_{\text{packet}} \approx 12.54 + 105.5 \approx 118 \text{ ms}$$

Final Result

Total Time on Air ≈ 118 milliseconds per packet

Duty-cycle perspective at 5-second interval
With one transmission every 5 seconds:

$$\text{Effective duty cycle} = \frac{0.118}{5} \approx 2.36\%$$

Duty Cycle: 2.36%

3.3.3 Frequency Hopping Strategy

To improve reliability in congested or interference-prone environments, FalconResQ implements a lightweight frequency hopping strategy at the application layer, built on top of raw LoRa physical-layer communication. This approach is not LoRaWAN frequency hopping, but a custom-designed multi-channel access mechanism tailored for decentralized emergency communication.

Changing Frequencies for Every Transmission:
FalconResQ defines four distinct carrier frequencies within the Indian 865–867 MHz ISM band, namely 866.1 MHz, 866.3 MHz, 866.5 MHz, and 866.7 MHz. These frequencies are preconfigured in firmware and represent independent logical channels available to the beacon.

Rather than transmitting repeatedly on a single fixed frequency, the system changes the transmission frequency on a per-frame basis. At the start of each transmission frame, the firmware selects one of the available channels and configures the radio accordingly before attempting transmission. This behavior ensures that consecutive packets are not concentrated on a single frequency, thereby reducing persistent collisions and narrowband interference effects.

This strategy is particularly important in scenarios where many FalconResQ beacons may be active simultaneously, such as disaster zones or crowded rescue environments.

3.3.3.1 Pseudo-Random Channel Selection

Channel selection in FalconResQ is pseudo-random, implemented through a software-based random choice among the four predefined frequencies. During the select_random_slot_and_channel() routine (of Arduino Code), the firmware randomly assigns both:

- A time slot within the uplink window
- A frequency channel from the available channel set

This pseudo-randomization ensures that different devices are statistically unlikely to choose the same frequency and time slot repeatedly. Over multiple frames, traffic is spread both in time and frequency, which significantly reduces the probability of repeated packet collisions even without centralized coordination.

3.3.3.2 Dwell Time and Hop Time Definitions

In the context of FalconResQ, dwell time refers to the actual Time on Air of a single LoRa transmission on a given frequency. This is determined by physical-layer parameters such as spreading factor, bandwidth, coding rate, preamble length, and payload size. Once a packet transmission is completed, the radio immediately returns to standby or receive mode, meaning the dwell time on any one frequency is limited to a single packet.

Hop time, on the other hand, is defined by the system's frame-based scheduling logic. FalconResQ divides time into frames of fixed duration, with each frame allowing exactly one transmission attempt per device. At the beginning of a new frame, the device hops to a newly selected frequency and slot. This results in a hop time equal to the frame duration, ensuring that the radio does not repeatedly occupy the same frequency across frames.

3.3.3.3 Interaction with Channel Activity Detection

Before transmitting on the selected frequency, FalconResQ performs a Channel Activity Detection (CAD) step using RSSI-based sensing. If the channel appears busy, the device refrains from transmitting in that slot and waits until the next frame to retry, potentially on a different frequency. This further strengthens the hopping strategy by combining frequency diversity with polite channel access, similar in spirit to carrier sensing mechanisms.

3.3.4 RF Power Measurements

RF power measurement refers to verifying the actual transmit power radiated by the LoRa radio, ensuring that the configured output power in firmware matches what is physically emitted by the antenna. In FalconResQ, transmit power is set at the physical layer and directly affects communication range, link reliability, and battery consumption.

The configured transmit power of the radio, for example 17 dBm, represents the output at the RF port of the transceiver. The effective radiated power also depends on antenna characteristics and losses in cables or PCB traces. Therefore, RF power measurements are typically performed using spectrum analyzers, power meters, or calibrated RF test setups to confirm that emissions remain within expected and permissible limits.

3.3.4.1 dBm (Decibels-milliwatt)

dBm is a logarithmic unit used to express absolute RF power relative to a fixed reference of 1 milliwatt. Unlike relative decibel units, dBm always refers to a real, physical power level, which makes it convenient for specifying transmitter output power, receiver sensitivity, and regulatory limits in RF systems.

The relationship between power in milliwatts and dBm is given by:

$$\text{dBm} = 10\log_{10}\left(\frac{Po}{1\text{mW}}\right) \text{ [Absolute Power]}$$

$$\text{dB} = 10\log_{10}\left(\frac{Po}{Pi}\right) \text{ [Relative Power]}$$

$$\{\text{If dB} > 0 \text{ it's Gain but if dB} < 0 \text{ Attenuation}\}$$

Where, Po – Output Power (W)

Pi – Input Power (W)

This logarithmic representation allows very small and very large power levels to be expressed compactly and makes it easier to compare gains and losses in an RF chain.

For example, 0 dBm corresponds to 1 mW of power. Increasing the power by 10 dB results in a tenfold increase in linear power, so 10 dBm equals 10 mW, 20 dBm equals 100 mW, and 30 dBm equals 1 W. Similarly, negative dBm values represent power levels below 1 mW, which are common when describing received signal strength in wireless systems.

3.3.4.2 dBi (Decibels-isotropic)

dBi is a unit used to describe antenna gain relative to an ideal isotropic radiator, which is a theoretical antenna that radiates power equally in all directions. Unlike dBm, which represents absolute power, dBi is a relative measure that indicates how effectively an antenna concentrates radiated energy in certain directions compared to this ideal reference. An antenna with 0 dBi gain radiates energy uniformly, matching the isotropic reference. A positive dBi value means the antenna focuses energy more efficiently in particular directions, resulting in higher signal strength in those directions without increasing transmitter power. This focusing effect improves communication range but usually comes at the cost of reduced radiation in other directions.

In practical LoRa deployments, typical compact antennas provide around 2 to 3 dBi of gain, which offers a good balance between omnidirectional coverage and improved link performance.

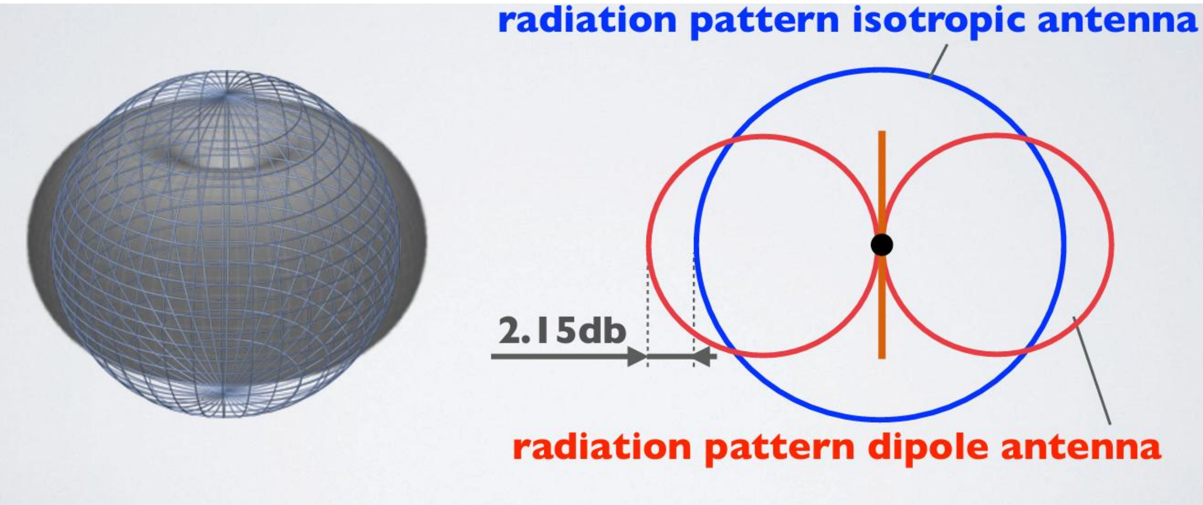
3.3.4.3 dBd (Decibels-dipole)

dBd is a unit used to express antenna gain relative to a reference dipole antenna, typically a half-wave dipole. Unlike dBi, which uses an ideal isotropic radiator as the reference, dBd compares an antenna's performance to a practical and commonly used antenna type.

A half-wave dipole itself has inherent gain compared to an isotropic radiator. Because of this, gain values expressed in dBd are always numerically smaller than the same antenna's gain expressed in dBi. The relationship between the two units is fixed and given by:

$$\text{dBi} = \text{dBd} + 2.15$$

This means that an antenna with 0 dBd gain has 2.15 dBi gain, and an antenna specified as 2 dBd corresponds to 4.15 dBi.



Difference in the radiation pattern between an isotropic and a dipole antenna

3.3.4.4 EIRP and ERP

Effective Isotropic Radiated Power (EIRP) is a measure of the total RF power radiated by a system when referenced to an ideal isotropic antenna. It combines the transmitter output power with antenna gain and accounts for any losses in cables or connectors. EIRP represents how strong the signal would appear if the same power were radiated equally in all directions, which makes it the most common reference used in regulations and link budget calculations.

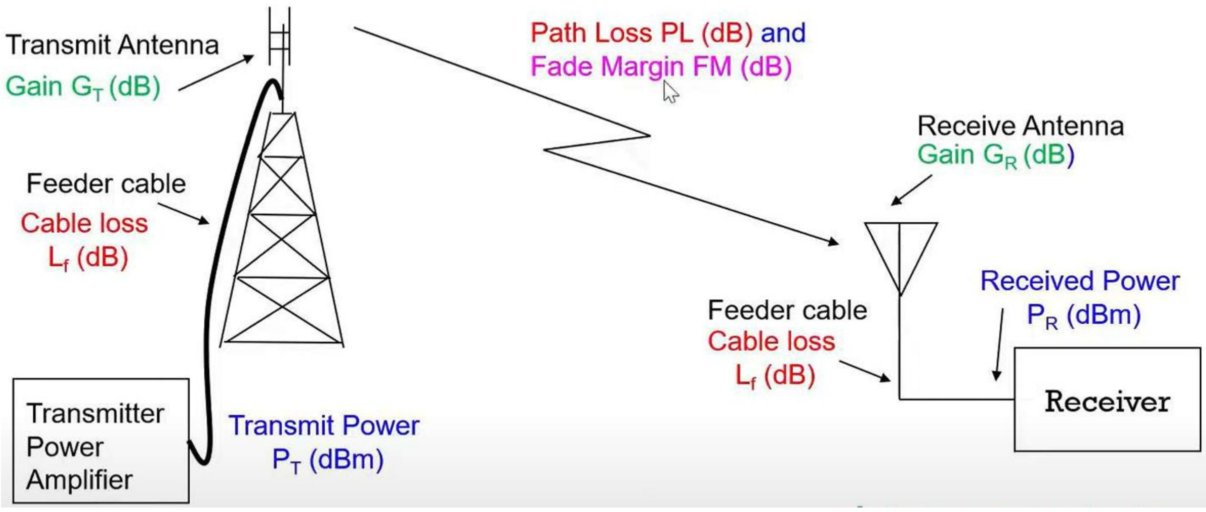
Effective Radiated Power (ERP) is similar in concept, but it is referenced to a half-wave dipole antenna instead of an isotropic radiator. Since a dipole has an inherent gain of 2.15 dB compared to an isotropic antenna, ERP values are numerically lower than EIRP for the same physical transmission. The relationship between them is fixed, where EIRP is always 2.15 dB higher than ERP for the same system.

From a regulatory standpoint, legal transmission limits are usually specified in terms of EIRP, because it provides a universal reference independent of antenna type. For systems like FalconResQ operating in unlicensed bands, compliance is ensured by keeping the combined effect of transmitter power and antenna gain within the permitted EIRP limit. Even if the transmitter output power is modest, using a higher-gain antenna can increase EIRP, which is why antenna choice is as important as radio power settings when evaluating legal and practical RF performance.

3.3.5 Link Budget Analysis[3.3e]

Link budget analysis is used to estimate whether a wireless communication link will work over a given distance. It accounts for transmitted power, losses during propagation, antenna gains, and receiver sensitivity. One of the most fundamental components of this analysis is Free Space Path Loss (FSPL), which models signal attenuation in an ideal, unobstructed environment.

Components Breakdown:



1. **Transmit Power (Pt)**
   RF power generated by the transmitter and fed into the antenna system, defined in dBm, for FalconResQ this is set by the Heltec module.

2. **Transmit Antenna Gain (Gt)**
   Measures how effectively the transmit antenna concentrates energy in space compared to an isotropic radiator.

3. **Transmit Feeder Cable Loss (Lt)**
   Power lost between the transmitter and antenna due to cables, connectors, or PCB traces.

4. **Path Loss (PL)**
   Signal attenuation as the wave propagates through space, primarily dependent on distance and frequency.

5. **Fade Margin (FM)**
   Extra design margin to account for real-world effects like fading, shadowing, and environmental variability.

6. Receive Antenna Gain (Gr)
   Improvement in received signal strength due to the receiving antenna's ability to capture RF energy.

7. Receive Feeder Cable Loss (Lr)
   Power loss between the receive antenna and receiver input, usually small in compact systems.

8. Received Power (Pr)
   Final signal power at the receiver input, compared against receiver sensitivity to determine link reliability.

$$P_R\,(\mathrm{dBm}) = P_T\,(\mathrm{dBm}) - L_f\,(\mathrm{dB}) + G_t\,(\mathrm{dB}) - L_p\,(\mathrm{dB}) + G_R\,(\mathrm{dB}) - L_f\,(\mathrm{dB}) - \mathrm{FM}\,(\mathrm{dB})$$

The above is the equation to calculate the received power (dBm) where, +ve is for source/gain & -ve is for loss, FM is the fade margin

3.3.5.1 Free Space Path Loss (FSPL)

Free Space Path Loss (FSPL) represents the reduction in signal strength as a radio wave propagates through free space, assuming a clear line of sight with no reflections, obstacles, or absorption. Although real-world environments introduce additional losses, FSPL provides a useful baseline for understanding how distance and frequency affect signal attenuation.

The link budgeting done when the beacon operates @ 866.1 Mhz for various distances (between beacon - drone module) are as shown below:

Case 1: Distance of separation is 500 m ~ 0.5 Km

	Frequency	866.1	Mhz			
	Wavelength	0.3463803256	m			
	Distance Between Tx Rx	500	m			
Free Space Path Loss (FSPL)	FSPL	3.29E+08				
		85.17253304	dB	Transmitted Power	0.0501187234	W
	Polarization loss		dB		17	dBm
	Total path loss	85.17253304	dB	Received Power	-68.17253304	dBm
						dBm=decibel relative to 1 milliwatt

Case 2: Distance of separation is 1 Km

	Frequency	866.1	Mhz			
	Wavelength	0.3463803256	m			
	Distance Between Tx Rx	1000	m			
Free Space Path Loss (FSPL)	FSPL	1.32E+09				
		91.19313296	dB	Transmitted Power	0.0501187234	W
	Polarization loss		dB		17	dBm
	Total path loss	91.19313296	dB	Received Power	-74.19313295	dBm
						dBm=decibel relative to 1 milliwatt

Case 3: Distance of separation is 5 Km

	Frequency	866.1	Mhz			
	Wavelength	0.3463803256	m			
	Distance Between Tx Rx	5000	m			
Free Space Path Loss (FSPL)	FSPL	3.29E+10				
		105.172533	dB	Transmitted Power	0.0501187234	W
	Polarization loss		dB		17	dBm
	Total path loss	105.172533	dB	Received Power	-88.17253304	dBm
						dBm=decibel relative to 1 milliwatt

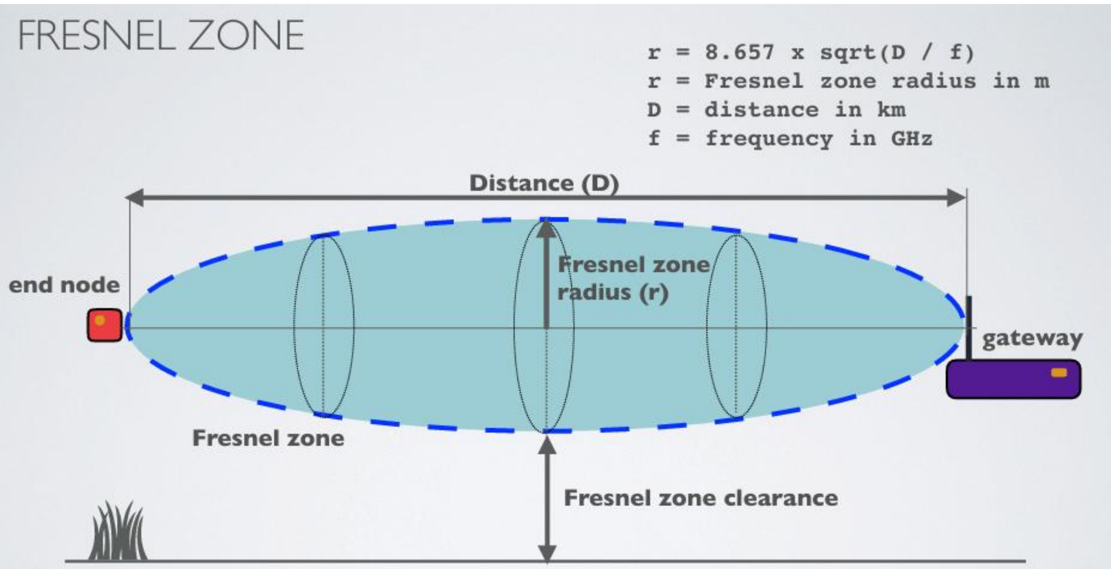
Case 4: Distance of separation is 10 Km

	Frequency	866.1	Mhz			
	Wavelength	0.3463803256	m			
	Distance Between Tx Rx	10000	m			
Free Space Path Loss (FSPL)	FSPL	1.32E+11				
		111.193133	dB	Transmitted Power	0.0501187234	W
	Polarization loss		dB		17	dBm
	Total path loss	111.193133	dB	Received Power	-94.19313295	dBm
						dBm=decibel relative to 1 milliwatt

Click here to view the sheet I made and used for calculating the link budget, below is the image of the same:

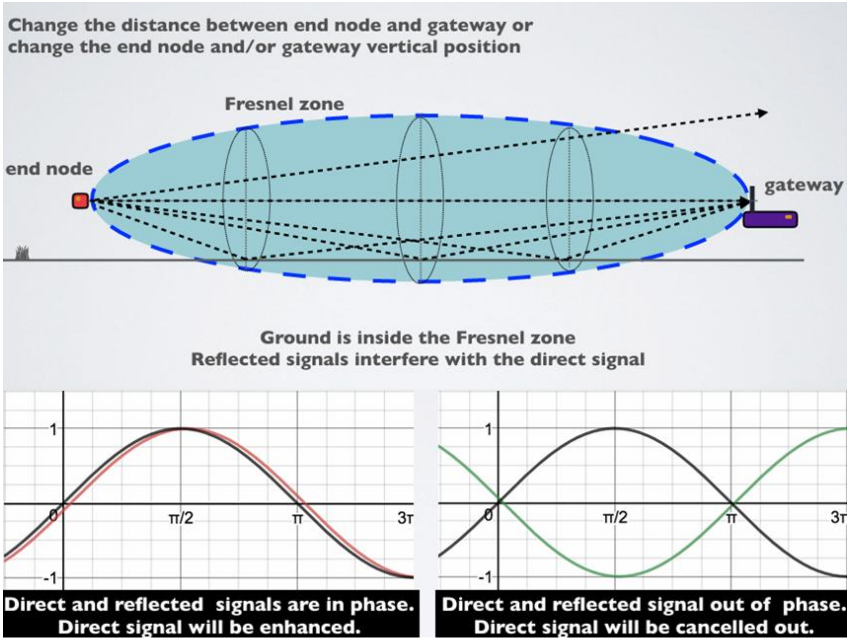
Legends:	Enter Value	Auto Calculated	Results			
	Basic Initial Values	Results to call again manually				
	Path Loss Calculation					
	Frequency	866.1	Mhz			
	Wavelength	0.3463803256	m			
	Distance Between Tx Rx	10000	m			
Free Space Path Loss (FSPL)	FSPL	1.32E+11				
		111.193133	dB	Transmitted Power	0.0501187234	W
	Polarization loss		dB		17	dBm
	Total path loss	111.193133	dB	Received Power	-94.19313295	dBm
						dBm=decibel relative to 1 milliwatt
	Height of Tx	0.1	m			
	Height of Rx	0.1	m			
Plane Earth Model	Path loss	200	dB	Transmitted Power	5	W
	Polarization loss		dB		36.98970004	dBm
	Total path loss	200	dB	Received Power	-163.0103	dBm
Okamura Hata Model *f ~ 150 - 1500 MHz* *Tx height ~ 30 - 200 m* *Rx height ~ 1 - 10 m* *Tx-Rx dist ~ 1 - 20 km*	A(hre)	-4.954303031	dB	*For, f >= 300 MHz*		
	Total path loss	216.6210829	dB			
	Link Budgeting					
	Transmitted Power	5	W			
		36.98970004	dBm			
	Tx Cable loss		dB			
	Gain of transmitter antenna		dB			
	Total path loss		dB	*To be entered on the basis of above 3 model's results*		
	Gain of receiver antenna		dB			
	Rx Cable loss		dB			
	Received Power	36.98970004	dBm			

3.3.5.2 Fresnel Zone

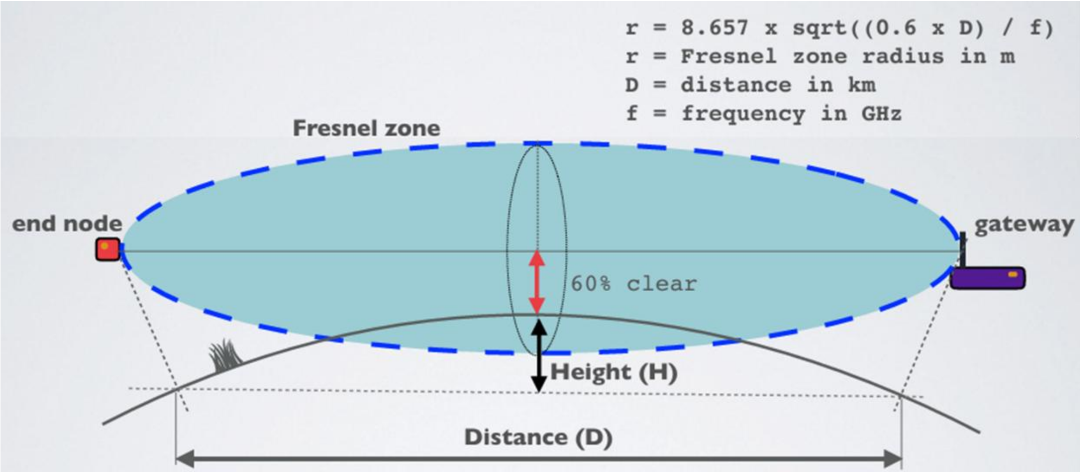


The Fresnel zone refers to an elliptical region around the direct line-of-sight path between a transmitter and a receiver through which radio waves propagate. Even when there is a clear visual line between two antennas, radio energy does not travel as a thin straight line, it spreads out into this surrounding region. Objects intruding into the Fresnel zone can cause diffraction and phase cancellation, leading to signal weakening even though line-of-sight technically exists.

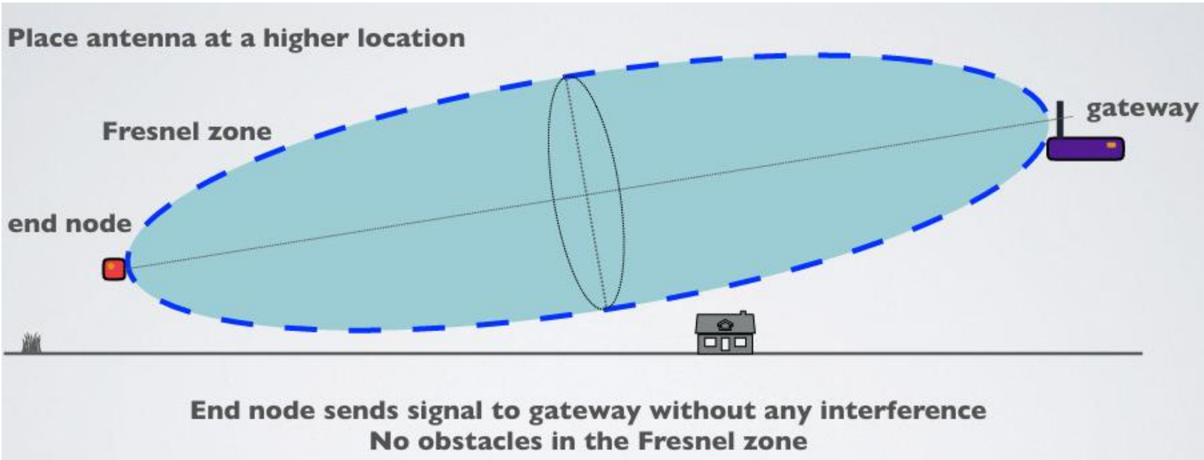
The Fresnel zone is important because obstructions within this region reduce received signal strength, increase fading, and make the link less reliable. This effect becomes more pronounced at longer distances and lower frequencies, both of which are relevant to long-range LoRa communication such as FalconResQ.



A commonly used engineering guideline is the 60% Fresnel zone clearance rule. This rule states that at least 60% of the first Fresnel zone radius should be free of obstacles along the entire link path. Full clearance is ideal, but 60% clearance ensures that most of the propagating energy is not significantly obstructed, keeping diffraction losses within acceptable limits.



In terms of impact on line-of-sight, Fresnel zone clearance explains why some links fail even when antennas can see each other visually. Buildings, terrain, trees, or even the ground itself encroaching into the Fresnel zone can degrade performance. For FalconResQ, this means that antenna placement height and positioning are as critical as transmit power or spreading factor. Ensuring adequate Fresnel zone clearance improves range, link stability, and overall reliability, especially in long-distance or emergency deployments.



Once we receive a signal, how do we know if it's good quality?, That's when the various signal quality metrics come into picture

3.3.6 Signal Quality Metrics

Signal quality metrics are used to evaluate how reliably a received radio signal can be decoded, beyond just whether it is detected or not. In long-range, low-power systems like FalconResQ, these metrics are critical because communication often occurs near the sensitivity limits of the receiver.

One of the primary metrics is RSSI (Received Signal Strength Indicator), which represents the total received signal power at the receiver input. RSSI gives a coarse indication of link strength and is useful for detecting whether a channel is occupied or estimating relative distance. However, RSSI alone does not indicate whether a signal can be successfully decoded, especially in noisy environments.

Another key metric is SNR (Signal-to-Noise Ratio), which measures how much stronger the desired signal is compared to the background noise. LoRa is designed to operate at very low, and even negative, SNR values, which is one of the reasons it achieves long-range communication. SNR is a more meaningful indicator of link reliability than RSSI, particularly when interference or noise is present.

Packet Error Rate (PER) and Bit Error Rate (BER) are higher-level metrics that reflect how often transmitted data is received incorrectly. These metrics capture the combined effects of noise, interference, fading, and synchronization errors. In FalconResQ, maintaining a low packet error rate is more important than achieving high data rates, since emergency messages must be delivered reliably even under adverse conditions.

3.3.6.1 Received Signal Strength Indicator (RSSI)

RSSI represents the power level of the received radio signal at the receiver input. It is a physical-layer measurement reported by the LoRa radio and indicates how strong the incoming signal is, independent of whether the data can be successfully decoded.

RSSI is measured in dBm, which is an absolute power unit referenced to 1 milliwatt. Because received signals in wireless systems are very weak, RSSI values are usually negative. Values closer to zero indicate stronger signals, while more negative values indicate weaker signals.

In practical interpretation, an RSSI of around –30 dBm corresponds to an extremely strong signal, typically observed when the transmitter is very close to the receiver. Values between –60 dBm and –90 dBm generally indicate good to usable link conditions for LoRa communication. RSSI values approaching –120 dBm represent very weak signals near the sensitivity limit of the receiver, where successful decoding depends heavily on spreading factor, noise conditions, and interference.

3.3.6.2 Signal to Noise Ratio (SNR)

SNR represents the relationship between the received signal power and the background noise floor at the receiver. It indicates how clearly the desired signal stands out from noise and interference, making it a key metric for assessing decoding reliability in wireless links.

SNR is measured in decibels (dB). A positive SNR means the signal power is higher than the noise floor, which generally corresponds to good link conditions and reliable decoding. A negative SNR means the signal is weaker than the noise floor. Unlike many conventional radio systems, LoRa can still successfully decode signals at negative SNR values due to its Chirp Spread Spectrum modulation and processing gain.

For FalconResQ, SNR is more informative than RSSI when evaluating link quality. Even when RSSI values are low, a sufficiently favorable SNR can allow packets to be decoded reliably. This capability is fundamental to achieving long-range communication with low transmit power, especially in emergency scenarios where signals often operate near the sensitivity limits of the receiver.

3.3.7 Antennas & connectors

3.3.7.1 Antenna Connectors (SMA, RP-SMA, U.FL)

Antenna connectors provide the physical interface between the RF module and the antenna, and their correct selection is essential to avoid signal loss, mismatch, or hardware damage. In LoRa systems like FalconResQ, connector choice affects reliability, mechanical robustness, and ease of deployment.

Connector types and compatibility

1. SMA connectors are threaded RF connectors commonly used in RF modules and external antennas. In an SMA connector, the male connector has a center pin and the female has a socket. SMA connectors are

mechanically robust and suitable for repeated connections, making them ideal for fixed installations and field-deployable systems.

2. RP-SMA (Reverse Polarity SMA) connectors look similar to SMA but have the center pin and socket reversed. RP-SMA was originally introduced to discourage the use of high-gain antennas in consumer devices. SMA and RP-SMA are not electrically compatible, even though they may appear to mate mechanically. Using the wrong combination can result in an open connection and severe signal loss.
3. U.FL connectors are very small, snap-on RF connectors typically used inside compact devices. They are designed for lightweight internal connections between the RF module and an external antenna via a short coaxial cable. U.FL connectors are not meant for frequent connect and disconnect cycles and are more fragile compared to SMA-type connectors.
4. N-Type connectors are larger, heavy-duty RF connectors designed for low loss, high power handling, and outdoor use. They provide excellent impedance stability and weather resistance, which makes them common in base stations, gateways, outdoor antennas, and long-cable runs. N-type connectors are not used directly on small LoRa modules, but are often found on high-gain outdoor antennas connected via coaxial cables. Like SMA connectors, N Type connectors also have reverse polarity variations known as RP-N Type connectors.

Selection criteria:
Connector selection depends on the mechanical constraints and usage scenario. SMA connectors are preferred when durability, external antennas, and repeated handling are required. RP-SMA should only be used when explicitly specified by the antenna and module to ensure polarity matching. U.FL connectors are suitable for compact, embedded designs where space is limited and the antenna is connected internally. N-type connectors are ideal for outdoor, long-range, or permanent installations where durability and low loss are critical.

<u>Comparison of Antenna Connectors</u>

Connector Type	Description	Advantages	Disadvantages	Typical Use
SMA	Threaded RF connector with standard polarity	Robust, low loss, suitable for repeated connections, wide antenna availability	Larger size, requires panel space	External antennas, field-deployed systems
RP-SMA	SMA connector with reversed center pin polarity	Prevents accidental antenna mismatch, common in consumer RF devices	Easily confused with SMA, incompatible despite similar appearance	Consumer devices, regulated products
U.FL	Small snap-on micro RF connector	Very compact, lightweight, ideal for small PCBs	Fragile, limited mating cycles, higher insertion loss	Embedded modules, internal antenna links

3.3.7.2 Antennas & it's types

Antennas determine how radio energy is radiated and received in space, and their selection directly affects coverage, range, and link reliability in LoRa-based systems like FalconResQ.

Omnidirectional vs directional antennas

Omnidirectional antennas radiate energy roughly equally in all horizontal directions. This makes them well suited for mobile or unknown-orientation scenarios, where the relative position between transmitter and receiver cannot be predicted. In FalconResQ, omnidirectional antennas are appropriate for beacons and drone-mounted receivers, since signals may arrive from any direction during rescue operations.

Directional antennas, on the other hand, focus energy in a specific direction, increasing gain and extending range along that direction. While they can significantly improve link budget, they require careful alignment and are less practical for rapidly deployed or mobile systems unless the link direction is well known.

PCB antennas vs external antennas

PCB antennas are integrated directly onto the circuit board. They are compact, low-cost, and mechanically robust, but their performance is highly sensitive to board layout, enclosure material, and nearby components. As a result, their gain and radiation pattern are often limited and inconsistent.

External antennas, connected via SMA or U.FL connectors, generally provide better and more predictable performance. They offer higher gain options, improved radiation efficiency, and flexibility in placement, such as positioning the antenna away from obstructions. For FalconResQ, external antennas are preferred when maximum range and reliability are required, especially in outdoor or long-distance scenarios.

Polarization considerations

Polarization describes the orientation of the electric field of the radiated wave, commonly vertical or horizontal. For optimal signal reception, the transmitting and receiving antennas should have matching polarization. A polarization mismatch can introduce significant signal loss even if RSSI appears strong. In practical LoRa deployments, vertical polarization is most commonly used because it aligns well with typical monopole and whip antennas.

3.3.8 GPS Technology

Global Navigation Satellite Systems (GNSS) are satellite-based positioning systems that allow receivers to determine location, velocity, and time anywhere on Earth. Modern GNSS receivers, including those used in FalconResQ, often support multiple constellations to improve accuracy and availability.

1. GPS (United States):
   GPS is the oldest and most widely used GNSS. It consists of a constellation of medium Earth orbit satellites and provides global coverage. GPS is known for its reliability and is the primary positioning system supported by most receivers.
2. GLONASS (Russia):
   GLONASS is Russia's global navigation system. It operates similarly to GPS but uses a different frequency allocation scheme. When used together with GPS, GLONASS improves satellite visibility, especially at higher latitudes and in challenging environments.
3. Galileo (Europe):
   Galileo is Europe's GNSS and is designed to provide high-accuracy civilian positioning. It offers improved signal structure and accuracy compared to earlier systems and enhances robustness when combined with GPS and GLONASS.
4. BeiDou (China):
   BeiDou is China's global navigation system. It provides worldwide coverage and adds further redundancy and availability when used in multi-constellation receivers. Inclusion of BeiDou improves positioning performance in urban or obstructed areas.

3.3.8.1 GPS Signal Structure

GPS satellites transmit navigation signals on multiple frequency bands, each designed for specific purposes and performance characteristics.

- L1 band (1575.42 ± 10.23 MHz):

The L1 band is the most commonly used GPS signal and is supported by virtually all civilian receivers. It carries positioning and timing information and is widely used due to its compatibility and global availability.

- L2 band (1227.60 ± 10.23 MHz):

The L2 band was originally intended for military use but is now also accessible for civilian applications in modern receivers. Using L2 along with L1 helps reduce ionospheric errors and improves positioning accuracy.

- L5 band (1176.45 ± 10.23 MHz):

The L5 band is a newer civilian GPS signal designed for safety-critical applications. It offers higher signal power, better interference resistance, and improved accuracy. L5 is particularly useful in environments with multipath or interference.

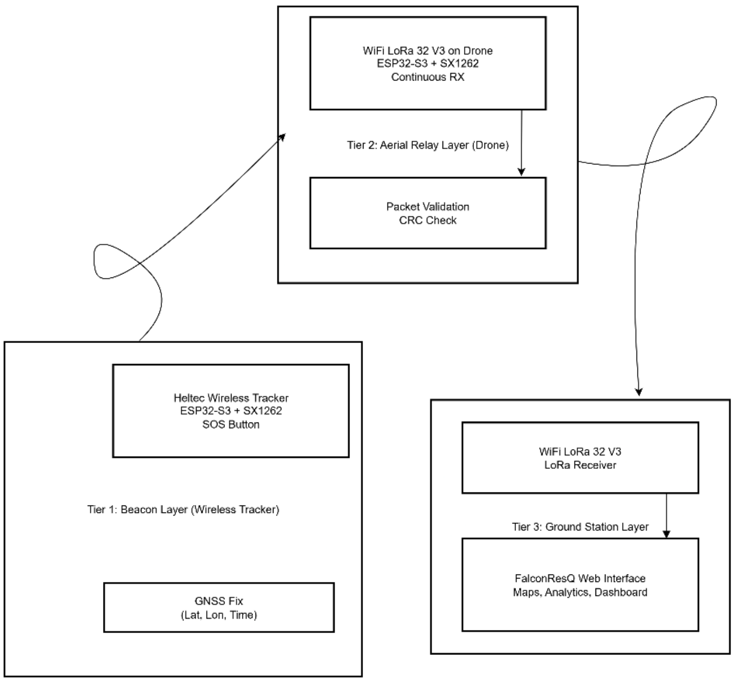
3.3.8.2 GNSS Start Times

GNSS receivers are characterized by how quickly they can acquire a position fix after power-up, commonly described using cold, warm, and hot start times. These start modes depend on how much satellite and system information is already available to the receiver.

- Cold start
  A cold start occurs when the GNSS receiver has no prior information about satellite positions, time, or its last known location. In this case, the receiver must search for satellites, download orbital data, and establish timing before computing a position fix. Cold start times are the longest, typically ranging from 30 seconds to a few minutes, depending on signal conditions and antenna quality.
- Warm start
  A warm start happens when the receiver has partial information available, such as approximate time and satellite orbital data, but no recent position fix. Since less data needs to be acquired, the receiver can lock onto satellites more quickly. Warm start times are moderate, usually on the order of 10 to 30 seconds.
- Hot start
  A hot start occurs when the receiver has valid satellite data, accurate time, and a recent position fix stored in memory. In this case, the receiver can immediately reacquire satellites and compute a position fix very quickly. Hot start times are typically a few seconds, often 1 to 5 seconds under good signal conditions.

CHAPTER 4:
Proposed Solution - System Design

4.1 Overall System Architecture



Three-Tier Wireless Architecture

FalconResQ follows a three-tier wireless architecture specifically chosen to match the capabilities and constraints of the Heltec boards used in the system. The design separates sensing, aerial relay, and data aggregation into distinct layers, improving range, scalability, and survivability in infrastructure-damaged environments.

At the first tier, the Wireless Tracker acts as the beacon module. According to Heltec's hardware documentation and schematics, the Wireless Tracker integrates an ESP32-S3, SX1262 LoRa transceiver, GNSS module, user button, and power-controlled peripheral rails on a compact board. In FalconResQ, this tier is responsible only for event detection and transmission: acquiring GNSS coordinates, packaging them into a compact payload, and broadcasting distress messages over LoRa. The tracker does not depend on internet connectivity or external infrastructure, aligning with its intended design as a low-power tracking and positioning device.

The second tier is the drone-mounted WiFi LoRa 32 V3, which functions as a mobile LoRa receiver and relay. Heltec's WiFi LoRa 32 V3 documentation shows that this board combines an ESP32-S3 with an SX1262 transceiver and flexible power and antenna routing, making it suitable for continuous receive operation. Mounted on a drone, this node exploits altitude to achieve improved line-of-sight reception. Its role in the architecture is not to generate distress data, but to listen continuously, validate received packets, and forward them onward. This tier effectively bridges the coverage gap between ground-level beacons and fixed infrastructure.

The third tier is the ground station, implemented using another WiFi LoRa 32 V3. Hardware-wise, this node is identical to the airborne receiver, but its function differs. Instead of mobility, it provides persistent connectivity to the FalconResQ web interface. Based on Heltec's software repositories and examples, the ESP32-S3 on the V3 board can simultaneously handle LoRa reception and higher-level data forwarding over USB, Wi-Fi, or serial links. In FalconResQ, this tier aggregates incoming packets and exposes them to the website for visualization, analytics, and decision support.

4.1.1 Communication flow:

Communication Flow Under Low-Traffic Conditions
In scenarios where the number of active beacons is small i.e, where the number of stranded people are less, FalconResQ operates in a single-channel uplink and single-channel relay mode, minimizing complexity and latency.
Under these conditions, all Wireless Tracker beacons transmit on 866.1 MHz, which is received directly by the drone-mounted WiFi LoRa 32 V3 listening on the same frequency. The drone then relays received packets to the ground station using a separate relay channel at 866.9 MHz, where the ground station remains in continuous receive mode.
This clear separation between uplink and downlink frequencies prevents self-interference at the drone and allows simultaneous reception from beacons and transmission toward the ground station. The flow can be summarized as:

- Beacon Tx @ 866.1 MHz → Drone Rx @ 866.1 MHz
- Drone Tx @ 866.9 MHz → Ground Station Rx @ 866.9 MHz

This mode is efficient when channel contention is minimal and packet collisions are unlikely.

Communication Flow Under High-Traffic Conditions

When a large number of beacon devices are active simultaneously, FalconResQ switches to a multi-channel, contention-aware communication strategy, inferred directly from the beacon, drone, and ground-station firmware design.

On the beacon side, Wireless Trackers no longer rely on a single uplink frequency. Instead, each beacon randomly selects one of four channels—866.1 MHz, 866.3 MHz, 866.5 MHz, or 866.7 MHz—and transmits within a randomly chosen time slot inside a defined uplink window. This is combined with a probabilistic transmission decision and basic channel activity detection, reducing the likelihood that multiple beacons transmit on the same frequency at the same time.

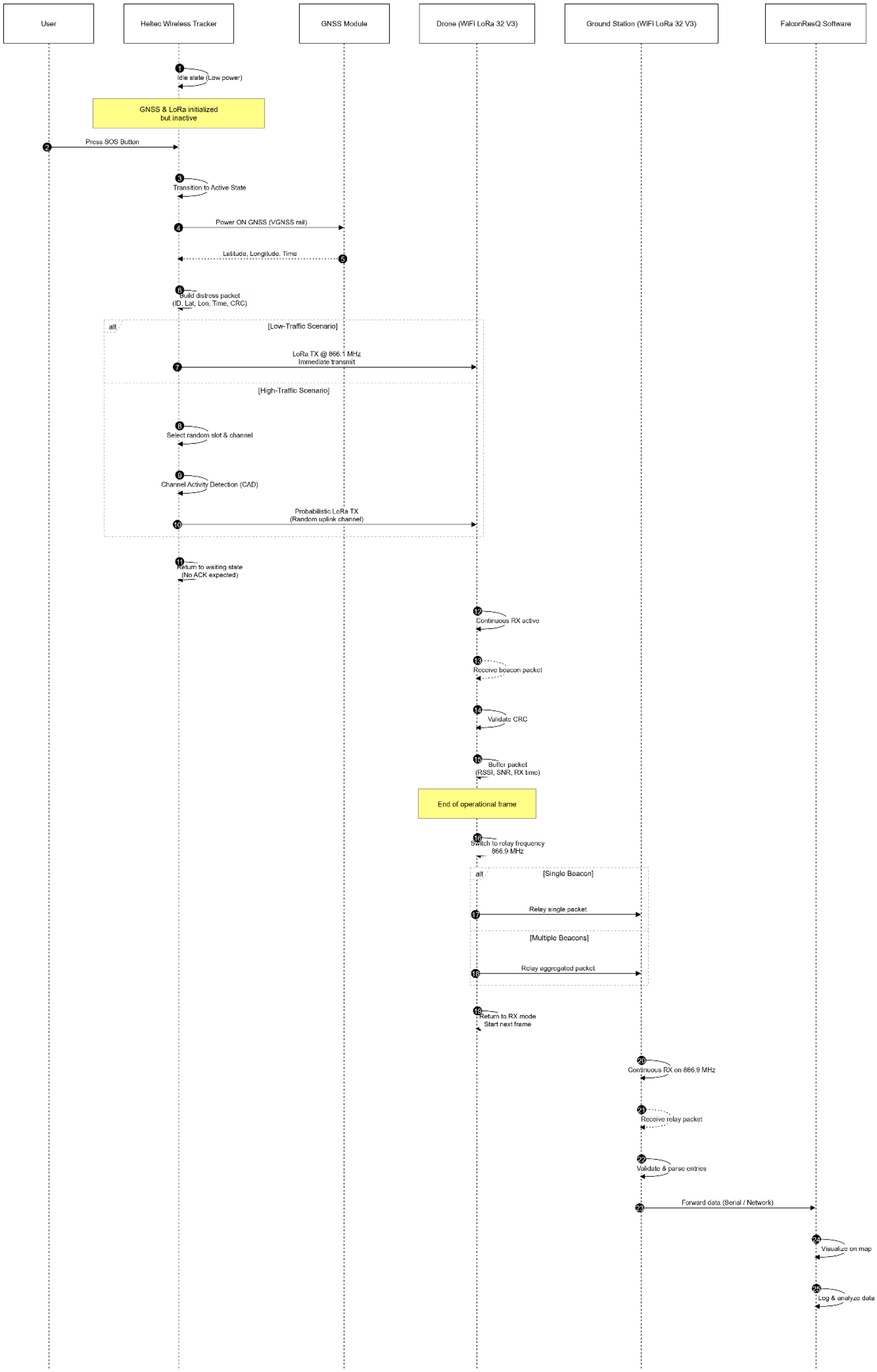
On the drone side, the WiFi LoRa 32 V3 continuously scans these four uplink channels in a round-robin manner, dwelling briefly on each frequency. Valid packets received on any of the four channels are buffered along with their RSSI and SNR metadata. Rather than forwarding each packet immediately, the drone aggregates multiple beacon packets over a frame period.

During a dedicated relay window at the end of each frame, the drone switches its radio to 866.9 MHz and transmits a single aggregated packet toward the ground station. This approach dramatically reduces airtime usage on the relay channel while still preserving data from many beacons.

At the ground station, the WiFi LoRa 32 V3 listens continuously on 866.9 MHz and receives these aggregated packets. The ground station firmware parses the combined data, extracts individual beacon entries, and forwards them in a clean, structured format suitable for further processing and visualization on the FalconResQ website.

Overall, this adaptive communication flow allows FalconResQ to operate efficiently across vastly different traffic conditions. In low-load scenarios, the system behaves like a simple two-hop relay. In high-load scenarios, it behaves like a coordinated multi-channel collection network, without requiring centralized scheduling or heavy protocol overhead, while remaining fully compatible with the Heltec hardware used in each tier.

The Sequence diagram on the next page give a detailed overview of the whole operational workflow;



User
Heltec Wireless Tracker
GNSS Module
Drone (WiFi LoRa 32 V3)
Ground Station (WiFi LoRa 32 V3)
FalconResQ Software
1
Idle state (Low power)
GNSS & LoRa initialized
but inactive
2
Press SOS Button
3
Transition to Active State
4
Power ON GNSS (VGNSS rail)
5
Latitude, Longitude, Time
6
Build distress packet
(ID, Lat, Lon, Time, CRC)
alt
[Low-Traffic Scenario]
LoRa TX @ 866.1 MHz
Immediate transmit
7
[High-Traffic Scenario]
8
Select random slot & channel
9
Channel Activity Detection (CAD)
Probabilistic LoRa TX
(Random uplink channel)
10
11
Return to waiting state
(No ACK expected)
12
Continuous RX active
13
Receive beacon packet
14
Validate CRC
15
Buffer packet
(RSSI, SNR, RX time)
End of operational frame
16
Switch to relay frequency
866.9 MHz
alt
[Single Beacon]
Relay single packet
17
[Multiple Beacons]
Relay aggregated packet
18
19
Return to RX mode
Start next frame
20
Continuous RX on 866.9 MHz
21
Receive relay packet
22
Validate & parse entries
23
Forward data (Serial / Network)
24
Visualize on map
25
Log & analyze data

4.2 Scalability & Collision Avoidance

As mentioned earlier, in high-traffic conditions, beacon transmissions are distributed across:

- Multiple frequency channels within the same sub-GHz band (866.1, 866.3, 866.5, and 866.7 MHz), and
- Multiple time slots within a defined uplink window.

This creates both frequency diversity and time diversity, significantly reducing the probability that two nearby beacons will transmit on the same channel at the same instant. Because all beacons follow the same rules but make random selections, the system naturally spreads load without any explicit coordination messages.

Beacon-Layer Collision Avoidance
Collision avoidance in FalconResQ is probabilistic and distributed, making it suitable for emergency scenarios where pre-negotiated schedules or acknowledgments are not feasible.

At the beacon layer, three complementary mechanisms are used:

1. Slotted transmission
   Time is divided into frames and short slots. Each beacon selects a random slot with the help of "select_random_slot_and_channel()" function, within the uplink window, ensuring that transmissions are temporally separated even when many devices are active.

2. Multi-channel randomization
   Each transmission attempt is assigned one of four uplink frequencies. Even if two beacons select the same slot, a frequency difference prevents collision at the receiver.

3. p-persistent access with channel sensing
   Before transmitting, the beacon briefly checks channel activity. If the channel appears busy, it defers transmission to a later frame. Even when the channel is clear, the beacon transmits only with a defined probability. This throttles the aggregate offered load on the channel as beacon density increases.
   Implementation: The radio is momentarily switched to receive mode to sample the instantaneous signal level on the selected channel. If the measured signal strength exceeds −100 dBm, the channel is considered

busy and transmission is skipped. When the channel is clear, a probabilistic decision is applied, allowing transmission only if a randomly generated value falls below the configured probability, with higher priority granted to SOS events.

These techniques together ensure that collisions are de-correlated in time, frequency, and probability, rather than relying on acknowledgments or retransmissions, which would increase airtime usage and complexity.

On the receiver side, the drone-mounted module complements this strategy by rapidly cycling across all beacon channels. It retunes the radio every 200ms ~ 0.2s, restarting RX each time and briefly listening on each frequency in turn and continuously buffering all valid packets along with their RSSI and SNR. By scanning rather than locking to a single channel, the drone acts as a passive concentrator, reliably collecting transmissions from many independent beacons even under heavy traffic conditions. Also, instead of forwarding each received beacon packet immediately, the drone buffers multiple packets and relays them together during a dedicated relay window. This ensures that increasing beacon count does not linearly increase relay airtime toward the ground station.

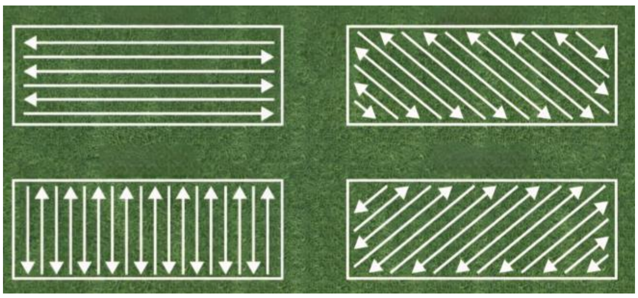
4.3 Drone Deployment Strategy

The drone in FalconResQ is not treated as a generic flying repeater, but as a mobile, line-of-sight LoRa collection platform whose movement directly impacts communication reliability and coverage efficiency. The deployment strategy is therefore tightly coupled to the communication architecture described earlier.

Search Pattern Algorithms

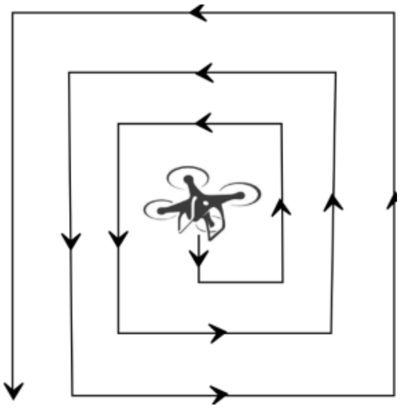
In the current FalconResQ implementation, the drone follows predefined geometric search patterns rather than reactive or beacon-guided navigation. This choice is intentional, as beacon transmissions are asynchronous and do not provide continuous tracking data.

Typical search patterns suitable for FalconResQ include:



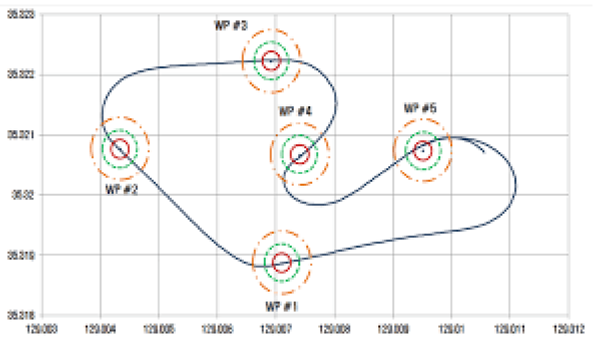
Lawnmower (parallel sweep) pattern

1. Lawnmower (parallel sweep) pattern, where the drone flies back-and-forth lanes over a defined rectangular area. This ensures uniform coverage and predictable revisit times, which is well matched to periodic LoRa beacon transmissions.



Expanding square or spiral patterns

2. Expanding square or spiral patterns, useful when the last known approximate location of victims is available. The drone starts near a reference point and gradually increases coverage radius.



Waypoint-based grid scanning

3. Waypoint-based grid scanning, where the drone pauses briefly at each waypoint. These short loiter periods improve packet capture probability, especially in high-traffic scenarios where beacons transmit in randomized slots.

Because the drone-mounted WiFi LoRa 32 V3 continuously scans uplink channels, packet reception does not require the drone to hover directly above a beacon. Instead, maintaining altitude and steady motion is sufficient, allowing coverage patterns to prioritize area efficiency over precision hovering.

Coverage Area per Drone

The coverage area of a single drone is primarily determined by altitude, antenna radiation pattern, and LoRa link budget, rather than by flight speed alone.

With the drone operating at moderate altitude and maintaining clear line-of-sight, the effective LoRa reception radius can extend up to 10km under favourable conditions. This translates to a theoretical coverage area on the order of hundreds of square kilometres for a single drone pass, assuming unobstructed terrain.

In practice, FalconResQ treats coverage conservatively. Factors such as terrain variation, urban clutter, foliage, and antenna orientation reduce usable range. Therefore, the operational coverage area per drone is defined not as a single static circle, but as the union of multiple overlapping reception footprints created as the drone follows its search path. This approach ensures that beacons transmitting intermittently still have multiple opportunities to be received during a mission.

CHAPTER 5:
Beacon Module (Transmitter)

The beacon is the lifeline for a stranded person. This chapter exhaustively details every aspect of the beacon's hardware design, circuit implementation, PCB layout, firmware development, and testing....

5.1 Introduction and Requirements[5.1a]

The beacon module selected for the FalconResQ system is the Heltec Wireless Tracker development board. This module serves as the wearable transmitter node that periodically obtains positional fixes and broadcasts them over LoRa to the airborne and ground receivers.

The design of the Wireless Tracker aligns closely with the core requirements for a beacon in a search and rescue context:

1. Core Processing, LoRa, and GNSS Subsystems:
   Central processing is handled by the ESP32-S3FN8, a dual-core 32-bit microcontroller featuring integrated Wi-Fi and Bluetooth radios. While these wireless interfaces are available, the beacon firmware prioritizes low-power MCU operation and LoRa-based communication, with Wi-Fi and Bluetooth remaining unused or disabled to conserve energy.
   Long-range communication is provided by the Semtech SX1262 LoRa transceiver, which is interfaced to the ESP32-S3 via SPI and dedicated RF control lines. The SX1262 supports operation across the 470–928 MHz ISM bands, enabling regional frequency flexibility. This architecture

allows fine-grained control over LoRa parameters such as bandwidth, spreading factor, coding rate, and transmit power, which is critical for optimizing range, reliability, and energy consumption in rescue deployments.

Positioning functionality is implemented using the UC6580 GNSS receiver, a high-sensitivity, multi-constellation, dual-frequency GNSS chip. It supports GPS (L1/L5), GLONASS, BeiDou (BDS), Galileo, NAVIC (IRNSS), and QZSS, enabling robust positioning even under challenging signal conditions. Dual-frequency reception improves accuracy and multipath rejection, providing reliable location estimates suitable for emergency localization use cases. GNSS RF signals are routed to a dedicated IPEX antenna connector, allowing the use of an optimized external GNSS antenna for improved satellite reception in outdoor environments.

2. Power Management and Battery Support:

   The Wireless Tracker includes a fully integrated lithium battery charging and power management subsystem, designed specifically for autonomous, wearable operation. It supports a 3.7 V single-cell Li-ion/Li-Po battery, with onboard charging via the USB Type-C interface.

   Key power-management features include:

   - Automatic switching between USB power and battery supply
   - Over-charge and over-discharge protection
   - Battery voltage sensing for runtime monitoring
   - Stable onboard regulation to generate the required 3.3 V rail for the MCU, LoRa transceiver, GNSS receiver, and peripherals

   This architecture enables safe, unattended operation over extended periods and simplifies deployment by removing the need for external charging or protection circuitry.

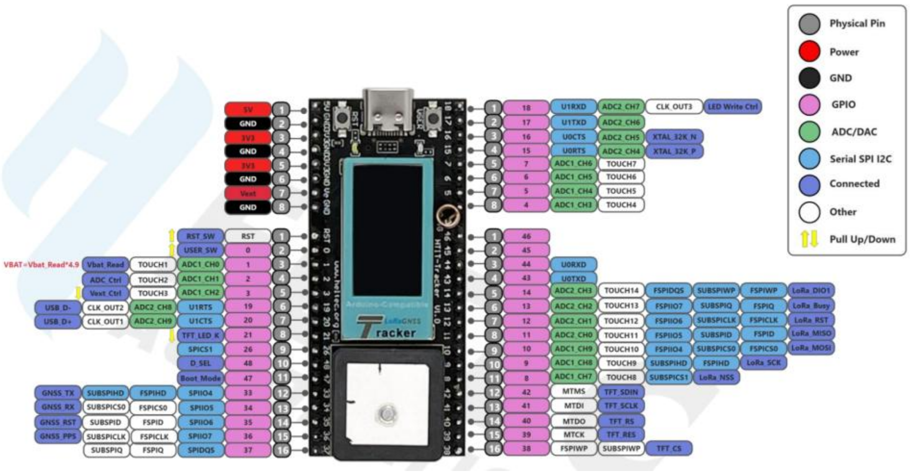
3. Peripheral Interfaces, Display, and Antennas:

   For user feedback and system diagnostics, the board integrates a 0.96-inch RGB TFT display with a resolution of 160×80 pixels. The display is driven over an SPI interface and is used to present real-time system status information such as GNSS fix availability, battery level, transmission state, and device activity.

   The RF design includes separate antenna paths for LoRa and GNSS, each routed to dedicated IPEX connectors. This separation allows independent antenna selection and placement, ensuring optimal radiation efficiency for sub-GHz LoRa communication and reliable satellite signal reception.

External antennas can be selected based on deployment requirements, such as compact wearable antennas or higher-gain antennas for improved range.

4. System I/O and Expansion Capabilities:
   The Wireless Tracker exposes multiple GPIOs and peripheral interfaces for firmware control, debugging, and future expansion. Broken-out pins include user buttons, battery voltage sense, and general-purpose I/O that can be used for sensor integration, signaling, or additional control logic.
   Debug and programming access is provided via the USB Type-C interface, simplifying firmware development and updates.
   Heltec's documented pin mappings and hardware references enable rapid custom firmware development while ensuring correct interaction with onboard peripherals.



Altogether, the Heltec Wireless Tracker meets the compact form factor, battery operation, and wireless transmission requirements of a beacon node tasked with periodically broadcasting location data for FalconResQ missions.

5.1.1 General Specifications

Parameter	Description
Master Chip	ESP32-S3FN8 (Xtensa® 32-bit LX7 dual-core processor)
LoRa Chipset	SX1262
GNSS Chipset	UC6580
Frequency	470–510 MHz, 863–928 MHz
Max TX Power	21 ± 1 dBm
Receiving Sensitivity	-135 dBm

Wi-Fi	IEEE 802.11 b/g/n
Bluetooth	Bluetooth LE (Bluetooth 5, Bluetooth Mesh)
Interface	Type-C USB; 2 × 1.25 mm lithium battery interface; LoRa ANT (IPEX); GNSS ANT (IPEX)
Battery	3.7 V lithium battery power supply and charging
Operating Temperature	−20 °C to 70 °C
Dimensions	65.48 mm × 28.06 mm × 13.52 mm

5.1.2 Power Supply

Except when USB or 5V Pin is connected separately, lithium battery can be connected to charge it. In other cases, only a single power supply can be connected.

Power Supply Mode	Minimum (V)	Typical (V)	Maximum (V)
Type-C USB (≥ 500 mA)	4.7	5.0	6.0
Lithium Battery (≥ 250 mA)	3.3	3.7	4.2
5V Pin (≥ 500 mA)	4.7	5.0	6.0
3V3 Pin (≥ 150 mA)	2.7	3.3	3.5

Power output

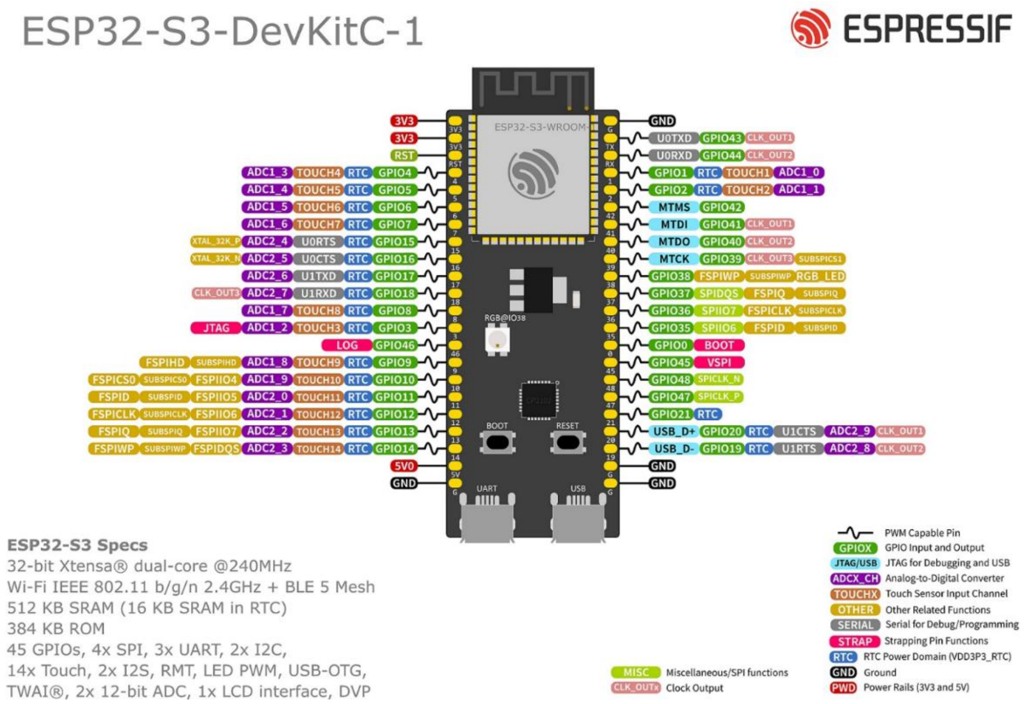
Output Pin	Maximum Current
3.3 V Pin	500 mA
5 V Pin (USB powered only)	500 mA
Vext Pin	350 mA

Power characteristics

Mode	USB Powered (mA)	Battery Powered (mA)	Unit
Wi-Fi Scan	100	74	mA
Wi-Fi AP	150	111	mA
Bluetooth	102	75	mA
GNSS	120	89	mA

TX @ 14 dBm	200	148	mA
TX @ 17 dBm	220	163	mA
TX @ 22 dBm	240	178	mA
RX (TX disabled, RX enabled)	80	59	mA
Sleep	2 mA	15 µA	—

5.2 ESP32-S3 Microcontroller



The beacon module uses the ESP32-S3FN8 microcontroller as its primary processing unit. This MCU forms the computational and control core of the Wireless Tracker, coordinating GNSS data acquisition, LoRa communication, power management, and user interaction.

Detailed Specifications:

The ESP32-S3FN8 is a dual-core 32-bit microcontroller optimized for embedded and battery-powered IoT systems.

- **CPU: Dual-core Xtensa LX7, up to 240 MHz**
- **Flash memory: 8 MB on-chip flash (FN8 variant)**
- **SRAM: On-chip SRAM for program execution and data buffers**
- **Operating voltage: 3.0–3.6 V**

- Wireless capability:
  - 2.4 GHz Wi-Fi (802.11 b/g/n)
  - Bluetooth Low Energy
    (Present but disabled in beacon operation to minimize power draw)
- Low-power modes: Light sleep, deep sleep, RTC-based wakeup
- Clock sources: Internal RC and external crystal support

5.2.1 Pin Count and Pin Classification

The ESP32-S3 package used on the Wireless Tracker exposes a high pin-count, enabling rich peripheral connectivity while still fitting a compact PCB.

Pin overview (SoC-level):

- Total pins (package-level): ~56–60 pins (package-dependent)
- Total GPIO-capable pins: up to 45 GPIOs
- Power and ground pins:
  - Multiple VDD3P3 and VDD_SPI power pins
  - Multiple GND pins for signal integrity and RF stability
- Special-function pins:
  - USB D+ / D−
  - Boot and strapping pins
  - Crystal oscillator pins

Pins used on the Wireless Tracker board:

- GPIOs actively routed:
  - SPI bus (LoRa transceiver)
  - UART (GNSS receiver)
  - Display SPI and control lines
  - User button (SOS)
  - Status LEDs

- Battery voltage sense

- Unused / reserved GPIOs:
  - Left unconnected or broken out for future expansion

This pin richness allows Heltec to route all essential subsystems without external multiplexers, preserving signal integrity and simplifying firmware design.

5.2.2 Pin Configuration and Hardware Integration

On the Heltec Wireless Tracker, ESP32-S3 pins are pre-assigned to onboard peripherals:

- SPI interface
  - Connected to the SX1262 LoRa transceiver
  - Handles register configuration, payload transfer, and radio control
- UART interface
  - Dedicated UART routed to the UC6580 GNSS receiver
  - Supports continuous GNSS data streaming
- GPIO assignments
  - LoRa control lines (reset, DIO/IRQ, RF switch control)
  - SOS user button input
  - Display control and status indication
  - Battery monitoring and power-enable signals
- USB interface
  - Native USB pins connected to the Type-C connector
  - Used for programming, debugging, and power input

5.2.3 Why ESP32-S3 Specifically Over Other Microcontrollers?

- High GPIO and Peripheral Density
  Supports up to ~45 GPIOs, allowing simultaneous interfacing with LoRa,

GNSS, display, battery sensing, and user inputs without external I/O expanders.

- **Native USB Support**
  Built-in USB OTG removes the need for an external USB-to-UART converter, reducing BOM cost, PCB area, and power loss while simplifying flashing and debugging.
- **RF-Friendly Peripheral Architecture**
  Multiple hardware SPI and UART controllers with robust interrupt handling are well-suited for time-critical LoRa radio control and continuous GNSS data reception.
- **Low-Power Operation with Burst Performance**
  Efficient deep-sleep and light-sleep modes enable long idle periods, while high clock speeds allow short, high-performance bursts for GNSS fixes and LoRa transmissions.
- **Lightweight ML and Signal-Processing Capability**
  Vector instruction support and acceleration features enable basic on-device ML and DSP tasks, such as signal classification, anomaly detection, or sensor data pre-processing, without additional hardware.
- **Mature Ecosystem and Long-Term Support**
  Well-established SDKs, extensive documentation, and a large developer community reduce development risk and improve long-term maintainability.

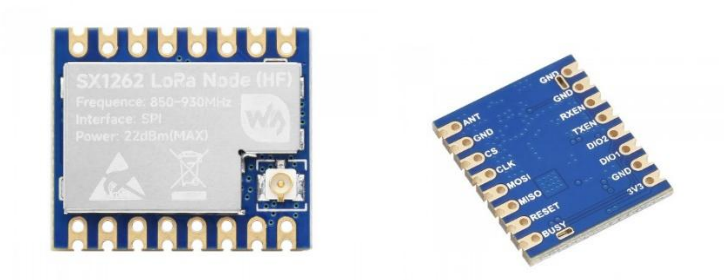
These factors together make the ESP32-S3 more capable, flexible, and future-ready than typical low-end microcontrollers for a compact GNSS-LoRa beacon system.

Below is a side-by-side comparison of boards similar to the HELTEC Wireless Tracker:

Feature / Board	HELTEC Wireless Tracker	HELTEC Automation Wireless stick ESP32-S3 v3	LILYGO T-Echo Meshtastic	LILYGO T-Beam Meshtastic	LILYGO T-BeamSUPREME	Seeed Studio Xiao ESP32 S3 Meshtastic Kit
MCU	ESP32-S3	ESP32-S3	Typically nRF52840	ESP32 (older) / S3 variant	ESP32-S3	ESP32-S3

LoRa Radio	SX1262	SX1262	SX1262	SX127x / SX1262 depending on version	SX1262	(may need add-on)
GNSS Built-In	✓ (UC6580 multi-constellation)	✗	Optional (module variant)	✓ (integrated GPS)	✓	✗
Display	Onboard TFT	Small OLED	Often no display	Often small OLED	Depends on SKU	No
Battery Support	Li-ion charging + battery switch	Li-ion support	Depends on board	Depends on board	Depends on board	No
USB for Programming	USB-C (native)	USB-C w/ CP2102	Yes	Yes	Yes	Yes
Typical Use Case	LoRa + GNSS tracking (out of box)	LoRa dev / Meshtastic	LoRa mesh node	LoRa GPS tracker	High-end LoRa/Meshtastic	Low-cost ESP32-S3 node
Typical Price Range	Mid (₹ ~2–3k)	Lower (₹ ~2k)	Higher (₹ ~7k+)	Mid (₹ ~4k)	Higher (₹ ~10k+)	Low (₹ ~900+)
Remarks	Integrated GNSS + LoRa + battery & display — best out-of-box tracker	Smaller board, OLED, LoRa + BLE, but no GNSS built-in	Meshtastic node, robust but pricier	Classic LoRa + GPS integration	Premium, more features & memory	Basic ESP32-S3 board good for custom add-ons

5.3 SX1262 LoRa Transceiver[5.3a][5.3b][5.3c][5.3d][5.3e][5.3g]



Below is a structured, technical description covering datasheet highlights, the SPI interface, and antenna matching network considerations for the Semtech SX1262IMLTRT, which is the core RF chip used on the Heltec beacon's LoRa radio subsystem.

Technical Datasheet Highlights

The SX1262 is a highly integrated sub-GHz RF transceiver optimized for long-range, low-power operation in IoT applications.

Key performance features:

- Sub-GHz frequency coverage: Operates across ~150 MHz to 960 MHz, enabling use in global ISM bands (including 433 MHz, 868 MHz, 915 MHz).
- Transmit power: Up to +22 dBm from an integrated power amplifier, supporting robust long-range links.
- Receiver sensitivity: Down to approximately –148 dBm in LoRa mode, giving a high link budget (~170 dB) for extended range.
- Modulation support: Native LoRa® spread-spectrum modulation for LPWAN and FSK/GFSK/MSK for legacy/other use cases.
- Data rates: LoRa up to ~62.5 kbps and FSK up to ~300 kbps.
- Low power: RX current typically ~4-6 mA; sleep current in the µA range, ideal for battery-powered IoT nodes.
- Integrated DC-DC and LDO: On-chip regulators support power efficiency.

These characteristics make the SX1262 suitable for long-range IoT, LPWAN, and beacon/tracking applications that demand high sensitivity and energy efficiency.

5.3.1 SPI Interface

Communication between the host MCU (e.g., ESP32-S3) and the SX1262 RF transceiver is done primarily via SPI:

- SPI Bus Signals:
  - SCK (Clock)
  - MOSI (Master Out Slave In)
  - MISO (Master In Slave Out)
  - CS (Chip Select)
  - BUSY and IRQ status pins for flow and event control.
- Operation:
  - Commands, configuration registers, and payload data are exchanged by writing SPI frames from the MCU to the SX1262.

- The SX1262 uses an opcode + address + data format for register access.
- The BUSY pin indicates when the RF IC is processing and when it can accept new SPI transactions.

- SPI Speed: Typical designs support up to ~10–18 MHz SPI clock rates without timing violations, enabling efficient command throughput.
- GPIO Lines: In addition to SPI, control and status pins such as RESET, TX/RX enable, and interrupt lines are used by firmware to synchronize mode changes (e.g., TX → RX transitions).

This interface enables flexible control and real-time interaction with the radio for packet transmission, reception, modulation configuration, and power management.

5.3.2 Antenna Matching Network

The RF transceiver itself is an IC that must be integrated into a proper RF front end to achieve good performance. A crucial part of this is the antenna matching network, which ensures efficient transfer of energy from the chip's PA/RF output into the antenna and from the antenna back into the receiver.

Why matching is required:

- The SX1262's RF port is designed for a 50 Ω system, which is the standard reference impedance for most antennas and RF front ends.
- Without proper matching, impedance mismatches can lead to reflections, reduced range, increased VSWR, and higher power consumption.

Typical design elements:

- A π-network or L-network of inductors and capacitors is used between the RF pin and the antenna feed to transform the chip's output impedance to 50 Ω.
- In many commercial LoRa modules, including ones based on SX1262, the impedance matching network and RF switch (for TX/RX switching) are included on the module PCB, simplifying integration.
- Designers often reserve PCB space or footprints for tunable capacitors/inductors near the antenna connection to support fine tuning after fabrication.

- Proper layout (grounding, clearances, antenna placement) is critical to maintain the designed 50 Ω path and avoid degrading sensitivity or output power.

Outcome: A well-designed matching network maximizes radiated power, improves receiver sensitivity, and ensures predictable RF performance across the intended frequency band.

5.3.3 LoRa RF characteristics

Transmit power

Operating Frequency Band (MHz)	Maximum Power Value (dBm)
470–510	21 ± 1
867–870	21 ± 1
902–928	21 ± 1

Receiving sensitivity

Signal Bandwidth (kHz)	Spreading Factor	Sensitivity (dBm)
125	SF12	−135
125	SF10	−130
125	SF7	−124

Operation Frequencies

Region	Frequency (MHz)	Model
EU433	433.175–434.665	Wireless Tracker-LF
CN470	470–510	Wireless Tracker-LF
IN868	865–867	Wireless Tracker-HF
EU868	863–870	Wireless Tracker-HF
US915	902–928	Wireless Tracker-HF
AU915	915–928	Wireless Tracker-HF
KR920	920–923	Wireless Tracker-HF
AS923	920–925	Wireless Tracker-HF

5.4 UC6580 GPS Module[5.4a][5.4b]

The UC6580 is a dual-frequency, multi-constellation GNSS positioning SoC (system-on-chip) used in the Heltec Wireless Tracker for robust satellite navigation and timing. It integrates RF, baseband, and positioning processing in a highly efficient package suitable for battery-powered IoT applications.

Parameter	Specification
Channels	96
Update Frequency	Maximum 10 Hz
Data Format	NMEA-0183, Unicore, RTCM 3.x
BDS Frequency	B2a
GPS Frequency	L1 + L5
GLONASS Frequency	G1
Galileo Frequency	E1 + E5a
QZSS Frequency	L1 + L5
SBAS Frequency	L1
NAVIC Frequency	L5* (specific firmware)

5.4.1 UART Interface

- Primary communication: The UC6580 supports a 1× UART (LVTTL) interface for GNSS data output in common formats such as NMEA-0183 or proprietary data.
- Baud rate: Typically configured for high-speed GNSS streaming (e.g., 115200 bps or higher) depending on application — ideal for continuous position updates.
- Protocol: Standard GNSS sentences (e.g., GGA, RMC, VTG) can be parsed by the host MCU (like ESP32-S3) to obtain latitude, longitude, time, and fix status.
- Fallback interfaces: The chip also supports 2× I²C and 1× SPI in some configurations, but in the Wireless Tracker it is exposed primarily over UART for simplicity.

5.4.2 Antenna Requirements

- **External GNSS antenna: To achieve reliable positioning, the UC6580 requires a proper external GNSS antenna connected via a dedicated RF input.**
- **Impedance matching: The antenna system should be matched to 50 Ω to minimize signal loss and reflection — typical for patch or helical GNSS antennas.**
- **LNA and SAW filters: Many designs include a low-noise amplifier (LNA) and SAW (Surface Acoustic Wave) filter at the antenna front end to improve sensitivity in weak signal environments.**
- **Placement: The antenna should be placed with clear sky-view (minimal obstruction or metallic blockage) to maximize satellite visibility and positioning performance.**

5.4.3 Time-to-First-Fix (TTFF) & Performance

- **Cold start: UC6580 typically achieves a first fix in < 26 seconds under open sky conditions (no prior almanac data).**
- **Hot start: With recent almanac/ephemeris data and previously known position, a fix can be obtained in < 2 seconds.**
- **Sensitivity:**
    - **Tracking (Maintaining lock on satellites): ~ –162 dBm**
    - **Cold start acquisition (First fix with no prior data): ~ –148 dBm**
    - **Hot start (Fix using recent data): ~ –156 dBm**
    - **Reacquisition (Restoring lost satellite lock): ~ –159 dBm**
      These values indicate excellent weak-signal performance.
- **Channels & constellations: 96 channels tracking GPS, GLONASS, BDS, Galileo, QZSS, NAVIC, and SBAS simultaneously, improving fix reliability and accuracy.**
- **Update rate: Supports configurable GNSS update rates such as 1 Hz, 5 Hz, and 10 Hz, making it suitable for both slow-moving beacons and faster dynamic applications.**

  Accuracy and TTFF Table:

Parameter	Specification
Horizontal Position Accuracy (RMS)	1.5 m
Vertical Position Accuracy (RMS)	2.5 m
Time Accuracy (RMS)	5 ns
Speed Accuracy	0.02 m/s
Cold Boot Time	< 26 s
Warm Boot Time	< 2 s
Recapture Time	1 s

5.4.4 Other Important Details

- Dual-frequency operation: L1 + L5 bands enable better multipath mitigation and improved urban performance compared to single-frequency GNSS receivers.
- Position accuracy: Single-point horizontal positioning < ~1.5 m RMS, and vertical ~2.5 m RMS in open sky conditions.
- Data formats: NMEA-0183 output compatible with standard GNSS parsers; also supports manufacturer-specific message formats for extended information.
- Power consumption: Typically < 40 mA at 3 V during tracking, suitable for battery-powered beacons when intermittent fixes are scheduled.
- Voltage range: Operates from ~1.7 V to 3.6 V, enabling flexible power supply choices in embedded designs.

5.4.5 Sensitivity (Unit: dBm)

Mode	BDS	GPS	GAL (Galileo)	GLONASS
Cold Boot	−148	−146	−148	−144
Warm Boot	−156	−155	−155	−148
Trace	−165	−163	−165	−158
Recapture	−156	−154	−156	−152

5.5 Overall Beacon Device Power Calculation

Battery selection (Li-ion / Li-Po)

- **Supported chemistry: Single-cell 3.7 V lithium battery (Li-ion or Li-Po) via the onboard battery connector.**
- **Charging + power-path: The board includes an integrated lithium battery management system (charge/discharge management, battery power detection, and automatic USB/battery switching), making it suitable for wearable beacon use.**

Practical selection guidance (for rescue beacons):

- **Li-Po (pouch): best for thin wearable enclosures (lighter + flatter).**
- **Li-ion (cylindrical, e.g., 18650): best for maximum capacity and ruggedness (bulkier).**
  ***(Both are supported as long as they are 1S, 3.7 V nominal.)**

5.5.1 Power consumption analysis (what dominates?)

Power draw depends heavily on which blocks are ON:

- **GNSS active (major load during fixing/tracking): community measurements for this board family often show GNSS drawing tens of mA when enabled.**
- **LoRa radio**
  - **RX current: SX1262 is designed for low RX current (Semtech states ~4.2 mA active RX).**
  - **TX current: at high power, reference designs show ~118 mA at +22 dBm (varies by power amplifier setting and board implementation).**
- **Deep sleep can be excellent if firmware powers down peripherals correctly: measurements as low as ~18.5 µA deep sleep are reported with proper shutdown.**
  - **But some users measure mA-level "deep sleep" if something remains enabled (GNSS rail, display, etc.), so firmware configuration matters a lot.**

5.5.2 How long will the battery last? (estimation method + example)

Battery life is set by average current:

$$\text{Battery life (hours)} \approx \frac{\text{Capacity (mAh)} \times \eta}{I_{\text{avg}}\ \text{(mA)}}$$

Or

If Duty cycle D is given, $I_{\text{avg}} = D \cdot I_{\text{active}} + (1 - D) \cdot I_{\text{sleep}}$

$$\text{Battery life (hours)} \approx \frac{\text{Capacity (mAh)} \times \eta}{D \cdot I_{\text{active}} + (1 - D) \cdot I_{\text{sleep}}}$$

Where,
- η is efficiency (typical 0.85–0.95 to account for regulator losses, temperature, aging).
- D is duty cycle

Battery Life Estimation (Given Conditions)
Assumptions (explicit):
- Beacon duty cycle: 2.36% (active), 97.64% sleep
- LoRa TX power: +17 dBm
- Battery: 3.7 V, 1000 mAh Li-Po (you can scale linearly)
- Deep sleep current: ~20 µA (ESP32-S3 + peripherals properly powered down)

- Active current (average):
    - ESP32-S3 active + GNSS ON + LoRa RX/TX bursts ≈ 90 mA (this is a realistic mid-range value for GNSS-enabled beacons at 17 dBm)

$$I_{\text{avg}} = (0.0236 \times 90\ \text{mA}) + (0.9764 \times 0.02\ \text{mA})$$

$$I_{\text{avg}} = 2.12\ \text{mA} + 0.0195\ \text{mA}$$

$$I_{\text{avg}} \approx 2.14\ \text{mA}$$

- Battery Life Calculation

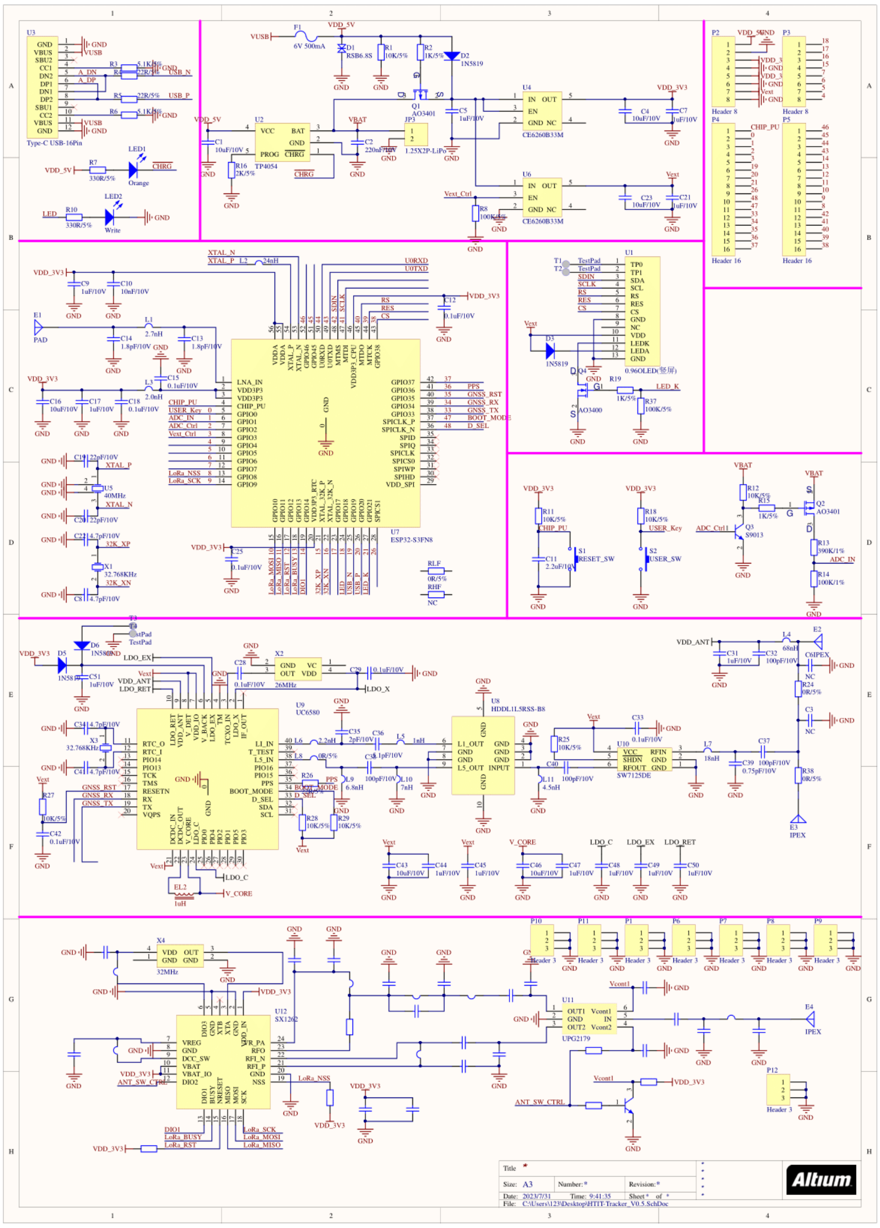
$$\text{Battery life (hours)} = \frac{1000\ \text{mAh}}{2.14\ \text{mA}} \approx 467\ \text{hours}$$

Battery life ≈ 19.5 Days, When continuously operating

Estimated Battery Life @ various battery capacities, when continuously operating:

BATTERY CAPACITY	ESTIMATED LIFE
500 MAH	~9.7 days
1000 MAH	~19.5 days
2000 MAH	~39 days

5.6 Schematic of the Beacon Module (Heltec Wireless Tracker)



5.7 Codes Uploaded to Beacon Device[Github Codes]

5.7.1 High traffic code:

This code implements an advanced beacon transmission strategy designed for high beacon density scenarios where packet collisions are likely. Upon SOS button activation, the device enters an active transmission mode and periodically sends GPS location packets using a slotted p-persistent CSMA approach combined with multi-channel operation. Time is divided into frames and slots, and each beacon randomly selects both a transmission slot and one of four sub-GHz channels (866.1–866.7 MHz). Before transmitting, the beacon performs channel activity detection (CAD) using RSSI sensing to probabilistically avoid busy channels. A transmission probability (high for SOS mode) further throttles channel usage, reducing collision probability without acknowledgments or centralized coordination. This distributed, randomized design makes the system scalable and robust under congestion, at the cost of increased protocol complexity.

5.7.2 Normal demo code for PoC:

This code represents a minimal, deterministic MVP implementation focused on reliability and clarity rather than scalability. After SOS button activation, the beacon transmits GPS location packets at a fixed interval of 5 seconds on a single LoRa channel (866.1 MHz) with constant parameters. Each packet contains JSON-encoded position data with CRC validation, and transmission status is clearly indicated via a TFT-based user interface, including idle, transmitting, success, and timeout states. There is no collision avoidance, slotting, or channel hopping; therefore, this firmware is best suited for low-traffic environments, early prototyping, demonstrations, and functional validation of the FalconResQ concept.

Libraries Used (Both Codes)

Library	Purpose	Used In
Arduino.h	Core Arduino framework and MCU abstraction	Both
LoRaWan_APP.h	Heltec LoRa driver and SX1262 radio control	Both
HT_TinyGPS++.h	GNSS data parsing (NMEA → latitude, longitude, time)	Both
TFT_eSPI.h	TFT display control and UI rendering	Code 2 only

5.8 Images & Videos of Beacon Module Operation

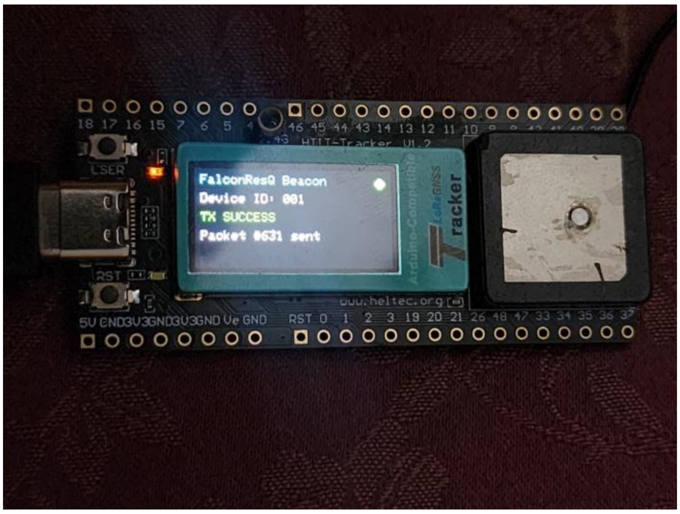


Image of Beacon Module

Click Here to view the video while the beacon module operates.

1. Tools & Technology used

Hardware Components

Category	Component	Details
Flight Controller	T-MOTOR Velox F7 SE	High-performance FC with support for Betaflight/INAV; enables real-time drone control and integration with GPS and telemetry.
ESC	T-MOTOR Velox 50A, 3-6S	Electronic speed controller to manage high-current brushless motors efficiently. Supports aggressive flight maneuvers.
Motors	T-MOTOR V2306 V3 (1950KV)	High-thrust brushless motors optimized for FPV and payload-carrying capacity.
Propellers	T-MOTOR P49436-3	Durable, aggressive tri-blade props for powerful lift and quick response.
Frame	TBS Source One V5	Lightweight, durable open-source quadcopter frame ideal for FPV and modular payloads.
Battery	High-capacity LiPo (3–6S)	Chosen to balance power, endurance (approx. 20 min hover), and safety. Ensures good thrust-to-weight ratio.
Video Transmitter + FPV Module	TDJI O4 Air Unit Pro	Records & sends FPV feed to goggles with minimal latency and good range.
FPV Goggles	DJI Goggles N3 FPV Goggles	High-resolution goggles for immersive piloting experience.
Onboard Camera	GoPro Hero 12	Mounted for recording high-quality footage, potentially used in post-analysis or rescue missions.
Drone Transmitter	TX-16S MK II	A powerful Tx for controlling the drone movements.
Drone Receiver	2.4 GHz ELRS Receiver	Compatible receiver module for controlling drone movements.
GPS Module	NEO-M8N	High-precision GPS module for accurate positioning, navigation, and geotagging.
Microcontroller	ESP32-S3	Dual-core Wi-Fi & Bluetooth-enabled MCU used in the ground beacon and potentially for onboard data handling.
LoRa Module	SX1262	For long-range communication between ground distress beacons and aerial drone unit, between aerial drone unit and the ground system

Software Tools

Tool	Purpose
Altium	PCB designing of user beacon- Tx modules and the on-drone receiver systems
Arduino IDE	Programming the ESP32-S3 and LoRa module for signal transmission and reception.
Betaflight/INAV	Flight controller configuration and tuning (PIDs, filters, failsafes, etc.).
QGIS	Mapping received GPS coordinates to visualize SOS signal sources.
Fusion 360	3D modeling of custom enclosures or drone frame modifications.
Python	Used for parsing GPS logs, visualizing data.

Communication Protocols

Protocol	Use Case
LoRa	Long-range data transmission from ground beacon to the drone (distress signals).
UART	Serial interface between ESP32 ↔ GPS, LoRa modules.
I2C	Optional use for additional sensors or displays.
SPI	Used internally in the LoRa module or GPS module (if configured that way).

2. Budget Estimate

S.NO	Component Type	Component Name	Quantity	Unitary Price	Net Cost
1	Flight-controller	T-MOTOR Velox F7 SE Flight Controller	1	₹ 6,599	₹ 6,599
2	ESC	T-MOTOR Velox 50 A, 3-6S ESC	1	₹ 6,199	₹ 6,199
3	Motor	T-MOTOR Velox V2306 V3 FPV Motor	6	₹ 1,350	₹ 8,100
4	Propeller	T-MOTOR P49436-3 (Pack of 4)	2	₹ 1,377	₹ 2,754
5	Frame	TBS Source One V5 5inch CF Frame	1	₹ 3,600	₹ 3,600
6	Battery	Pro-Range 22.2V 16000mAh 25C 6S Li Po Battery	1	₹ 15,500	₹ 15,500
8	FPV Camera Module	DJI O4 Air Unit Pro	1	₹ 28,000	₹ 28,000
9	FPV Goggles	DJI Goggles N3 FPV Goggles	1	₹ 37,000	₹ 37,000
10	GPS Module	NEO-M8N	2	₹ 712	₹ 1,424
11	Action Cam	Go Pro HERO 12	1	₹ 30,000	₹ 30,000
12	Microcontroller	ESP32-S3 Devkit C1	3	₹ 1,500	₹ 4,500
13	LoRa Module	LoRa SX1262	3	₹ 1,086	₹ 3,258
14	Antenna	Antenna	3	₹ 300	₹ 900
		Total:			₹ 1,47,834

3. Technicalities of the Project

Thrust to Weight Ratio calculation of the drone:

Component	Specification	Weight (g)
Motor * 4	T-MOTOR Velox V2306 V3 FPV Motor	33.7 * 4
Propeller * 4	T-MOTOR P49436-3 (Pack of 4)	3.5 * 4
Flight Controller	T-MOTOR Velox F7 SE Flight Controller	10
ESC	T-MOTOR Velox 50 A, 3-6S ESC	19
Battery	Pro-Range 22.2V 16000mAh 25C 6S Li Po Battery	1900
Frame	TBS Source One V5 5inch CF Frame	125
FPV System	DJI O4 Air Unit Pro	40
GPS Module	NEO-M8N	15
µController Unit	ESP32-S3 Devkit C1	50
LoRa Module	LoRa SX1262	10
GoPro Hero 12	Go Pro HERO 12	154
TOTAL		**~2482**

From the motor's datasheet,

- The *min.* throttle needed for the drone to take off/hover ~ 50%
- The *max.* net thrust generated per motor = 1467 g
- Overall *max.* thrust generated = 1467*4=5868 g
- Assumed net weight of the drone (incl. misc) = 2482 g
- Max. Thrust to weight Ratio @100% throttle = $\dfrac{\text{Overall thrust generated (g)}}{\text{Assumed net weight of the drone (g)}} = \dfrac{5868}{2482} \approx$ **2.3:1**

Expected flight time calculation:

Propeller	Type	Throttle	Voltage (V)	Current (A)	RPM	Thrust (g)	Power (W)	Efficiency (g/W)
T-MOTOR P49436-3	1750KV	20%	24.0	1.9	11818.1	176.6	45.1	3.92
		40%	24.0	6.0	18030.9	439.4	142.9	3.07
		60%	23.9	10.7	22021.2	664.2	255.2	2.60
		80%	23.8	17.8	26399.3	953.8	422.3	2.26
		100%	23.6	30.0	31486.2	1353.1	706.6	1.91
	1950KV	20%	24.0	2.3	12593.7	194.3	55.6	3.49
		40%	23.9	7.3	19012.8	483.5	175.5	2.76
		60%	23.8	13.3	23336	740.1	316.1	2.34
		80%	23.7	22.0	27880.2	1074.2	520.8	2.06
		100%	23.5	36.8	32945.3	1466.9	863.9	1.70
V2306 V3 Motor's Datasheet	2550KV	20%	16.0	2.3	10520.9	121.4	36.2	3.35
		40%	15.9	6.8	16221.2	332.5	108.3	3.07
		60%	15.9	12.3	19987	531.8	195.3	2.72
		80%	15.7	19.4	23741	758.5	305.6	2.48
		100%	15.5	32.3	28139.9	1087.0	502.2	2.16

Thrust per motor @ 100% throttle : 1467 g

Current " " " " " : 36.8 A

Total Current Req: 36.8 * 4 => 147.2 A

Inorder to avoid heating issues assumed net current req is ≈ 155 A

necessity from datasheet

Assuming 16,000 mAh, & 22.2V

∵ Battery Capacity * C Rating = Net Current

$16000 * 10^{-3} \times C = 155$

$\therefore C = \dfrac{155}{16000 \times 10^{-3}} \approx 9.68$

So, for 16,000 mAh battery the min C rating is 9.68

∴ We go with 25C & 16,000 mAh battery

Flight time Calculation

A lipo battery can only discharge upto 78 %, so effective capacity of battery is :

$0.78 \times 16000 \times 10^{-3}$

$\approx 0.78 \times 16$

≈ 12.48 Ah ⇒ ①

Net Current drawn = 147.2 A ⇒ ②

& Flight time = $\dfrac{\text{Total Capacity of battery (Ah)}}{\text{Net Current drawn by drone (A)}}$ (hr) ⇒ ③

From ①, ② & ③;

$\dfrac{12.48 \text{ Ah}}{147.2 \text{ Ah}} \approx 0.084$ hours

× 60

≈ 5.08 min

⇒ 5 min & 5 seconds

∴ The Min approx flight time of the drone is 5.08 minutes @ 100% throttle

So, ideally we would get :

@ 100% Throttle — 5 min 5 sec

@ 80% " — approx 8 min 30 sec

@ 50-60% " — approx 14 ~ 18 min

{ Ideal use case when just hovering over disaster struck zone }

This is the most realistic flight time acheived in the given Scenario. By the designed drone

Expected Flight Time is 14 - 18 mins

4. Testing & Experimentation

TO BE UPDATED HERE

5. Deployment Plan

Mass-Produce TX Units Using PCB Fabrication

Once the prototype is validated, the transmitter (TX) modules can be scaled for wider use through:

- Custom PCB design and fabrication, ensuring compact size, reliable connectivity, and optimized power usage.
- Integrating the ESP32-S3, LoRa SX1262 module, GPS unit, and battery management system on a single PCB to reduce cost and assembly time.
- Batch production via manufacturers or PCB prototyping services for rapid deployment during emergencies.

Partner with Disaster Response Teams or NGOs for Drone Operations

To ensure the system is used where it is needed most:

- Collaborate with disaster relief organizations, search-and-rescue teams, or non-profits working in rural or disaster-prone areas.
- Equip drones operated by these agencies with the receiver system, allowing them to aerially scan for SOS beacons and pinpoint survivor locations using GPS + LoRa data.
- Offer training modules and technical documentation to aid adoption and real-world deployment.

6. Challenges Faced & Solutions

TO BE UPDATED HERE

7. Future Improvements

1. Add 2-Way Communication (TX Gets Acknowledgment)

- Implement an acknowledgment (ACK) protocol where the drone or ground receiver sends a confirmation message back to the TX beacon after successful GPS packet reception.
- Enables confirmation for the user that their SOS signal has been received.
- Helps reduce unnecessary repeated transmissions, improving battery efficiency.

2. Solar Charging for TX Units

- Integrate miniature solar panels into the beacon casing to allow continuous trickle charging in outdoor environments.
- Increases operational time during prolonged field deployments or in post-disaster scenarios where recharging may be limited.
- Adds sustainability and reduces dependence on external charging.

3. Autonomous Drone Path Planning

- Equip the drone system with autonomous navigation algorithms using GPS waypoints, geofencing, or SLAM (Simultaneous Localization and Mapping).
- Drones can automatically scan large areas in a grid pattern, reducing the need for manual piloting during search operations.
- Improves efficiency in search-and-rescue and disaster relief missions.

4. SMS/LoRaWAN Fallback If Network Resumes

- If cellular service becomes available mid-mission, the RX system (or drone base station) can fallback to GSM/SMS or LoRaWAN to forward critical GPS coordinates to a central command or emergency contact.
- Adds redundancy and resilience, ensuring that data can still reach authorities even if local infrastructure is partially restored.

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