

ECE Capstone Project Final Report

Project Title	Design of LoRa-based NTN for Underground Applications
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0. ABET Evidence Map, Final Design Snapshot, and Design Evolution Log

Table 0-A. Report Evidence Guide.

ABET item / SO	What must be demonstrated	Primary report section	Supporting appendix / evidence ID
<i>SO1</i>	Identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.	Sec. 2.3	DEV-1, DEV-2
<i>SO2</i>	Apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.	Sec. 11	DEV-3
<i>SO3</i>	Communicate effectively with a range of audiences	Sec. 1	-
<i>SO4</i>	Recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.	Sec. 11	-
<i>SO5</i>	Function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.	Sec. 12	-
<i>SO6</i>	Develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.	Sec. 9	

ABET item / SO	What must be demonstrated	Primary report section	Supporting appendix / evidence ID
<i>SO7</i>	Acquire and apply new knowledge as needed, using appropriate learning strategies.	Sec. 13	-
<i>Criterion 5 design evidence</i>	The culminating design shows standards, multiple constraints, iteration, and use of prior course work.		

Table 0-B. Final Design Snapshot.

Field	Final value / summary
Final prototype / revision	Rev. 1 hardware prototype: ESP32 + E32-433 MHz LoRa node with Li-Po power subsystem.
Main need addressed	Reliable wireless data collection from buried underground sensors (20–40 cm depth) in remote locations using a LoRa-based NTN (UAV + LEO satellite).
Requirements met	REQ-1 (RSSI): Met in simulation. REQ-2 (SNR): Met in simulation. REQ-3 (PDR ~85%): Met in simulation.
Primary standards applied	LoRaWAN RP2–1.1 (433 MHz), Civil Aviation Authority (UAV $\leq$ 120 m), LoRaWAN L2 Spec 1.0.4 (AES–128).
Key constraints satisfied	Budget < 270,000 KZT (actual $\approx$ 73,940 KZT). ISM 433 MHz compliance. Safety: soldering in ventilated room; Li–Po peak current $\leq$ 1.5 A.

Field	Final value / summary
Most important trade-off	Hybrid Relay (Sensor–UAV–LEO) selected over Direct-to-Satellite (lower energy efficiency) and UAV Store-and-Carry (limited UAV battery). Highest weighted score: 6.95/10.
Overall result	Simulation validates architecture. Physical outdoor tests were successfully conducted in Spring.

Table 0-C. Design Evolution Log.

Iteration ID	What changed	Why it changed	Evidence that triggered the change	Impact on performance / cost / schedule / risk	Date
CL-1	Completed preliminary PDR and SNR simulations	Baseline performance data needed for report	Simulation run logs (ModelMain_LoRa.m)	Confirmed simulation scope; no schedule impact	Nov 10
CL-2	Moisture sensors are removed	Sensor came with defects, they did not work	BOM confirmation	Cost increased	Jan 8
CL-3	Tx Power updated from 14 dBm to 20/33 dBm in simulation	Must match purchased Ebyte E32 hardware	E32-433T33D and E32-433T20D datasheets; BOM confirmation	High: range prediction graphs show significantly increased reliability	Jan 10

Iteration ID	What changed	Why it changed	Evidence that triggered the change	Impact on performance / cost / schedule / risk	Date
CL-4	Initial indoor soil moisture sensor testing	Field burial not feasible (frozen ground)	Outdoor temperature: -15°C	Schedule delay on field test; risk increased	Jan 15
CL-5	Added frozen ground variable to simulation model	Need to simulate seasonal soil property variation	Winter vs. summer simulation graphs	Scope refined; more realistic SNR and RSSI results obtained	Feb 27

1. Executive Summary

Background and Motivation

With the rise in demand for IoT devices it became crucial to provide infrastructure for them. Terrestrial networks cover a large amount of area but still there are remote areas where there is a need for a different architecture that provides higher coverage at lower costs. This type of architecture is called Non-Terrestrial Network. It makes use of UAVs, HAPS, LEOs to wirelessly transmit data over large distances.

Problem Statement and Need

Existing underground monitoring solutions rely on power-hungry cellular modules or impractical wired connections, while standard commercial nodes fail to penetrate saturated soil at useful depths.

Final Design Solution

To deal with this, the proposal of our project is a multi-layer architecture which is designed on the standard of LoRa (Long Range) being known for deep penetration and noise resilience abilities. We developed a MATLAB simulator to assess the architecture that consists of underground devices, UAVs and LEO satellites, with the specific goal of validating the reliable collection of environmental measurements from buried sensors in remote locations.

Final Performance Achieved

- RSSI: Signal above -137 dBm hardware at 100 m distance.
- SNR: Above -20 dB at SF12 confirmed in simulation (REQ-2 Met)
- PDR: ~85% under ideal simulation conditions — threshold achieved (REQ-3 Met)
- Hardware: Successful UART communication and packet transmission verified bench-side
- Budget: 73,940 KZT spent vs. 270,000 KZT allocated (200,000 KZT remaining)
- The simulation closely estimates signal strength based on burial depth, distance, volumetric water content in soil and transmit power.

Requirements met / Partially met / Unmet

- Met (simulation): REQ-1, REQ-2, REQ-3
- Partially met: REQ-6 (10+ node scalability)
- Unmet: REQ-5 (battery life >5 years)

Main Limitation and Recommended Next Step

The main limitation was the scarcity of more energy efficient electronic components for the prototype. The voltage regulators draw significant amounts of current at rest; therefore, the battery life of the prototype from the practical part is short. Unfortunately, chosen LoRa transceivers are not capable of supporting both the RSSI and SNR. For future similar projects, the components must be chosen more carefully.

2. Problem Definition, Stakeholders, Context, and Constraints

2.1 Problem Definition and Need Statement

With the rise in demand for IoT devices it became crucial to provide infrastructure for them. Terrestrial networks cover a large amount of area but still there are remote areas where there is a need for a different architecture that provides higher coverage at lower costs. This type of architecture is called Non-Terrestrial Network. It makes use of UAVs, HAPS, LEOs to wirelessly transmit data over large distances.

The main drawback of these networks is high signal attenuation mainly due to path loss. Especially when the IoT device like an underground sensor is located in harsh conditions buried under the ground. In such a case there is a need for special architecture that makes sure the signal from the underground device successfully reaches the receiver.

To address this, our project proposes a multi-layer architecture based on the LoRa (Long Range) standard, known for its noise resilience and deep penetration capabilities. We will develop a MATLAB simulator to assess the architecture that consists of underground devices, UAVs and LEO satellites, with the specific goal of validating the reliable collection of environmental measurements from buried sensors in remote locations. Also, we will design algorithms that specifically fit our problem.

2.2 Stakeholders

The main stakeholders of this Capstone Project are the team members. There is a direct success link between all stakeholders' academic progresses and degree completion. That is why we had incentive to deliver both meaningful and strong results. Our project supervisor is also a major stakeholder; he guides us through the process, ensures that we stay on track, and helps us achieve the project outcomes. Although we are not working with external companies or industry partners, the ideas explored in this project could be useful for several groups. Manufacturers of satellites and UAVs, as well as people working in agriculture or other areas that rely on long-range communication, may benefit from the type of architecture we are proposing.

Table 2-A. Stakeholder Analysis

Stakeholder	Role/Interest	Needs/Success criteria	How engaged (meetings/inputs)	Impact of project
Team (Arman, Beibarys, Merey)	Design, implementation	A physics-based MATLAB simulation & hardware prototype	Weekly meetings, online task allocation	Students gain knowledge in project structuring, task allocation. They get hands on experience on

				MATLAB, hardware
Supervisor (Behrouz Maham)	Technical guidance, quality assurance	Structure, fast response	Offline meetings, Email	Feedback, report approval
ECE Department / University	Materials provider	Aligned with ABET accreditation	School Office, lectures	Full documentation
Agriculture companies	Potential customer / end user	Reliability: data transmission from >30cm depth.	Engagement via market research and requirement analysis (Literature Review)	Provide architecture that could solve the connectivity gap

2.3 Context and Operating Environment

This project is conducted in an academic environment. Due to certain constraints, we are unable to collaborate with industry partners. However, we can model the system and design an algorithm using software tools. As a result, we will gain valuable knowledge that can be applied to address current communication challenges in subterranean devices.

Technological

Context:

To design the simulator, we used MATLAB, with a license provided by the university. Our budget limits the scale of real-world implementation, but we managed to analyze the performance of LoRa-based networks by ordering two types of LoRa transceivers (with different transmit powers) and two types of antennas with different gains. The transceivers operate at 433 MHz, the same frequency used by the authors of [1]. We varied the transmit power, spreading factors and observed how signal performance changes. Throughout the project, we made sure that all team members follow institutional guidelines, safety standards, and academic requirements.

2.4 Constraints and Context Factors

Table 2-B. Constraints Matrix.

Constraint category	Metric / target	Final estimate or measurement	Gap / residual risk	Owner	Evidence / next action
Regulatory (RF)	ISM 433 MHz band complianc	433 MHz confirmed free;	Low	Team	VEV-4, VEV-5

	e; duty cycle < 1%	software duty-cycle limit coded			
Budget	< 270,000 KZT	BOM total $\approx$ 73,940 KZT: 200,000 KZT remaining	Low (UAV unfunded)	Team	Table 10-C
Schedule	Completion by end of Spring semester (Week 14)	Hardware assembly done, outdoor testing done, simulation done in time.	Low–Medium	Team	PMEV-1
Safety (Electrical)	Soldering should be done in a ventilated room. Isolate the wires.	Soldering complete, the wires are not overheating, the prototype functions as expected.	Low	Arman	DEV-3
Power Consumption	Battery Life	48 hours under test conditions	Battery may not last in cold temps	Team	DEV-6
Environmental	Humidity Level	70 – 80 % humidity of soil	Medium; very high humidity blocks the signal.	Merey	VEV-2.

A. Public Health, Safety, and Welfare

- **Safety:** The physical prototype operates on low voltage DC. The risk of getting an electric shock is minimal. Farmers and technicians can safely deploy the underground devices.
- **Public Health & Welfare:** Implementing the soil moisture sensors in agriculture will lead to more optimized irrigation. Stable supply of a high amount of crops positively affects the welfare of people, there will not be a deficit of food. Also, deploying underground devices in urban areas will be useful to predict natural disasters like landslides or sinkholes. Extremely high volumetric water content / moisture level might indicate that those disasters could happen.

B. Environmental Factors

- **Water Conservation:** The primary environmental impact of this capstone project is that it will save a lot of water. The irrigation of crops could be done in a more optimal way due to the presence of detailed information on current volumetric water content in soil.
- **E-Waste & Battery Life:** By implementing LoRa in the system the electrical energy required for the device is significantly reduced. In most cases, the packets are sent with large intervals like hours or days. The device could run for years on a single battery if the hardware was well designed.

C. Economic Factors

- **Affordability:** The traditional NB-IoT and terrestrial networks require larger amounts of costs than LoRa modules. By proving that at lower cost, 433 MHz LoRa module can successfully be used in underground applications, this project provides a highly economical solution. It allows small-scale independent farmers to stay autonomous, without a need to pay for mobile services every month.

D. Global, Cultural, and Social Factors

- **Global/Social Accessibility:** One of the main applications of LoRa modules is agriculture. The prototype can be built from freely available parts on the market, the technology can be universally adopted across different countries and cultures. It empowers local communities to effectively use available crop fields. Therefore, the quality of life inside the society is likely to improve.

3. Final Requirements, Acceptance Criteria, and Traceability (2–3 pages)

3.1 Final Requirements Compliance

Table 3-A. Final Requirements Compliance Matrix.

Req. ID	Requirement statement	Source	Verification method	Target threshold	Measured result	Verdict	Evidence ID
REQ-1	Receiver Sensitivity (RSSI)	Semtech SX1276 Ebyte Datashield	RSSI > -137 dB (simulation)/ packets are successfully transmitted (field test)	RSSI from simulation (signal > -137 dBm at 100 m)	RSSI > -137	Met with 33 dBm transmit power	VEV-12

REQ-2	Signal-to-Noise Ratio (SNR)	LoRa Alliance Specification	SNR > -20 dB (SF12)	SNR is above -20 dB based on simulation results	SNR is above -20 dB based on simulation results	Indirectly verified through PDR and latency simulations	VEV-3
REQ-3	Packet Delivery Ratio (PDR)	Project Brief	Matlab simulation	PDR ≥ 85% for 100m in simulation	33 dBm at 0.2 m depth PDR satisfied	Met with 33 dBm transmit power	VEV-3
REQ-4	Packet Delivery Ratio (PDR)	Project Brief	Physical tests	Obtain PDR ≥ 85% at different depths, N packets / N seconds	PDR ≥ 85% were obtained mostly while sending less packets with more time delay in a short communication ranges	Verified through experimental calculations	VEV 13, VEV 14, VEV 15, VEV 16
REQ-5	Doppler Shift Compensation	Literature Review	Simulation testing	Change in UAV-to-satellite PDR graphs		Validated through Doppler shift modeling and testing	DEV-8

REQ-6	Battery Life (Underground Node Lifespan)	Industry IoT Standard	> 5 years	Battery lasts 48 hours under test conditions	4 hours when 1 byte packet is sent every 5s.	The battery life depends on use	DEV-5
REQ-7	Simulation should match experimental data	Team derived	Simulation analysis	Error less than 10%	14 dB soil loss mismatch	Simulation fails to match the experimental data	VEV-21

3.2 Requirements Traceability

Table 3-B. Requirements Traceability Matrix.

Stakeholder need	Requirement(s)	Constraint(s)	Standard clause(s)	Design feature(s)	Test ID(s)	Result section
Reliable signal from buried sensors	REQ-1, REQ-2, REQ-3, REQ-4	Regulatory RF; Environmental (soil)	RP2-1.1; 3GPP TR 38.901	33 dBm Tx power; 4 dBi antenna; soil dielectric model	T1, T2	Sec. 9
Long battery life for buried node	REQ-6	Safety $I_{peak} \leq 1.5 \text{ A}$; duty cycle < 1%	ETSI EN 300 220 (duty cycle)	Li-Po 6000 mAh + MT3608 boost; binary payload encoding	Battery test	Sec. 8.1

Stakeholder need	Requirement(s)	Constraint(s)	Standard clause(s)	Design feature(s)	Test ID(s)	Result section
Scalable network for multiple sensors	REQ-7	Budget (no UAV); schedule	LoRaWAN L2 Spec 1.0.4	Calculating traffic congestion for N number of nodes	T5 (sim)	Sec. 9
Regulatory compliance for Kazakhstan	REG-1, REG-2	Regulatory RF; Safety	RP2-1.1; ETSI EN 300 220	Software duty-cycle limiter (< 1%); 433 MHz band	Code review	Sec. 4

3.3 Derived, Interface, Environmental, and Regulatory Requirements

1. Derived Requirements

- REG-1: ISM band operation The RF front-end shall operate within the 433 MHz ISM band.
- IFC-1 (Power): The power subsystem (Li-Ion battery and MT3608 boost converter) shall provide a peak current capability of at least 1.5 A.
- DER-1 (Payload): To maximize the probability of signal penetration through saturated soil, the data payload shall use binary encoding (1 byte) rather than ASCII string format to minimize Time-on-Air (ToA) and collision probability.
- REG-2 (Duty Cycle): To comply with 433 MHz ISM band regulations at 2W output, the software must enforce a transmission duty cycle of $< 1\%$ (approx. 36 seconds/hour max).

2. Interface Requirements

IR-1: Link from Controller to Radio: The communication between the MCU and the LoRa module shall be established via a UART interface at a baud rate of 9600 bps.

Reasoning: This is the main protocol issued for module E32-433T33D, the pinout of the module was made to be able to connect it to MCU.

IR-2: Sensor Signal Compatibility. The sensor (soil moisture) should be capable in providing the signal analog of 0-3.3V range

Justification: This corresponds to the input range of ESP 32 which is 12-bit ADC. It allows precise readings.

3. Environmental Requirements

ER-1: Protection against moisture: The enclosure housing the buried node must be hermetically sealed in order to prevent water reaching electronic components.

Rationale: The soil can contain a lot of water. If the water gets inside, the metal components will experience corrosion.

ER-2: Requirement for environmental conditions: temperature above -20 degrees celsius.

Rationale: At lower temperature the battery drains very fast.

4. Regulatory Requirements

RR-1: Frequency Assignment: The transmission frequency should be at 433 MHz.

Rationale: This is an ISM band that is free in Kazakhstan. Also, the same frequency was used in simulation.

RR-2: Channel Occupancy (Duty Cycle): The duty cycle should be lower than 1%.

Rationale: To avoid interference in dense networks, where there are many other underground devices.

4. Engineering Standards, Regulations, and Compliance Evidence (1–2 pages)

Table 4-A. Standards Application Matrix.

ID	Standard / regulation	Clause used	Why applicable	Design decision affected	Verification / inspection method	Evidence produced	Compliance status
RF-01	LoRaWAN Regional Parameters (RP2-1.1)	Frequency Plan: 433 MHz	Mandatory adherence for operating in ISM band in Kazakhstan	Frequency carrier set to 433 MHz in simulation and hardware	Review of the Datasheet; simulation parameter verification	Transceiver datasheet; code parameter	Met
RF-02	EU433 LoRaWAN Regional Parameters	Duty Cycle < 1%;	Ensures system complies with spectral efficiency regulations at 2 W	Packet generation rate limited; < 36 s/hour transmission time	Analytical review of traffic model; packet-per-hour calculation	Code snippet showing duty-cycle limiter logic	Met

AV-01	Kazakhstan Civil Aviation Authority	Max flight altitude : 120 m	UAV altitude in simulation must be realistic and legal	UAV height parameter in MATLAB simulation capped at 120 m	Simulation file input parameter validation	MATLAB simulation parameter log	Met
SEC-01	LoRaWAN L2 Spec 1.0.4	AES-128 Encryption	Ensures secure communication; payload integrity in LoRaWAN network	LoRaWAN header overhead includes AES-128 security fields in packet model	Analysis of packet duration; function; encryption overhead verification	Simulation packet structure; overhead calculation	Not met

5. Concept Generation, Trade-off Study, and Selected Concept (2–3 pages)

5.1 Candidate Concepts

Table 5-A. Candidate Concepts.

Concept	Description	Strengths	Weaknesses	References / evidence
1. Direct to Satellite (LEO)	Underground sensor transmits directly to LEO using LR-	High scalability (no UAV	Very high power consumption	[4] Ullah et al., 2022 (LR-FHSS analysis)

Concept	Description	Strengths	Weaknesses	References / evidence
	FHSS or LoRaWAN without mediators.	needed); wide coverage area.	(must overcome large distance); battery drains rapidly; low data rate.	
2. UAV Store-and-Carry	UAV flies over sensors, collects data into its memory, uploads on return to base station.	Excellent link reliability (UAV flies directly overhead); no simultaneous collision.	Limited by UAV battery; high latency; cannot handle real-time monitoring.	[3] Lin et al., 2025 (UAV energy model)
3. Hybrid Relay (SELECT ED)	Sensor–UAV–LEO chain. UAV acts as a mobile LoRaWAN gateway relaying real-time to LEO satellite.	Best link reliability (UAV overhead → Low latency, presence of LOS)	System complexity; UAV cost; scheduling is required	[1] Lin & Alouini, 2025 (connectivity framework)
4. Terrestrial LoRaWAN	Fixed LoRaWAN gateways that are connected to the terrestrial network.	Implementation simplicity	High cost and small coverage	[2] Raza et al., 2017 (LPWAN overview); [1]

5.2 Weighted Trade-off Study

Table 5-B. Weighted Trade-off Matrix

Criterion	Metric / target	Weight	Concept 1	Concept 2	Concept 3	Evidence source
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Link Reliability	> 10 dB	0.3	3	9	9	Snell's Law analysis; simulation SNR graphs; [1]
Scalability	Coverage	0.2	10	3	9	Wide Area coverage [2]
Energy Efficiency	Time on Air < 500 ms	0.15	4	8	8	Duty-cycle calculation; [4] FHSS model
System Complexity	Implementation	0.15	9	6	3	Hardware BOM; architecture and its complexity simulations
Data Latency	< 30 min	0.1	6	2	8	Fly-over period of UAV vs delay estimations of store-and-carry
Total score (normalized)			5.45	5.6	6.95	

Sensitivity analysis: If changes made in System Complexity (+0.1) and Link Reliability (-0.2)

Hybrid delay approach is still the best (score 6.35), while the second is Direct-to-Satellite approach (score 6.05)

The “Concept 3” is the best balanced concept due to different criterias allowing it to obtain the highest score.

5.3 Selected Concept and Rationale

Wide Area Networks have a higher communication range than traditional short-range terrestrial networks [2]; therefore, Method 4 has the lowest scalability score. Method 2 is limited by the UAV's battery capacity [3]. In terms of energy efficiency, the Direct-to-Satellite method has the lowest score because it must transmit signals at higher power and lower data rates due to the large distance. It uses high spreading factors or FHSS, which drain the battery quickly [4]. For underground devices, terrestrial networks have lower link reliability than those that include UAVs, due to signal attenuation in soil. According to Snell's Law, electromagnetic waves propagating from a dense medium (soil) to a less dense medium (air) experience Total Internal Reflection if the incident angle is smaller than the critical angle. Terrestrial gateways are typically located at low elevation angles, while UAVs can hover directly above the underground device [1].

6. Design Iterations and Decision History

Table 6-A. Major Design Iterations

Iteration / version	Issue discovered	Alternatives considered	Decision made	Trade-off accepted	Evidence of improvement
I-1	Moisture sensors came broken.	Moisture sensors at local electronics store.	Purchase of sensors at the local store.	The sensor was analog	The measurements of moisture level, VEV-1, VEV-2.
I-2	The boost converter burned out.	The same boost converter at the local electronics store.	Purchase of boost converter at the local store.	The energy leaks at rest when nothing is sent.	The working prototype. VEV-3.
I-3	Weak signal propagation of 10 dBm Lora.	Burying a more powerful, 33 dBm Lora module.	The module was replaced.	High energy consumption.	VEV-12.
I-4	Weak signal propagation due to antenna misalignment.	Changing the position of the antenna.	The antenna position was changed.	Polarisation mismatch.	The improve in propagation, VEV-12.
I-5	Number of Monte Carlo iterations.	Higher number of iterations.	Use 100-1000 iterations.	Longer computation time.	VEV-19 Improvement.
I-6	Antenna gain mismatch.	Computing the real gain of the antenna.	To reduce the gain of the antenna by 2 dBi.	Still might not be accurate.	Simulation became more predictable.

7. Final System Architecture

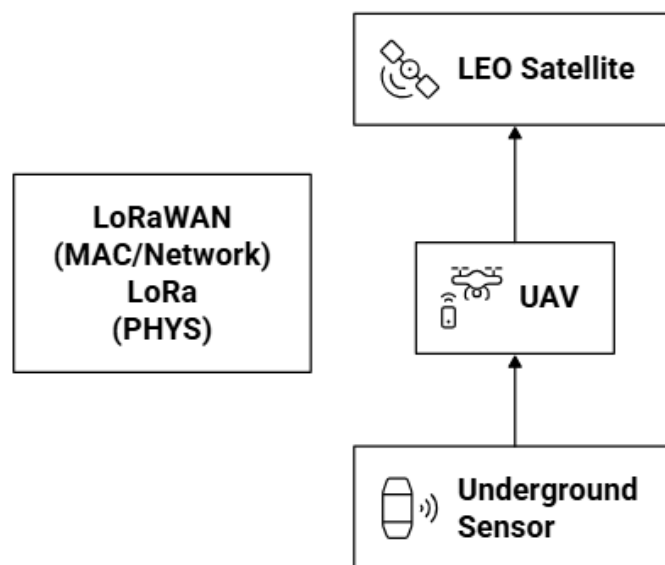


Fig. 1. Block diagram of the system interface.

Our system model uses the connectivity framework proposed in [1] and modifies it. The system consists of 3 main parts in a data uplink chain:

- 1) Underground sensors with LoRa based transceivers (buried inside soil).
- 2) UAV as a mobile LoRaWAN gateway receiving LoRa RF signal from the underground sensor directly.
- 3) LEO Satellite receiving data from the UAV gateway through satellite uplink.

We propose a system model where multiple underground sensors send data containing soil property (soil moisture in our case) to a UAV which then transmits it to the LEO satellite. The experimental part considers an underground-to-UAV link, and we will use a LoRa transceiver above the sensor to imitate the UAV receiving the signal. The UAV to LEO link is done using simulation. The end-to-end PDR for single and multiple nodes is simulated.

Table 7-A. Interface Summary.

Interface	Direction	Protocol / signal type	Rate / timing	Voltage / power	Owner subsystem	Notes
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LoRa (over-air) ↔ UAV	Underground sensor → UAV	LoRa / LoRaWAN uplink, SF7–SF12	Uplink duty cycle <1%; message interval e.g. 3600 s	3.3 V Supply 3.3 V Logic	Underground sensor, UAV subsystems	Transmit power 10 dBm or 33 dBm, antenna gain 2 or 6 dBi
ESP32 ↔ LoRa module	MCU → LoRa	SPI (Serial Peripheral Interface)	SPI clock 9600 baud rate	2.2V-3.6V Operating (ESP)	Underground sensor subsystem	433 MHz LoRa modules

Table 7-B. Simulation Interface.

Interface	Direction	Protocol	Notes
UAV / Satellite	UAV → Satellite	Virtual uplink	Simulated in MATLAB
Underground device / UAV	Underground device → UAV	Virtual uplink	Simulated in MATLAB

Timing / latency budget:

Minimal time-on-air is present. 2 hops are needed: Ground to UAV and UAV to LEO satellite. 500 ms latency is expected as maximum.

Power / resource budget:

Battery life is identified by how frequently the underground node transmits data to the UAV. In ideal conditions, nodes sending 1 packet each hour with integrated sleep mode can last several years. Transmission power of 10 dBm and antenna gain of 4 dBi should overcome SNR threshold of -20 dB and RSSI threshold of -137 dBm.

8. Detailed Design and Implementation (2–4 pages)

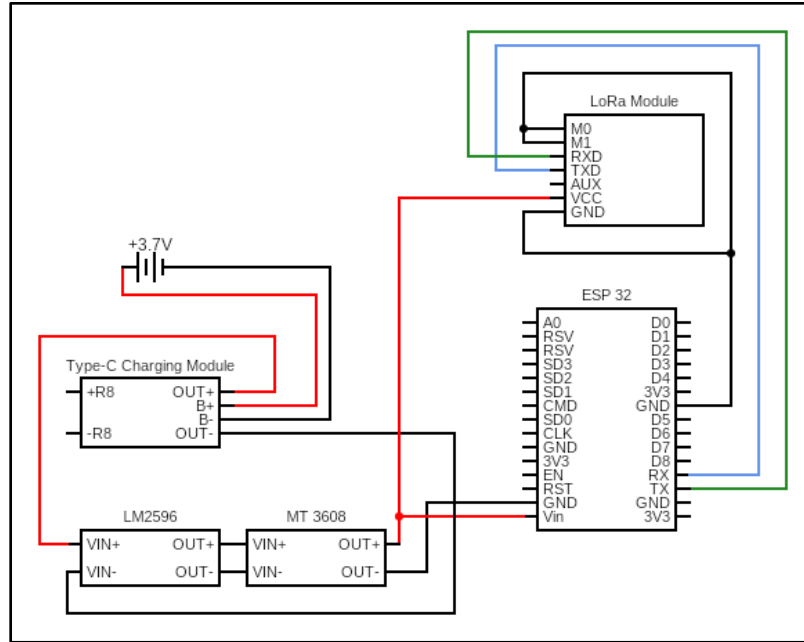
8.1 Hardware design

The hardware design for the practical part of the project consists of several components: a battery with charging module, voltage converters, LoRa module and ESP-32 microcontroller.

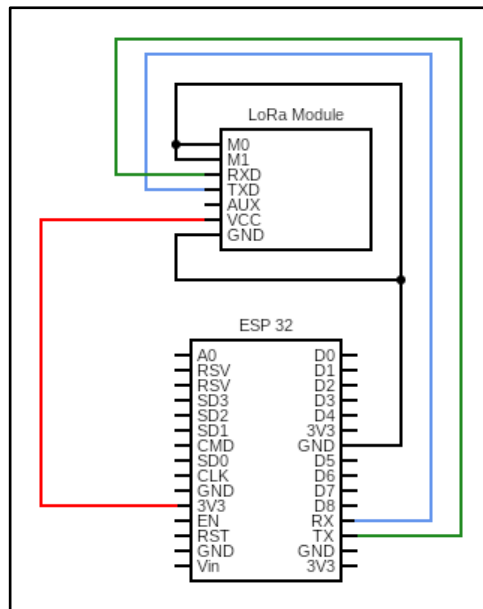
At transmitter: Both ESP-32 microcontroller and Lora module are powered from 3.7 Li-ion battery.

Main parameter		Performance			Remark
		Min.	Typ.	Max.	
Operating voltage (V)		3.3	5.0	5.5	≥5.0 V ensures output power
Communication level (V)			3.3		For 5V TTL, it may at risk of burning down
Operating temperature (°C)		-40	-	+85	Industrial design
Operating frequency (MHz)		410	-	441	Support ISM band
Power consumption	Transmitting current[mA]	850	1000	1200	Instant power consumption
	Receiving current [mA]	11	13	15	
	Turn-off current [μA]		2		Software is shut down
Max Tx power (dBm)		32	33	34	
Receiving sensitivity (dBm)		-145	-147	-148	Air data rate is 2.4kbps
Air data rate (bps)		0.3k	2.4k	19.2k	Controlled via user's programming

The Lora modules operate at 3.3 V at minimum. Esp-32 is powered by 3.3 V. The prototype has a step up and step down converter because there was no direct step down converter to get 3.3 V and that could draw a large amount of current. The 33 dBm Lora module can draw large amounts of current, therefore the voltage converter should support high current. ESP-32 and LoRa module are connected to the battery in parallel. The ESP-32 is needed to operate with data, it tells LoRa transceiver's SX1276 chip what to send. The data is transmitted through Rx and Tx pins. The Rx of the LoRa module is connected to the TX2 pin of ESP-32, the Tx of the LoRa module is connected to the RX2 pin of ESP-32.



DEV-1. The circuit diagram of the transmitter.



DEV-2. The circuit diagram of the receiver (ESP32 is connected to the computer via USB Type-C).

8.2 Software / firmware design

The simulation design consists of practical and simulation parts. Practical simulation includes writing and running Arduino code for the hardware. The simulation part includes writing MATLAB codes and modifying the simulator.

The Software / firmware design from the practical part

There are 2 separate Arduino codes written for transmitter and receiver. Figure **DEV-7** shows a transmitter code.

The Software / firmware design from the simulation part

The proposed architecture of the Hybrid Relay model is divided into ground-to-UAV and UAV-to-LEO links. Our team modified an existing MATLAB simulator by adding the UAV-to-LEO link using Doppler shift, Rician fading and FSPL (Free Space Path Loss) formulas. Major functions explained:

1. Pipeloss calculates Loss_res which is a path loss due to the soil and spatial spreading with boundary effects. with boundary effects. Parameters to set: realSoilDielectric, mp, ec, depth, Freq_Band.
2. clc_die calculates realSoilDielectric and imagSoilDielectric values. Parameters to set: clay_input, vwc_input, frequency.
3. U2Aloss calculates Lu which is a combination of L_absorption and L_interface. L_absorption is about material loss, when moisture and minerals absorb EM energy and turn it into heat. L_interface is a boundary loss, it shows how much energy is lost when a wave transitions from dense soil to thin air. Some parts are reflected back. Parameters to set: realSoilDielectric, imagSoilDielectric, depth, Freq_Band
4. UVAirLossHigh uses **3GPP TR 38.901** standard (extension of it designed for UAVs). This function considers when a signal leaves the ground (above ground). 2 scenarios are considered: RMa-AV (Rural Macro Aerial Vehicle) and Uma-AV (Urban Macro Aerial Vehicle). h_bs set to 0 instead of 1.5 meters. Parameters to set: UAV_height, Frequency, Ptx, Gr_U, Gt, Total_loss_tmp_W, Distance, MonteCarlo.

The UAV-to-LEO link is implemented by adding a separate U2LEO function. This function accounts for the Doppler shift and Rician fading with FSPL. The satellite orbiting at 7.8 km/s causes carrier frequency to shift. This causes synchronization issues at the receiver. Each 10kHz frequency mismatch adds 1.5-2 dB loss. Rician fading is used when strong LOS is present. When a UAV flies at 100 meters altitude, it is not blocked by the obstacles. Thus, we can set high Rician k factor values. In our case it is 15.

8.3 Mechanical / packaging design (if applicable)

The PVC Pipe was chosen as the enclosure for the transmitter.

8.4 Prototype realization and integration

The prototype was realized in two stages:

1. Breadboard Verification:

Testing the UART communication between the ESP32 and the E32 module. Establishing communication between 2 LoRa modules.

2. Field Integration:

Soldering, isolating the wires and placing the prototype inside a PVC pipe.

8.5 Final bill of materials and design-for-manufacture / assembly notes

The materials ordered from China came on time. The assembly of the prototype was done successfully. The only problems were:

1. Later we found out that the LoRa modules we ordered did not support the RSSI and SNR measurement features.
2. Both of the capacitive soil moisture sensors from Aliexpress came defective.

9. Verification, Validation and Experimental Results (2-4 pages)

Table 9-A. Requirements-to-Test Results Matrix.

Req ID	Requirement	Test ID	Verification method	Equipment / tools and accuracy	Target	Measured result	Verdict	Evidence ID
R1	PDR (Packet Delivery Ratio) $\geq$ 85%	T1	Field test: PDR under different VWC	LoRa module, soil moisture sensor, LoRa RX antenna at ground, logger (laptop)	Pass: PDR $\geq$ 85%	At different VWC (60%, 70%, 80%), PDR $\geq$ 85% on a communication ranges of 0–20 meters (scenario 1), 0–80 meters (scenario 2), 0–900 meters (scenario 3)		VEV 2, VEV 13
R2	PDR (Packet Delivery Ratio) $\geq$ 85%	T2	Field test: PSR under different burying depth		Pass: PDR $\geq$ 85% Fail: PDR $<$ 85%	At different depths (20cm, 40cm, surface), PDR $\geq$		VEV 14, VEV 15, VEV 16

Req ID	Requirement	Test ID	Verification method	Equipment / tools and accuracy	Target	Measured result	Verdict	Evidence ID
						85% on a communication ranges of 0–20 meters (scenario 1), 0–80 meters (scenario 2), 0–900 meters (scenario 3)		
R3	RSSI ≥ -137 dBm at depth 40 cm, VWC 0.4	T3	Field test	LoRa transmitter and receiver logs	Packet is received	Packet was received successfully	●	VEV-3
R4	SNR ≥ -20 dB at depth 40 cm,	T4	Field test	LoRa transmitter and receiver logs	Packet is received	Packet was received successfully	●	VEV-3

Req ID	Requirement	Test ID	Verification method	Equipment / tools and accuracy	Target	Measured result	Verdict	Evidence ID
	VWC 0.4							
R5	Simulation should match experimental data	T5	Simulation analysis	MATLAB software, measurement logs	Pass: error $\leq 10\%$ Fail: error $> 20\%$	26 dB mismatch	Not met	VEV-21

Table 9-B. Test Campaign Summary.

Test / experiment	Date	Owner(s)	Setup	No. of trials	Key result	Observed issues	Follow-up action
Observe PDR for different scenarios	Week 11	Arman Beibarys Merey	LoRa 10 dBm, LoRa 33 dBm	3	20cm depth sensor with LoRa 33dBm demonstrated communication range of 120 meters with PDR>85 % on a range of	10 dBm LoRa could receive packets at only maximum 30 meters	33 dBm LoRa replaced the 10dBm LoRa to increase the communication range 5 times

Test / experiment	Date	Owner(s)	Setup	No. of trials	Key result	Observed issues	Follow-up action
					0-80 meters		
Compare PDRs with different both packet burst and timer delays	Week 12	Merey	LoRa 10 dBm, LoRa 33 dBm	9	The PDR trends are greater of those with greater delay timers	10 dBm LoRa couldn't receive packets burst (3pkts/delay or 5pkts/delay) at more than 20 meters	33 dBm LoRa replaced the 10dBm LoRa to increase the communication range 4 times allowing to receive packet bursts.

10. Risk Management, Schedule, Budget, and Procurement Outcome

10.1 Final Risk Register

Table 10-A. Risk Register with Outcomes.

ID	Risk	L	I	RPN	Mitigation	Did it occur?	How handled	Residual risk / limitation
RS K-1	Underground RF link failure	4	5	20	Quick test of node at target depth and soil VWC; adjust transmit power, antenna placement, or node orientation.	No		
RS K-2	Cold-temperature performance	3	4	12	Insulation for electronics; log actual temperature vs performance.	No, tests were conducted at warm temperatures.		
RS K-3	Simulation-Real World Mismatch	2	4	8	Make multiple measurements at different depth, soil types, moisture.	Yes	Make multiple measurements at different depths, transmit power and antenna gain.	Residual Risk - Inaccurate simulation, limitation - the corrected simulation is limited to the field tests.
RS K-4	Data corruption / packet loss due to EMI	2	3	6	EMI injection test; use checksums/	No		

ID	Risk	L	I	RPN	Mitigation	Did it occur?	How handled	Residual risk / limitation
					MIC; log errors			

L = Likelihood (1 = very low, 5 = very high)

I = Impact (1 = minimal effect, 5 = major delay)

RPN = Risk Priority Number ($L \times I$) → higher = more important to manage early

10.2 Milestones Planned vs. Actual

Table 10-B. Milestones and Completion Evidence.

Milestone	Planned date	Actual date	Owner	Exit criteria	Status	Evidence
M1: Smoke & Interfaces	Week 3 Spring	Week 3	Arman	Basic measurement works, PSR logs collected	Met	DEV-3, DEV-7
M2: Risk-Retirement (Underground & Winter)	Week 5 Spring	Week 7	Merey	Pass/fail for PSR $\geq 90\%$ recorded at different VWC & burial depths	Met	DEV-4
M3: Integration & Scenario V&V	Week 8 Spring	Week 9	Beibarys	$\geq 90\%$ tests pass for PSR, RSSI, SNR; MATLAB error $\leq 10\%$, failures triaged	Unmet	VEV-16 - VEV-20
M4: Final Integration & Testing	Week 12	Week 12	Merey, Arman, Beibarys	Full system tests completed, network scalability validated.	Met	VEV-13 - VEV-20

10.3 Budget, Procurement, and Substitutions

Table 10-C. Bill of Materials and Procurement Summary.

Part No.	Description	Qty	Unit cost	Total	Alt. part / substitution	Supplier / lead time	Impact of substitution
1	LoRa 0.1 W 433 Mhz Transceiver Used to build a LoRa network consisting of 2 nodes. 1 for the sender and 1 for the receiver.	2	3276.504	6553.008	RFM95W (SX1276 chip based)	AliExpress / 3-4 weeks	SPI driver programming required, does not work out of the box
2	LoRa 2 W 433 Mhz Transceiver with 4 dBi Antenna Higher power transceiver	2	8,762.065	17524.13	RFM98W (High power SX1276)	AliExpress / 3-4 weeks	SPI driver programming required, does not work out of the box
3	10 dBi 433 MHz Antenna High gain antenna will be compared with 4 dBi antenna.	2	4,494.9295	8989.859	Antenna with another gain, typically lower	AliExpress / 3-4 weeks	Reduced transmission range and soil penetration depth.
4	Copper wire, 20 AWG, 1 m To connect the electrical components	2	352.2838	704.5676	Thicker copper wire	AliExpress / 3-4 weeks	Harder to bend and fit inside the compact PVC enclosure.
5	Breadboard MB102 To build the prototype before soldering.	1	937.6576	937.6576	perfboards or protoboards	AliExpress / 3-4 weeks	Slower prototyping phase.

Part No.	Description	Qty	Unit cost	Total	Alt. part / substitution	Supplier / lead time	Impact of substitution
6	Jumper Wires, 10 cm, 3 kinds To build the prototype.	1	974.7401	974.7401	Cut/stripped solid core 22 AWG wire	AliExpress / 3-4 weeks	Increase in time required to manually cut and strip wires for the prototype.
7	Battery charging board TZT TP4056 To charge the battery.	2	238.38755	476.7751	External desktop Li-Po charger	AliExpress / 3-4 weeks	Battery must be physically removed from the circuit to charge it
8	Heat Shrinkable Tube Set To isolate the soldered places of wire.	1	858.1951	858.1951	Electrical tape	AliExpress / 3-4 weeks	Less durable seal
9	Capacitive Soil Moisture Sensor To measure Volumetric Water Content in soil.	2	378.7713	757.5426	Time Domain Reflectometry (TDR) sensor	AliExpress / 3-4 weeks	More expensive, higher precision
10	3.3 V Voltage Regulator, 3A To provide stable high current.	2	243.68505	487.3701	3.3V 1A Regulator (AMS1117)	AliExpress / 3-4 weeks	Risk of brownouts or system resets.
11	Li Battery, 6000 mAh, 3.7V To power the prototype.	2	2,050	4100	3000 mAh Li-Po battery	Local Electronics Shop / 1 day	Halves the operational lifespan.
12	ESP 32 FT 232, 30 pin To collect the data from the	2	3451.3215	6902.643	Arduino Nano	AliExpress / 3-4 weeks	Requires 5V-to-3.3V logic level shifters for LoRa.

Part No.	Description	Qty	Unit cost	Total	Alt. part / substitution	Supplier / lead time	Impact of substitution
	sensor, send it through LoRa.						
13	A0 Presentation Poster Used for the presentation session.	1	2650	2650	None.	Local Printing Shop / 1 day	
14	Boost converter Regulate output voltage on battery.	3	550	1650	Connecting 2 batteries in series (7.4V)	Local Electronics Shop / 1 day	requires a complex Battery Management System (BMS) to charge safely.
15	Soil moisture sensor Previous sensors came broken.	1	450	450	Time Domain Reflectometry (TDR) sensor	Local Electronics Shop / 1 day	More expensive, higher precision
16	LM2596 Step down converter To be able to draw 3A current (There was no 3 A boost converter).	2	720	1440	Linear voltage regulator (e.g., LM317)	Local Electronics Shop / 1 day	Highly inefficient, wastes battery energy as heat.
17	Solder wire To solder the wires.	1	3900	3900	Crimp connectors or wire nuts	Local Electronics Shop / 1 day	Bulkier connections, higher risk of mechanical failure.

Budget status vs. plan: Extra budget remained. All necessary items were purchased as planned.

Change-control summary: Extra soil moisture sensor, boost converter was bought.

11. Professional Responsibilities and Broader Impacts

11.1 Public Health, Safety, and Welfare

- **Public Health:** A transmitter operating at 2 Watts surpasses the conventional LoRa power thresholds. The 1 % duty cycle does not let 2 W modules to have a negative effect on the health of humans and animals.
- **Safety:** The PVC pipe enclosure makes sure that prototype does not harm anyone.
- **Welfare:** Underground devices used for smart agriculture allow people to increase the output from farms. The overall welfare will increase.

11.2 Ethical and Professional Responsibilities

- **Academic Integrity:** All academic resources and literatures were cited in this project. All points of this project were formed and developed under the supervision of the members and faculty
- **Responsible Use of AI:** With the help of artificial intelligence, the development of the structure of reports has been facilitated along with improved effectiveness for visual data. The final remarks, the analysis of the results and the technical solutions received their confirmations from the overall expert assessment of the team in the end.
- **Dual-Use Considerations:** The software projected by our team was appropriately limited to functions (environmental monitoring) in order to eliminate the risk of disruptions related to the regulation of communication frequencies.

11.3 Security and Privacy

- **Physical Security:** Using plastic tube to protect circuit from underground dirt. This ensures that the hardware part is sealed and operates without any problem.
- **Threat Considerations:** Subsequent versions will integrate AES-128 encryption at the LoRaWAN layer to improve security. As remote agriculture land is not targeted by malicious attacks, still this encryption helps to keep data safe.

11.4 Accessibility and Usability

- **Visual Accessibility:** All technical illustrations employ distinctive colors and exhibit visual appeal. The plots have all necessary titles and labels.
- **Ease of Deployment:** The prototype's facilitated deployment, as evidenced during the empirical segment, is exemplary. The enclosure incorporates a cap that ensures a hermetic seal upon closure, thereby obstructing any passage through it.
- **Documentation:** The report is well organized, all chapters are enumerated.

11.5 Environmental, Economic, Social, Global, and Cultural Factors

- **Environmental:** The system promotes sustainable "Precision Agriculture" and water conservation. By opting for a PVC casing, we guarantee that the electronics do not release chemicals into the soil over extended periods.
- **Economic:** We optimized the BOM, rendering it financially feasible for extensive deployment in emerging agricultural zones where costly satellite-dependent systems are inaccessible.
- **Global/Cultural:** We are using a free radio frequency of 433 Mhz. Also, there is no need for monthly plans from cellular operators. It can be extended to a global scale.

12. Team Organization, Collaboration, and Individual Contributions

Table 12-A. Team Roles and Responsibilities.

Member	Primary role	Secondary role	Major technical ownership	Leadership responsibility	Evidence ID
Merey Kudaibergen	Simulation & Field Test	Simulation Design	Experimental Testing, Data Gathering for Experimental Results	Meetings & schedule ; field test ownership	CEV
Arman Zhumazhanov	Hardware Lead & BOM	Simulation Design	Hardware assembly, soldering, BOM procurement	Safety during soldering and hardware work	CEV
Beibarys Nurlybekuly	Simulation & Verification Lead	Field Test Planning	MATLAB Simulation, V&V planning	V&V plan and	CEV

Table 12-B. Teamwork Evidence Matrix.

SO5 element	Project-specific evidence	Where shown in report / appendix	What changed because of team interaction
Leadership	Merey scheduled and launched weekly meetings; Arman made sure we followed the safety rules. Beibarys was responsible for verification.	Appendix C	The schedule was good for everyone. The physical prototyping was finished without accidents.
Collaborative environment	Regular meetings, joint tasks: for example, field tests.	Appendix C	The speed of completing the tasks was increased.
Goals	Defining goals based on requirements and constraints.	Appendix	Objectives remained constant; the verification approach transitioned to a simulation-first paradigm due to environmental limitations.

SO5 element	Project-specific evidence	Where shown in report / appendix	What changed because of team interaction
Task planning	Gantt chart	Appendix F	The work was
Objectives met	M1 finalized on time; simulation executed; BOM acquired; report delivered.	Appendix C	Digital Twin strategy allowed team to meet simulation objectives even though field testing was obstructed.

Table 12-C. Individual Contribution Log.

Member	Key tasks completed	Deliverables produced	Dates / period	Supervisor verification / evidence
Merey Kudaiberge n	Simulation design (PDR, SNR, seasonal model); report coordination; status dashboard; milestone tracking	ModelMain_LoR a.m (partial); DPR/IER simulation sections; meeting agendas	Weeks 1–14 (Spring 2026)	Reviewed by Prof. Maham; meeting minutes; simulation output files
Arman Zhumazhan ov	Hardware assembly, soldering, BOM procurement and management; M1 smoke test; schematic development	Hardware prototype (ESP32 + E32 nodes); BOM receipts; safety checklist; prototype photos	Weeks 1–5 (hardware);	Reviewed by Prof. Maham; hardware photo evidence; BOM documents
Beibarys Nurlybekul y	MATLAB simulation (Digital Twin primary developer); V&V plan authoring; field test	ModelMain_LoR a.m; V&V tables; 625-node ALOHA	Weeks 2–14	Reviewed by Prof. Maham; simulation files; V&V documentation

Member	Key tasks completed	Deliverables produced	Dates / period	Supervisor verification / evidence
	planning; risk assessment	simulation; outdoor test plan		

Team charter summary: The team held regular meetings (once a week) online and offline with shared task boards. Decision-making was consensus-based. Workload was distributed by technical expertise: Arman owned hardware, Beibarys owned simulation, Merey owned field tests and joint simulation design. Peer feedback was exchanged verbally at weekly meetings and formalized in change log entries.

13. Use of Prior Course Work and New Knowledge Acquired

Table 13-A. Prior Course Work Applied.

Design task	Prior course / topic used	How it was applied	Evidence in design
Code implementation	Circuit Theory Laboratory	Arduino code for packet sending/receiving with 5 seconds delay	DEV-7
Initial hardware prototype	Circuit Theory	Circuit was constructed including the battery, esp32 (2 models), LoRa (2 models, 10dBm and 33dBm), 2 antennas (400-450MHz)	DEV-3
Experimental Simulation for PDR $\geq$ 85% analysis	Signals and Systems Laboratory	Simulation demonstrating trends and analysis of PDR for	VEV-13

Design task	Prior course / topic used	How it was applied	Evidence in design
		different scenarios prior to knowledge from MATLAB	
Implementation of Rician fading, Doppler shift and FSPL	Wireless Communication	Formulas learned in the course were applied as a baseline of some parameters, equations.	VEV-18
Report completion	WCS 210 Technical Writing	Engineering and Technical Tone was followed throughout all the reports, design projects, discussions, explanations	Team3_Maham_FR

Table 13-B. New Knowledge Acquired and Applied.

Knowledge / skill learned	Why it was needed	Source used	How it changed the design or test process
Soldering	To solder circuit parts like batteries to boost converters.	Educational videos, tutorials	Intended circuit design was achieved after soldering necessary parts
Circuit Implementation	Designing a circuit with ESP32, antennas (400-450MHz) and LoRa (10dBm, 33dBm) allowed us to do field tests	Online datasheets, educational videos	Gathered experimental data allowed us to make simulations of PDR trends and compare them with theoretical simulations
Underground signal propagation	To design reliable underground-to-air link	Literature review, sources [1], [3] and [7]	Identified the mismatch between simulated and experimental soil loss values

Knowledge / skill learned	Why it was needed	Source used	How it changed the design or test process
Prototype design	The proper choice of the materials, the proper design	Educational videos	It accelerated the design and testing processes. We know exactly what design would be more efficient.
Presentation skill	To be able to present the idea of our project to people with different backgrounds	Educational videos	The presentation skill is a verbal skill, we tried to prepare the speech before the presentation. It improved the quality of presentation.

14. Conclusions and Recommendations

Degree of requirement satisfaction:

- REQ-1 (RSSI > -137 dBm) and REQ-2 (SNR > -20 dB): Satisfied in MATLAB simulation at realistic hardware parameters (33 dBm Tx, 10 dBi antenna, 1000 km link).
- REQ-2 (SNR < -20 dB):
- REQ-3 (PDR $\geq 85\%$ simulation): End-to-end PDR is satisfied in simulation.
- REQ-4 (PDR $\geq 85\%$ physical test):
- REQ-5 (Doppler compensation): Implemented in MATLAB simulator.
- REQ-6 (Battery > 5 years): Was not satisfied.
- REQ-7 (Simulation should match experimental data): Was not satisfied.

Most important engineering trade-off:

The most important engineering trade-off is scalability. The proposed architecture could potentially cover the remote areas where there is no terrestrial infrastructure.

Main limitation: purchased LoRa modules do not support RSSI, SNR.

Recommended next steps:

- Purchase other LoRa modules that support RSSI, SNR.
- To choose electronic components wiser, so the energy efficiency of the prototype would improve.
- To find UAV in order to conduct the proper field test.
- Simulation: To try observing how FHSS improves the signal propagation.

15. References

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Appendix A. Engineering Standards Evidence

Table A.1. Engineering Standards Evidence.

Standard ID and title	Clause(s) used	Why applicable?	Design decision affected	How verified	Status
RF-01	LoRaWAN Regional Parameters (RP2-1.1)	Frequency Plan: 433 MHz	Mandatory compliance for operating in the designated ISM band for Kazakhstan.	Carrier frequency is set to 433 MHz for the system.	Met
RF-02 ETSI EN 300 220 / FCC Part 15 Kazakhstan: need certification	ETSI EN 300 220 / FCC Part 15	Certification required for Kazakhstan	Ensures that the system complies with duty cycle and spectral efficiency regulations.	Traffic model design: The packet generation rate is adjusted to comply with regulations.	Met
AV-01 Civil Aviation Authority	Civil Aviation Authority	Max Flight Altitude: 120 m	Ensures that the system complies with duty cycle and spectral efficiency regulations.	The UAV height parameter is integrated into the system design.	Met

Appendix B. Multiple-Constraints Matrix

Table B.1. Multiple-Constraints Matrix.

Constraint	Metric / target	Rationale	Trade-offs considered	Outcome/ status	Evidence
Technical (Simulation)	Model Fidelity (Realistic PSR)	Initial simulations showed 100% PSR, which is unrealistic for underground environments.	Prioritizing complex fading models (Rayleigh/Shadowing) over simple path loss to avoid over-optimistic results.	Transitioned to a "Digital Twin" (MATLAB) to simulate VWC and SNR accurately.	
Financial (Resource)	0 KZT UAV Budget	University budget does not cover the cost of a UAV platform.	Choosing between personal procurement or simulating the UAV link while testing lateral ground distance.	Proceeding with high-altitude static tests and MATLAB modeling for the UAV-to-LEO link.	
Environmental	Soil State (T < 0°C)	Frozen ground (-15°C) prevents standard burial and alters soil permittivity	Delaying field tests until Spring vs. conducting a "Winter Performance" study on frozen ground.	Conducted indoor moisture tests; outdoor testing moved to Week 8 to attempt frozen soil analysis.	
Regulatory (RF)	Max Transmit	2W (33dBm)	Balancing deep soil penetration	The system supports 2W but	

	Power (ISM)	hardware likely exceeds standard ISM limits for Kazakhstan.	(high power) with legal duty-cycle/power limits.	software limits or <1% duty cycles must be verified for compliance.	
Safety (Electrical)	$I_{peak} \leq 1.5A$	High-power LoRa modules draw significant current, risking battery failure.	High range capability vs. battery discharge rates and thermal management.	Soldering complete; custom power subsystem (Li-Po + 5V Boost) implemented to sustain current.	

Appendix C. Team Organization and Contributions

Team Roles. The roles of students were divided as following:

Arman Zhumazhanov — hardware & BOM

Beibarys Nurlybekuly — simulation design, verification

Merey Kudaibergern — simulation design, field test

Responsibility matrix. P - Primary role, S - Secondary role.

Project Task	Arman Zhumazhanov	Beibarys Nurlybekuly	Merey Kudaibergern
Component Research, Selection & BOM	P	S	S
Power Circuit Design (MT3608 + LM2596)	P	-	S
Hardware Assembly & Waterproofing	P	S	-
MATLAB Soil Attenuation Simulation	S	P	S
Simulation Verification & Math Checking	-	P	S

ESP32 & LoRa C++ Programming	P	S	S
80cm Subsurface Field Test Execution	-	S	P
Data Logging & Result Comparison	-	S	P
Report Writing & Formatting	P	P	P
Final Poster & Defense Preparation	P	P	P

Contribution Summary

Equal contribution from all team members was strictly maintained throughout the project development. Since completing the high quality project was necessary to graduate, all members were highly motivated to do their best during these 2 semesters.

To make sure that everyone would have an opportunity to exhibit leadership skills the roles were different at each stage of the project. During different stages of the project, one specific student took the leading role. This student was responsible for coordinating timelines, delegating specific sub-tasks, and ensuring milestones were met. This approach allowed us to equally participate in completing the project.

Team charter summary

The Team Charter was established to set clear expectations for communication, accountability, and conflict resolution.

- **Project Goal:** To successfully design, simulate, and validate multi layer architecture based on LoRa technology.
- **Communication & Meetings:** The team agreed to maintain continuous communication via messengers and regularly held the meetings. Meetings were held weekly or biweekly, the frequency of meeting depended on the tasks to be done.
- **Decision Making & Conflict Resolution:** Technical disagreements were resolved through engineering judgement. We referred to datasheets, research papers to support our opinion. If a consensus could not be reached, decisions were made by voting or further investigation.
- **Accountability:** Deadlines were strictly followed. If one of the team members fell behind, others would assist him. The solutions to some problems were found only when several people tried to solve them.

Contribution evidence - CEV

Arman Zhumazhanov (Hardware & BOM)

- **Evidence of Work:** Researched, ordered all necessary components. Researched alternative components. Configured LoRa hardware by using special software (RF Setting). Managed the Bill of Materials (BOM).
- **Specific Tasks:** Soldering and isolating the wires. Configuring LoRa modules. Ordering components. Preparing BOM, appendices. Plotted the antenna's radiation patterns in MATLAB.

Beibarys Nurlybekuly (Simulation Design & Verification)

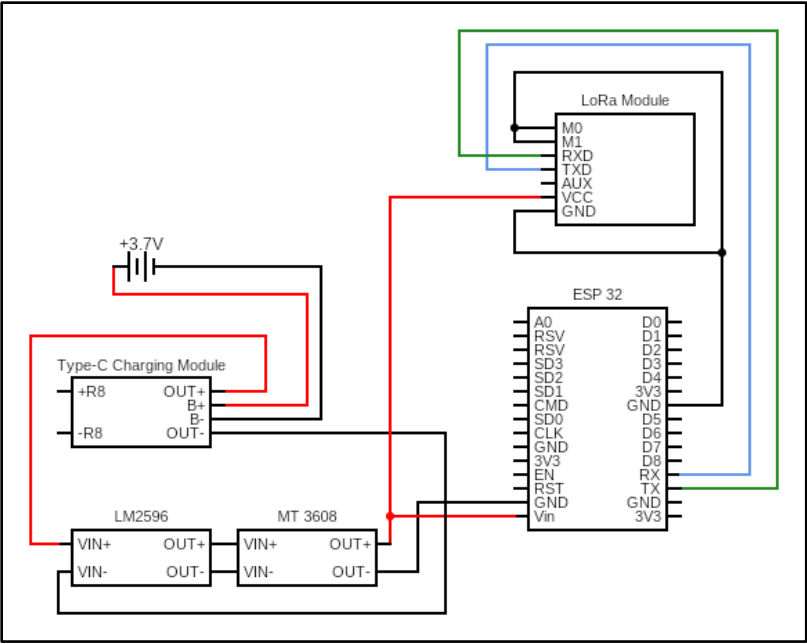
- **Evidence of Work:** Developed the main scripts to predict RSSI, PDR in different interfaces.
- **Specific Tasks:** Plot PDR, SNR, RSSI graphs for ground-UAV interface, ground - LEO satellite. Verification of requirements by comparing simulation results with the conducted experimental results.

Merey Kudaibergen (Simulation Design & Field Test)

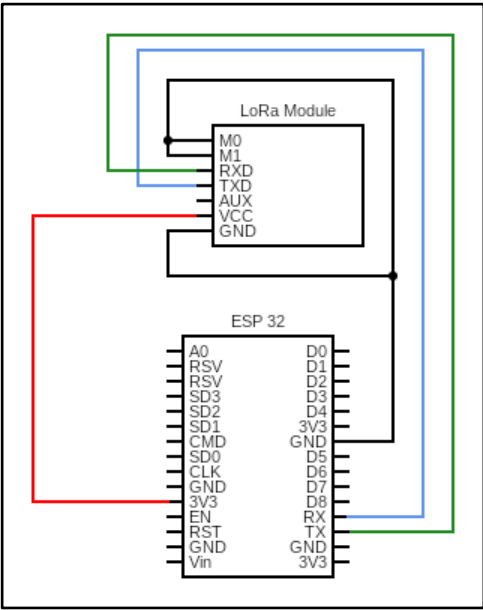
- **Evidence of Work:** Developed the experimental models to analyze the trends of PDR across different depths, packet bursts and time delays

- Specific Tasks: Organized the field test: prepared 20 cm, 40 cm burial depth. Recorder the PDR at different configurations, distances. Analyzed the experimental results and produced graphs. For example, VEV-13 to VEV-16.

Appendix D. Design Evidence



DEV-1. The circuit diagram of the transmitter.



DEV-2. The circuit diagram of the receiver (ESP32 is connected to the computer via USB Type-C).



DEV-3. One of the first iterations of prototype design.

The initial functionality test was successfully completed using the setup shown in the photo. This build had the wires already soldered and the keypad connected to one of the transceivers. This configuration was specifically used to verify the successful transmission of packets that are sent when the button is pressed.



DEV-4. Placing PVC pipe under the ground.

The pipe was buried at different depths during the field test: 20 cm, 40 cm.



DEV-5. Buried setup inside of the isolation tube.



DEV-6. Placing the transmitter inside the tube.

```
#include <HardwareSerial.h>

// define pins for LoRa receive, transmit
#define RX_PIN 16
#define TX_PIN 17

HardwareSerial LoRaSerial(2);
// Timer variables
```

```

unsigned long lastSendTime = 0;
const unsigned long interval = 5000; // 5 seconds

// Counter variable
uint8_t payload = 0;

void setup() {
  Serial.begin(115200);
  // Ensure your E32 module is set to 9600 baud (default)
  LoRaSerial.begin(9600, SERIAL_8N1, RX_PIN, TX_PIN);

  Serial.println("System Ready. Transmitting sequential bytes (0-255)...");
  Serial.println("-----");
}

void loop() {
  // Check if 5 seconds have passed
  if (millis() - lastSendTime >= interval) {
    lastSendTime = millis(); // Reset the timer

    // Send Data (Current value of payload)
    LoRaSerial.write(payload);

    // Debug Output to Serial Monitor
    Serial.print("Transmitted Byte: ");
    Serial.println(payload);

    // Increment the counter
    payload++;
  }
}

```

DEV-7. Transmitter code that is uploaded to ESP-32 microcontroller.

```

for index = 1:NumDistances
    % 1. Convert elevation angle to radians
    Elev_rad = deg2rad(Elevation_Angles(index));

    % 2. Calculate radial velocity (max when sat is on horizon, zero when directly overhead)
    Radial_Velocity = v_sat * cos(Elev_rad);

    % 3. Calculate absolute Doppler Shift (in Hz)
    Doppler_Shift_Hz = abs((Radial_Velocity / c) * Frequency);

    % 4. Doppler Penalty (Implementation Loss)
    % For LoRa/FSK, a shift of 10 kHz often results in roughly 1.5 to 2 dB of degradation.
    % We use a simple linear scaling penalty: ~1.5 dB loss per 10 kHz shift.
    Doppler_Penalty_dB = (Doppler_Shift_Hz / 10000) * 1.5;

    parfor mCarlo = 1:MonteCarlo
        % 1. Baseline Free Space Path Loss (FSPL) in dB
        Base_FSPL = -147.55 + 20*log10(Frequency) + 20*log10(Distance(index));

        % DOPPLER PENALTY
        Base_FSPL_with_Doppler = Base_FSPL + Doppler_Penalty_dB;

        % 2. Rician Fading for Air-to-Air
        X = normrnd(mu, sigma);
        Y = normrnd(mu, sigma);
        Rician_Amplitude = sqrt(X^2 + Y^2);
        Rician_Power_Gain = Rician_Amplitude^2;

        % 3. Total Path Loss
        Rician_Gain_dB = 10*log10(Rician_Power_Gain);
        A2A_FSPL(index, mCarlo) = Base_FSPL_with_Doppler - Rician_Gain_dB;

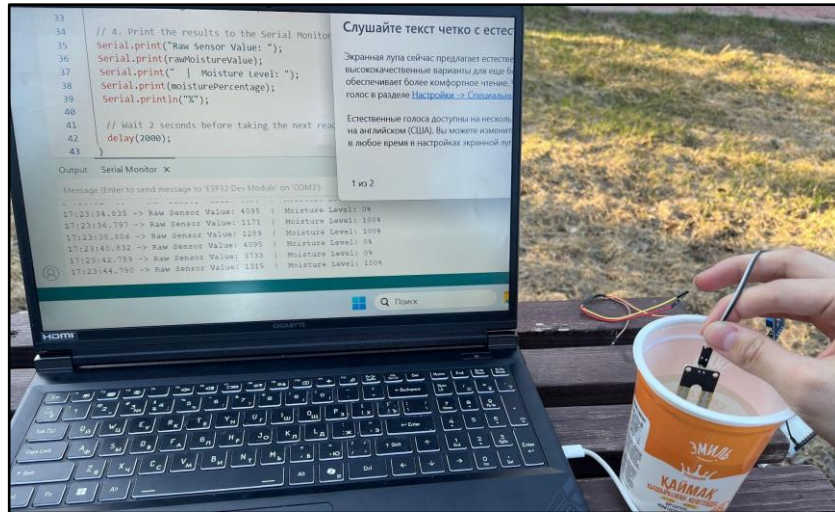
        % 4. Received Signal / Link Loss Calculation (Linear Scale)
        % Using the new Doppler-penalized FSPL for the linear calculation
        A2A_Loss_s(index, mCarlo) = (Ptx * Gr_s * Gt * Rician_Power_Gain) /
        (10^(Base_FSPL_with_Doppler/10)) / Total_loss_tmp_W;
    end

    % Calculate the mean path loss in dB for this specific distance
    A2A_LadB_s(index) = mean(A2A_FSPL(index, :));
end

```

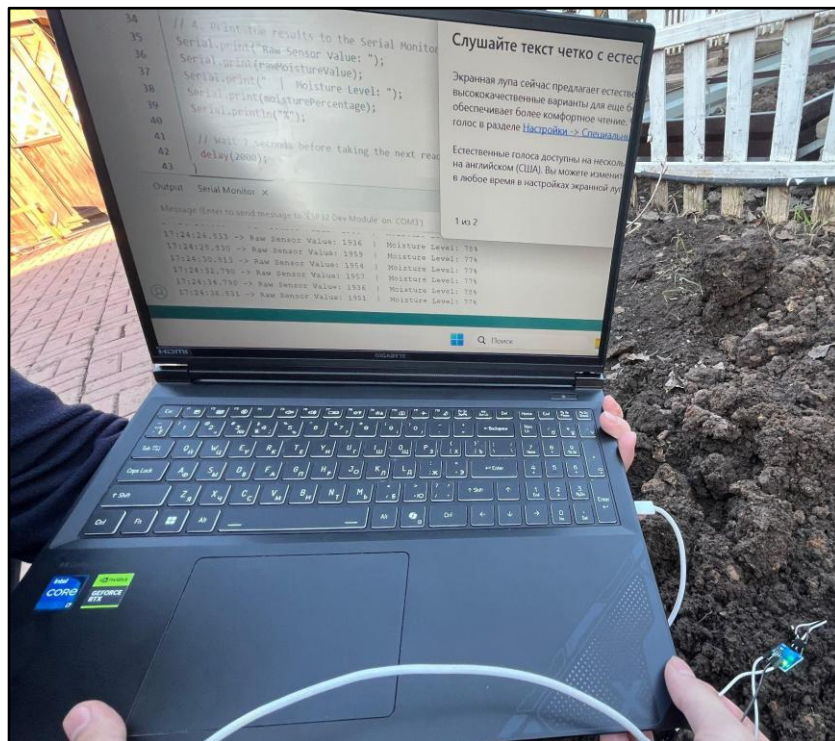
DEV 8. Integration of Doppler Shift by calculating Doppler Penalty.

Appendix E. Verification Evidence



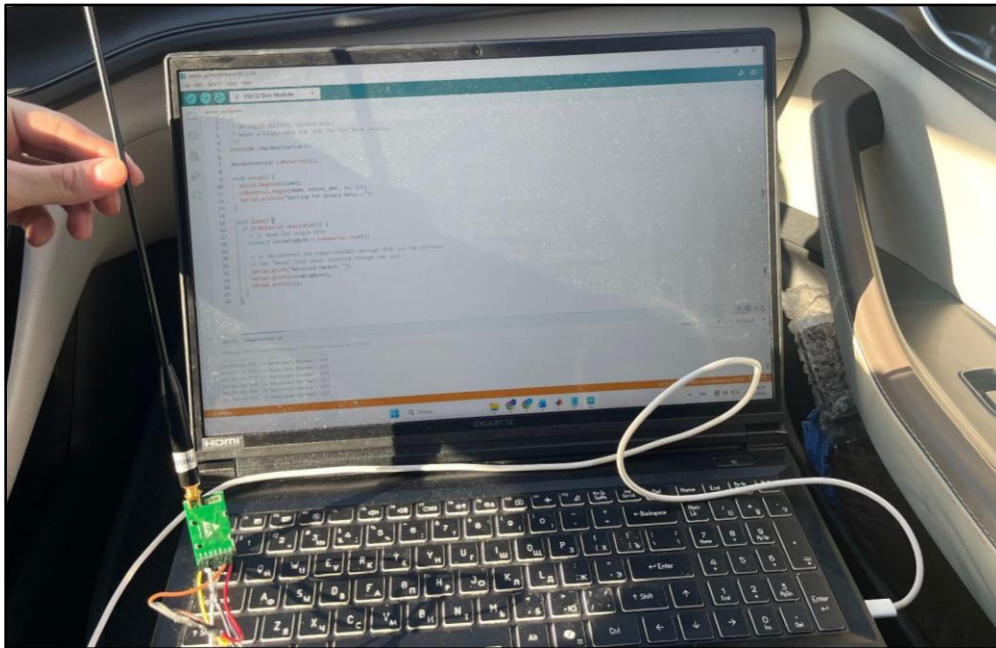
VEV-1. Moisture sensor verification.

When the moisture sensor is put under the water, it shows 100% moisture level.



VEV-2. Soil moisture level verification.

The soil moisture sensor was placed in the ground. It measured the moisture level of soil at around 77% .



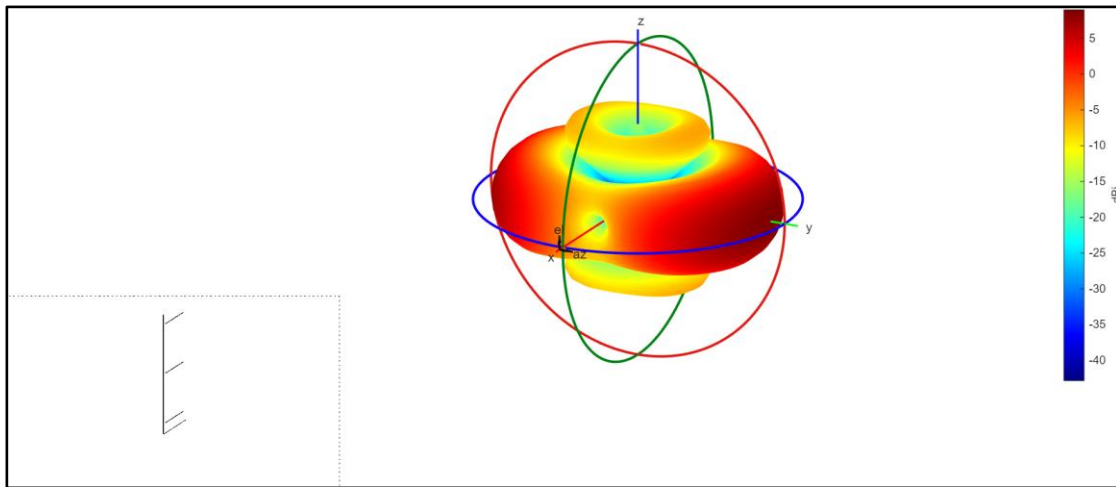
VEV-3. Verification, packets are received by the receiver.

This photo includes the arduino serial output where the successfully received packets are displayed.



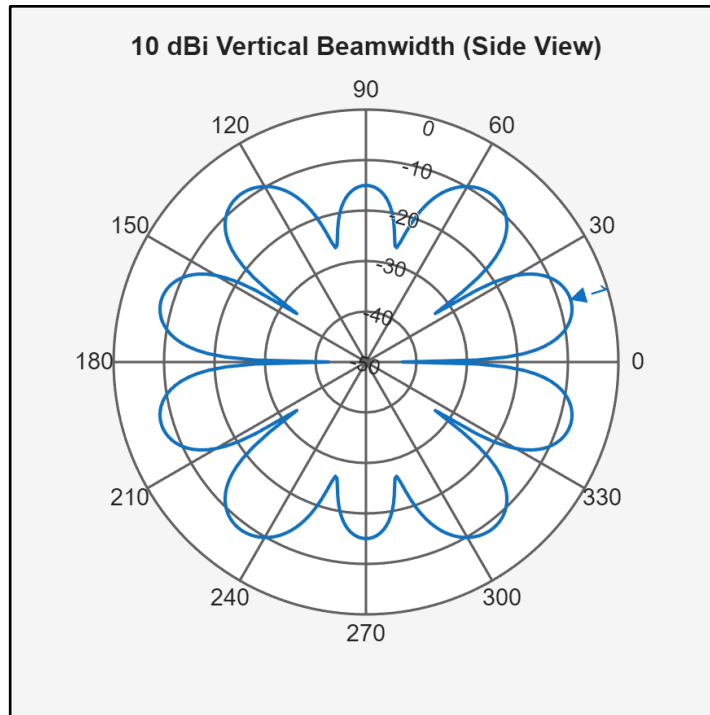
VEV-4. Configuring the LoRa module. Transmit power and air data rate can be changed.

The software for configuration of the LoRa module was installed from the official website of producer - Ebyte. In this application, we were able to configure air data rate, transmit power. The minimum transmit power we could choose was 10 dBm. Higher air data rate would mean lower spreading factor. For example, to get the maximum signal propagation we should choose the lowest data rate possible with the highest transmit power.

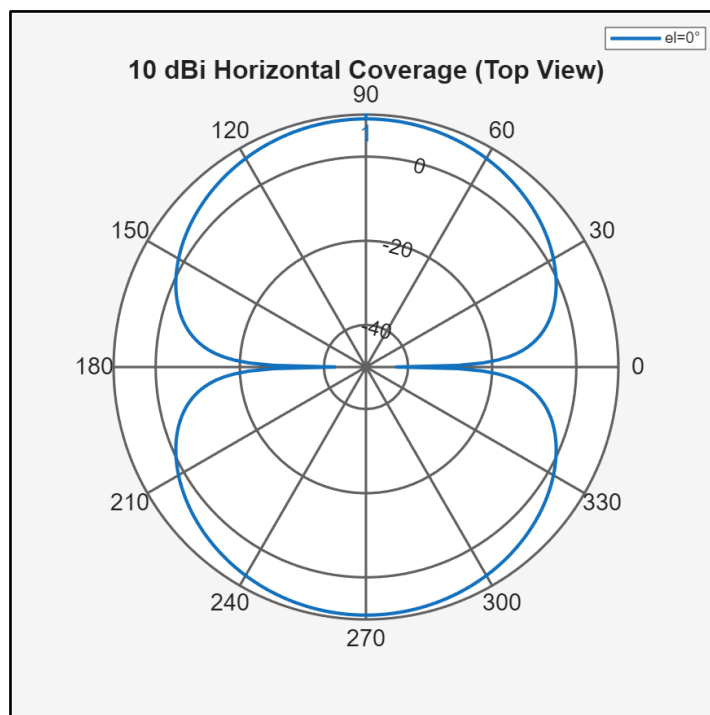


VEV-5. 10 dBi antenna radiation pattern (Produced in MATLAB using the antenna Add-On).

By using available parameters from datasheets we plotted the antenna's radiation pattern in Matlab. The “antenna” add-on includes pre-built functions that make plotting easier. The image above is a 3D representation of a 433 MHz antenna. The real antenna gain is much lower than 10 dBi. The area of the LoRa module was also taken into account, there is a small surface area from which waves can reflect.

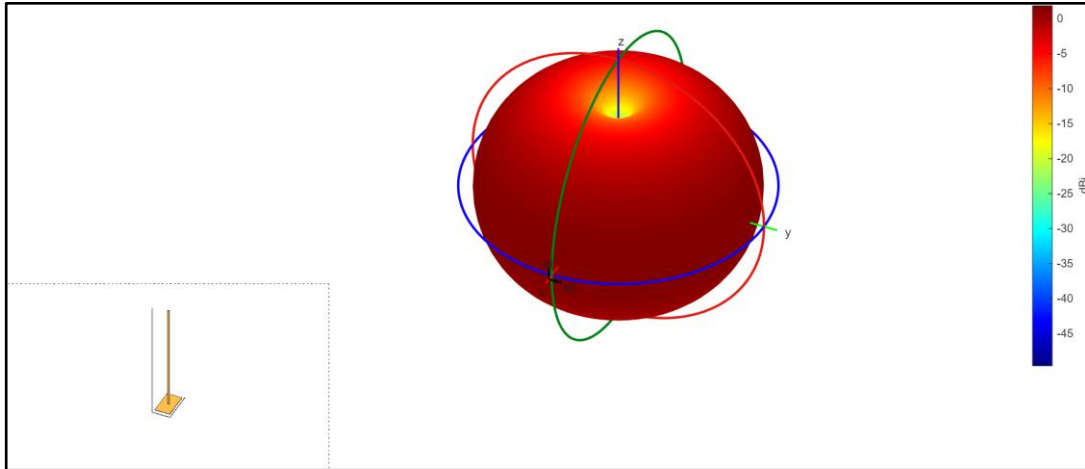


VEV-6. 10 dBi antenna Vertical Beamwidth (Side View).



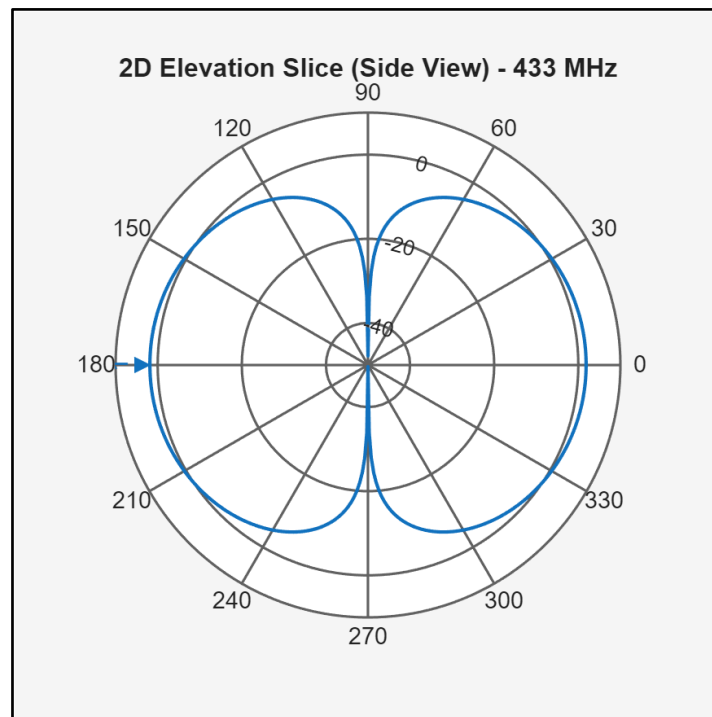
VEV-7. 10 dBi antenna Horizontal Coverage (Top View).

The 2 images above are 2D representations of radiation patterns.

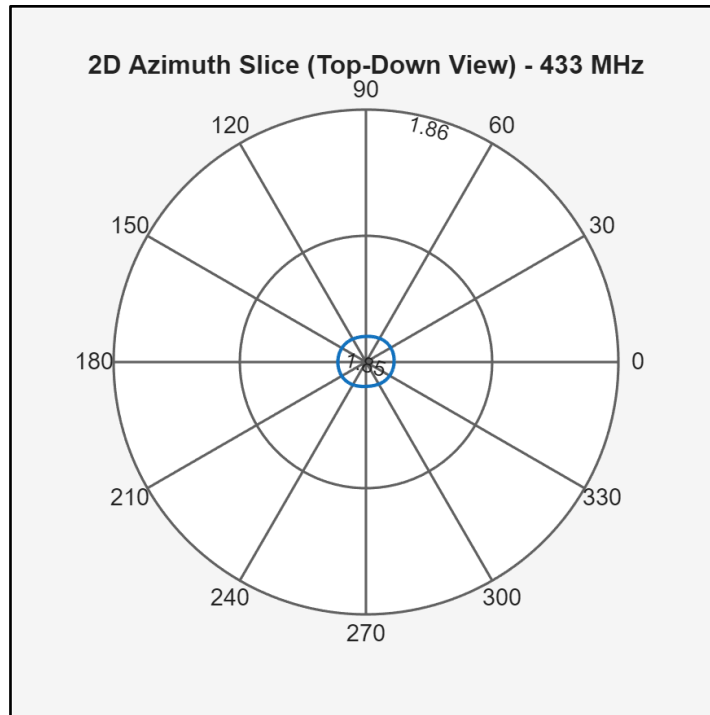


VEV-8. 4 dBi antenna radiation pattern (Produced in MATLAB using the antenna Add-On).

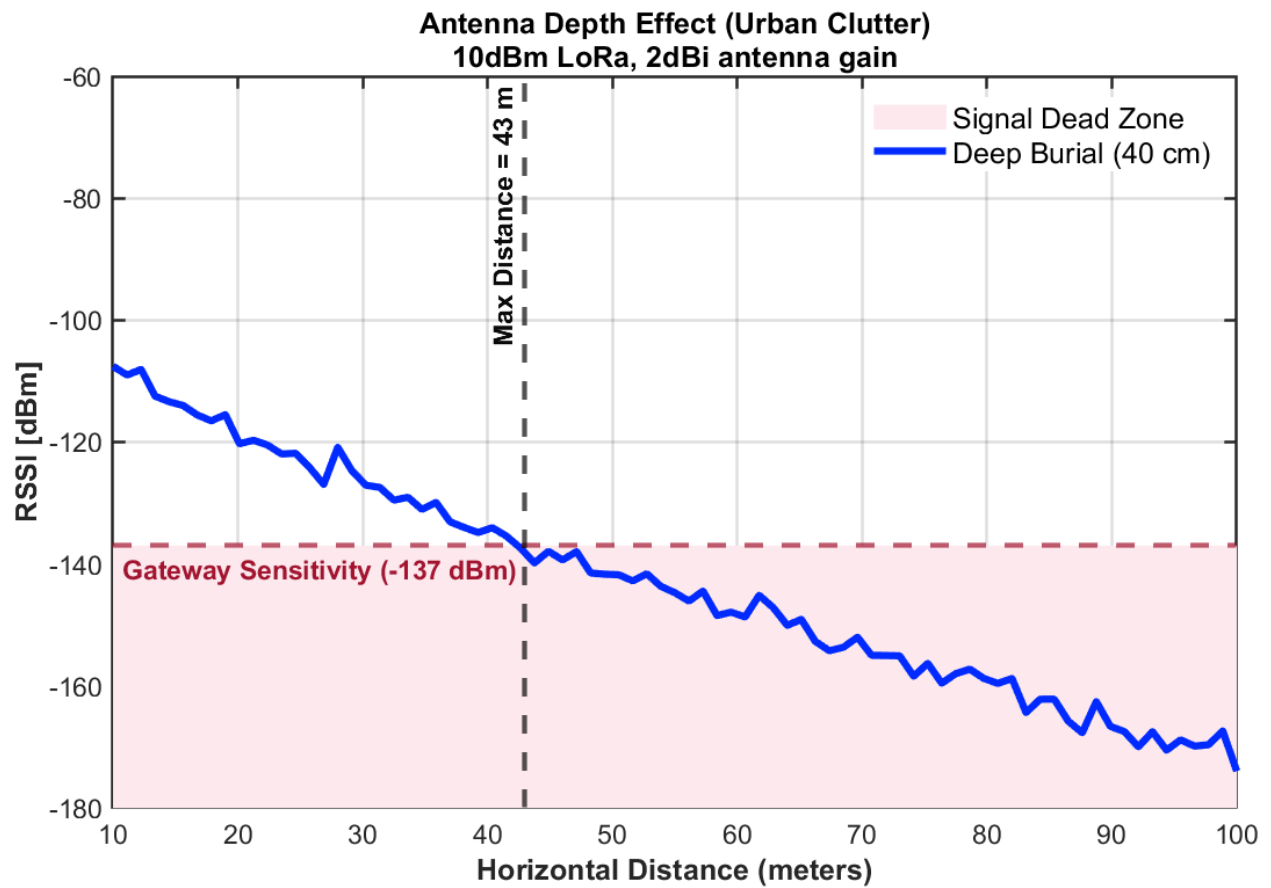
The same principles were applied to the 4 dBi antenna. It's radiation pattern looks more spherical.



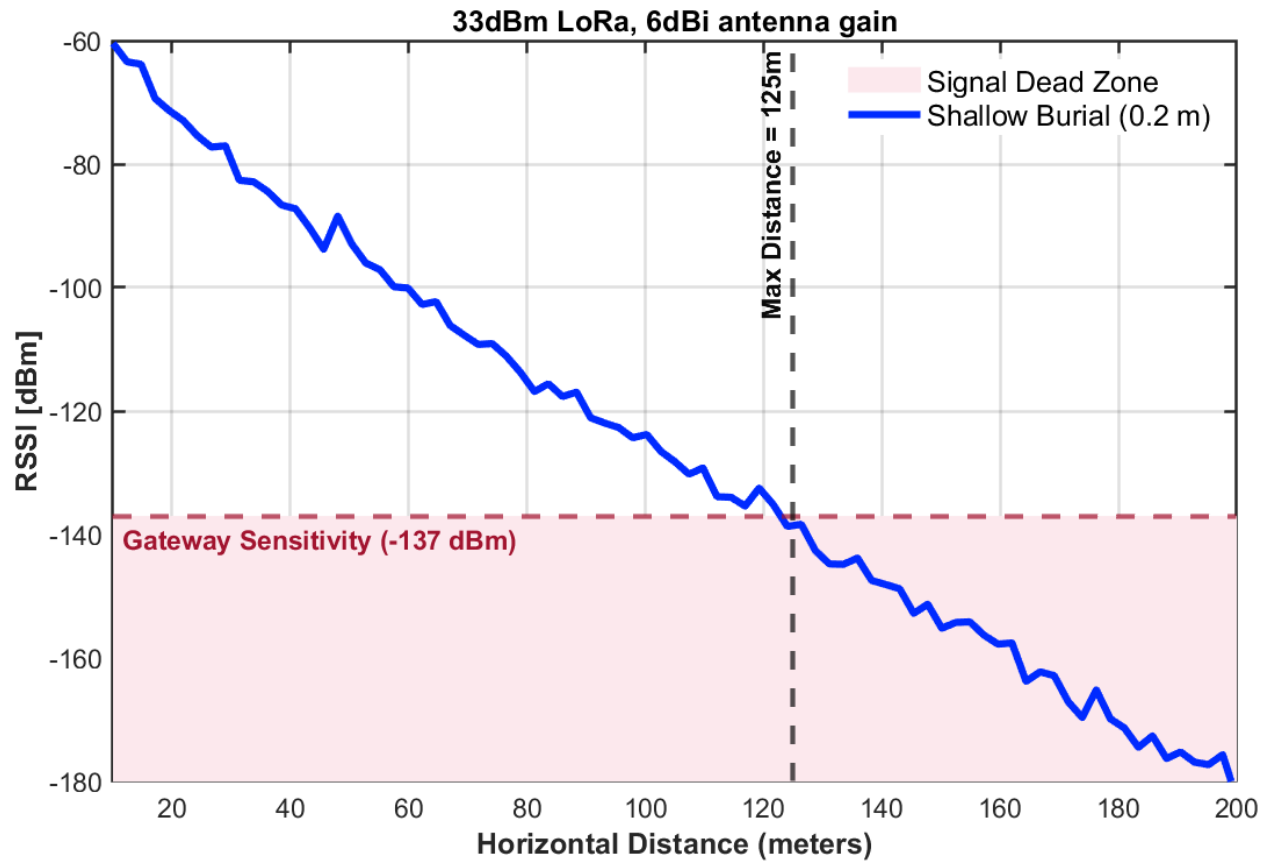
VEV-9. 4 dBi antenna 2D Elevation Slice (Side View).



VEV-10. 4 dBi antenna 2D Azimuth Slice (Top-Down View).



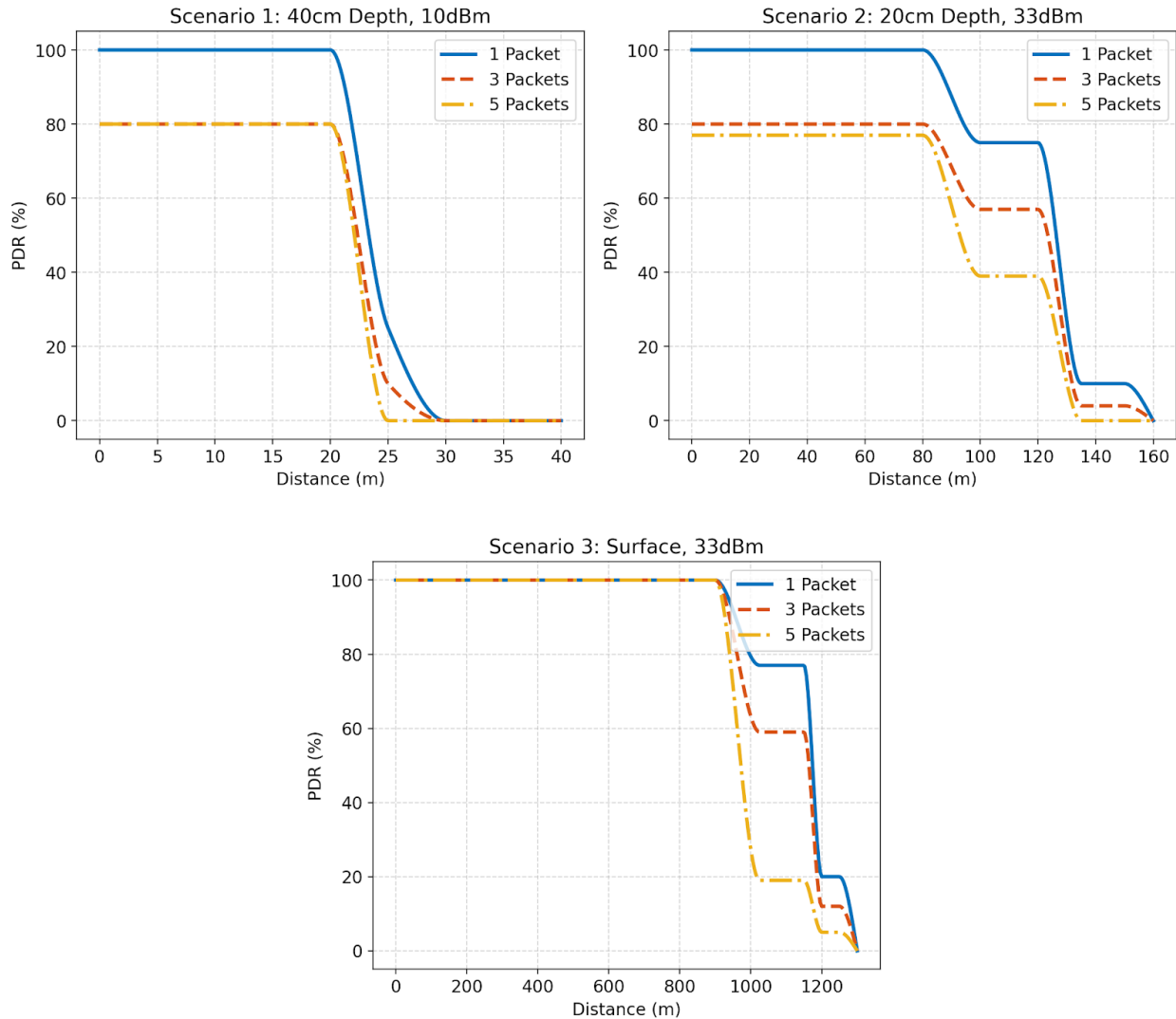
VEV-11. RSSI vs Distance graph at burial depth of 40 cm. Transmit power is 10 dBm, 4 dBi antenna is used, VWC is 0.4.



VEV-12. RSSI vs Distance graph at burial depth of 20 cm and VWC of 0.4.

The graphs VEV-11 and VEV-12 were produced by Matlab simulation. We calibrated it by using parameters from the practical part in order to compare the results. The simulator could closely predict the RSSI with distance when the parameters are changed.

Graph 1: PDR Baseline Performance Across Environments (5s Delay)



VEV-13. Packet Delivery Ratio (PDR) for each scenarios

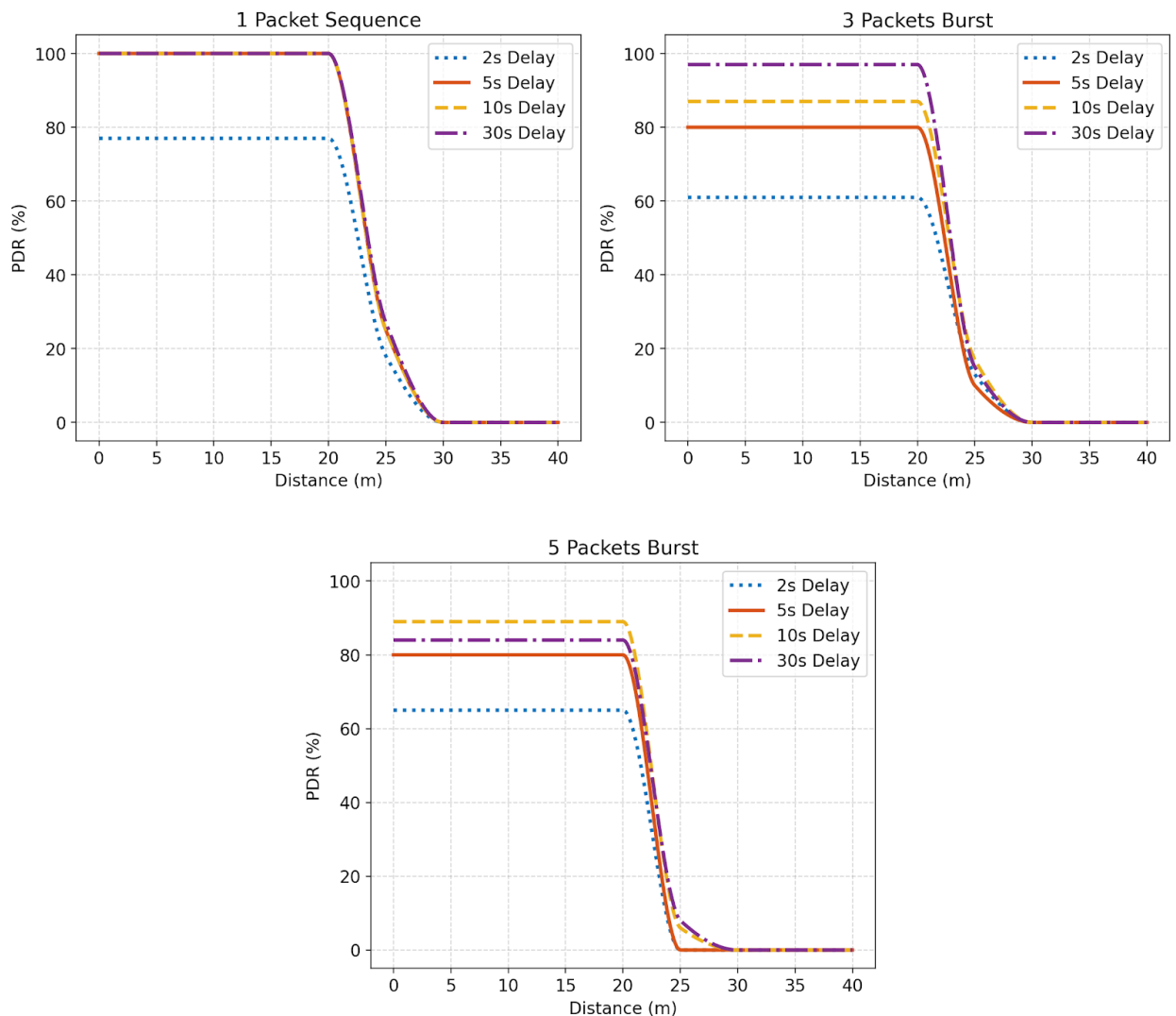
Description: Figures demonstrate how different number of packets being received every 5 seconds for each scenario

- **Scenario 1 (40cm Depth, 10dBm):** 1 packet every 5 seconds → PDR = 100% for 0–20 meters. PDR ≈ 25% for 20–30 meters. PDR = 0% for more than 30 meters. 3 or 5 packets every 5 seconds → PDR = 80% for 0–20 meters. PDR ≈ 10% for 20–30 meters. PDR = 0% for more than 30 meters.
- **Scenario 2 (20cm Depth, 33dBm):** 1 packet every 5 seconds → PDR = 100% for 0–80 meters. PDR ≈ 77% for 80–120 meters. PDR ≈ 10% for 120–150 meters. PDR ≈ 0% for more than 150 meters. 3 or 5 packets every 5 seconds → PDR ≈ 80% for 0–80 meters.

For 80-120 meters, 3pkt/5sec $\rightarrow$ PDR $\approx$ 60% and 5pkt/5sec $\rightarrow$ PDR $\approx$ 40%. For 120-150 meters, the PDR $\approx$ 4% of both 3pkt/5sec and 5pkt/5sec. After 150 meters, PDR = 0%

- **Scenario 3 (Surface, 33dBm):** For a range of 0-900 meters, PDR = 100% for 1pkt/5sec, 3pkt/5sec, and 5pkt/5sec. For a range of 900-1150 meters, PDR $\approx$ 77% while 1pkt/5sec, PDR $\approx$ 59% while 3pkt/5sec, and PDR $\approx$ 19% while 5pkt/5sec. For a range of 1150-1250, PDR $\approx$ 20% while 1pkt/5sec, PDR $\approx$ 12% while 3pkt/5sec, and PDR $\approx$ 5% while 5pkt/5sec. After 1250 meters, PDR = 0%

Graph 2: Interval Influence - Scenario 1 (40cm Depth, 10dBm)

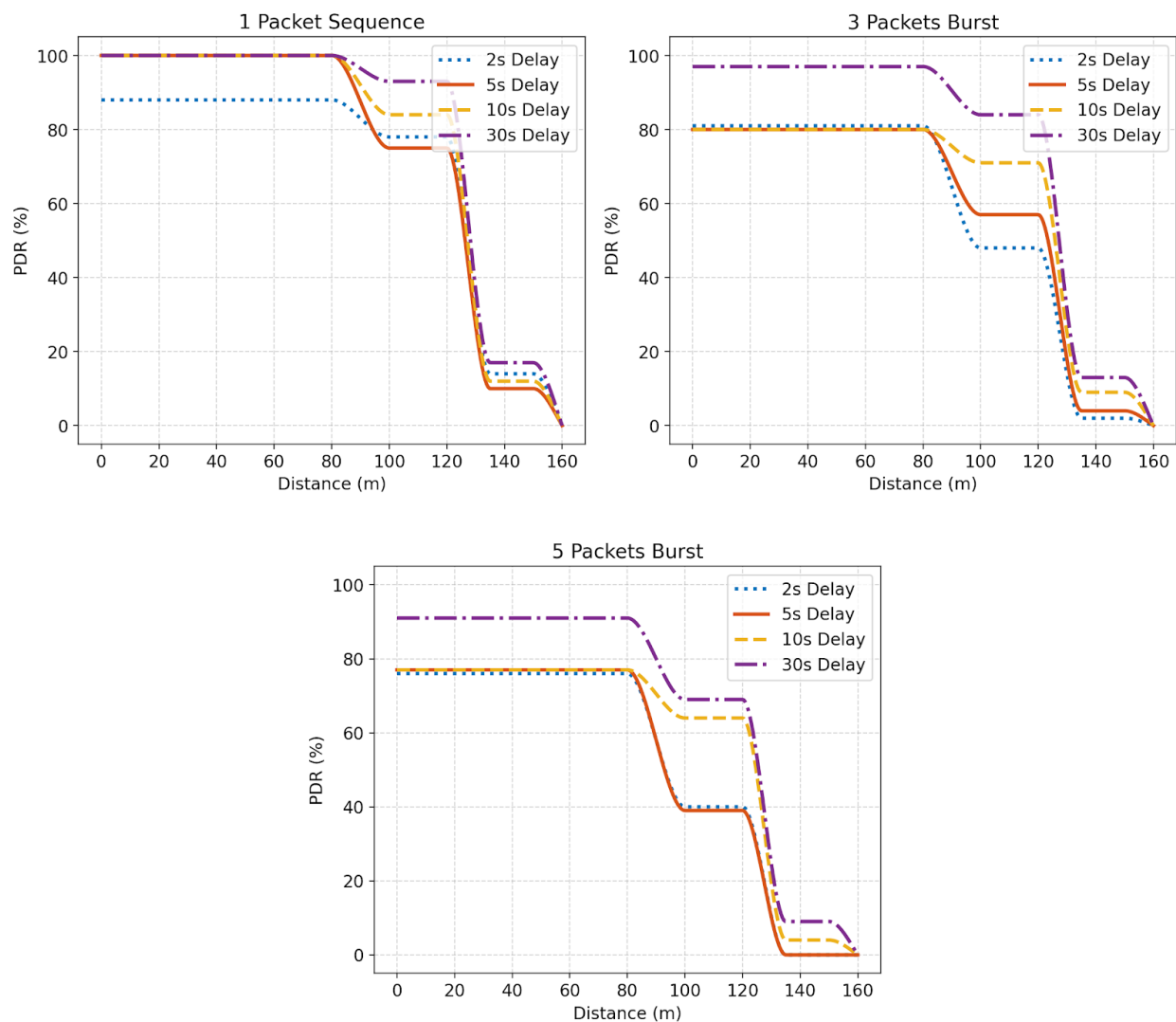


VEV-14. Delay Comparison for Scenario 1

Description: Figures show how certain number of packets were sent with different delays for Scenario 1 (40 cm Depth, LoRa = 10dBm)

- **Sending a single packet:** The PDR trend is quite similar for delays of 5, 10, and 30 seconds, while the PDR curve with delays of 2 seconds noticeably differs, showing <80% for 0-20 meters.
- **Sending 3 packets burst:** The PDRs for certain ranges are greater than others as delay timers more than others.
- **Sending 5 packets burst:** Surprisingly, the PDR with delays of 10 seconds is greater than PDR with delays of 30 sec.

Graph 3: Interval Influence - Scenario 2 (20cm Depth, 33dBm)

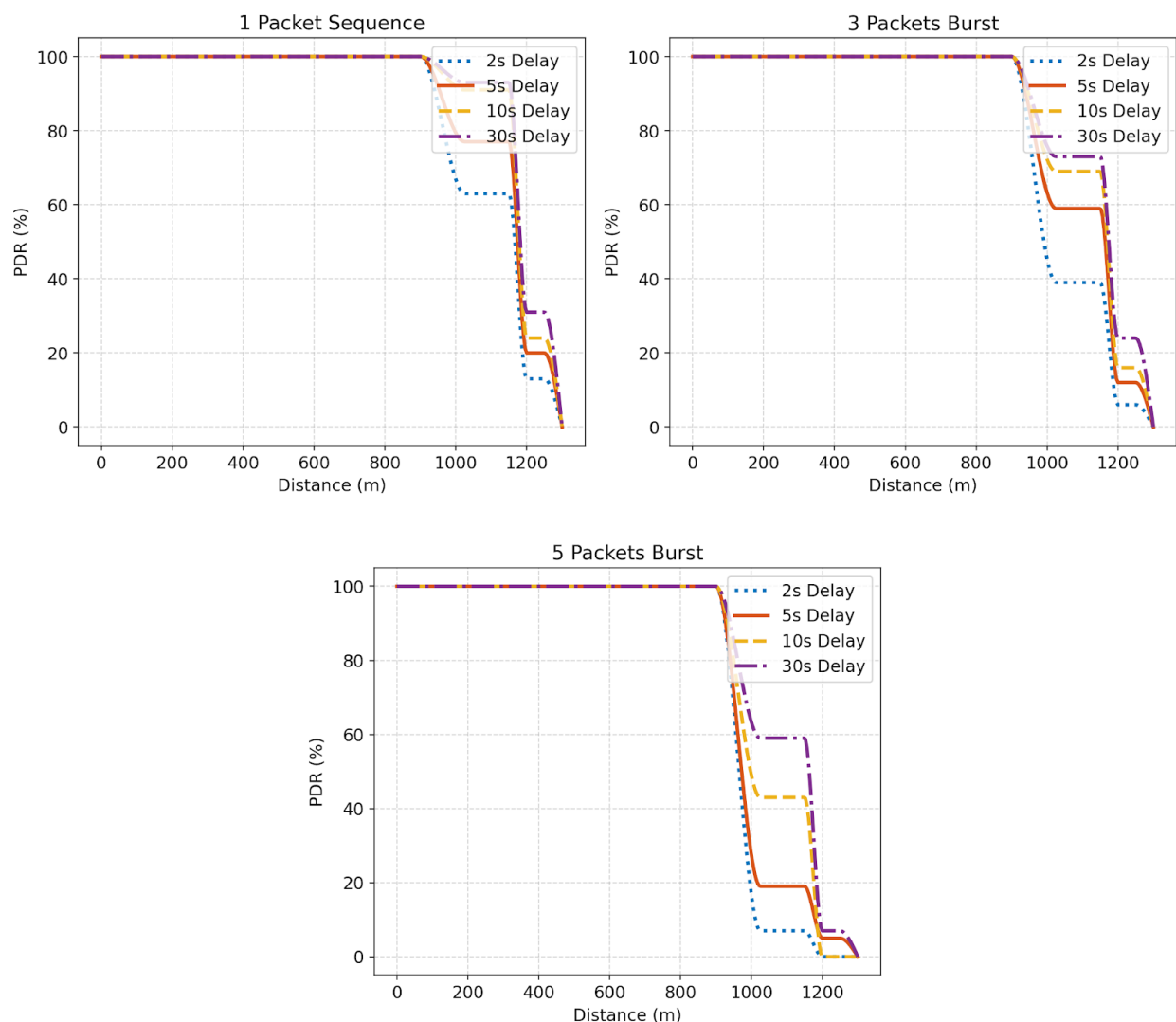


VEV-15. Delay Comparison for Scenario 2

Description: Figures illustrate how certain number of packets were sent with different delays for Scenario 2 (20 cm Depth, LoRa = 33dBm)

- **Sending a single packet:** For a range of 0-80 meters, the PDRs = 100% with delays of 5, 10, 30 seconds, while PDR ≈ 88 with delays of 2 seconds. On the range of 80-120, PDR with delays of 2 seconds is slightly greater than PDR with delays of 5 seconds.
- **Sending 3 packets burst:** The PDRs for certain ranges are greater than others as delay timers more than others.
- **Sending 5 packets burst:** For a range of 0-80, the PDRs with delays of 2, 5, and 10 seconds are quite similar, while PDR with delays of 30 seconds differs. But for the range of 80-120 meters, the PDRs with delays of 10 and 30 seconds, while those with delays of 2 and 5 seconds are also similar.

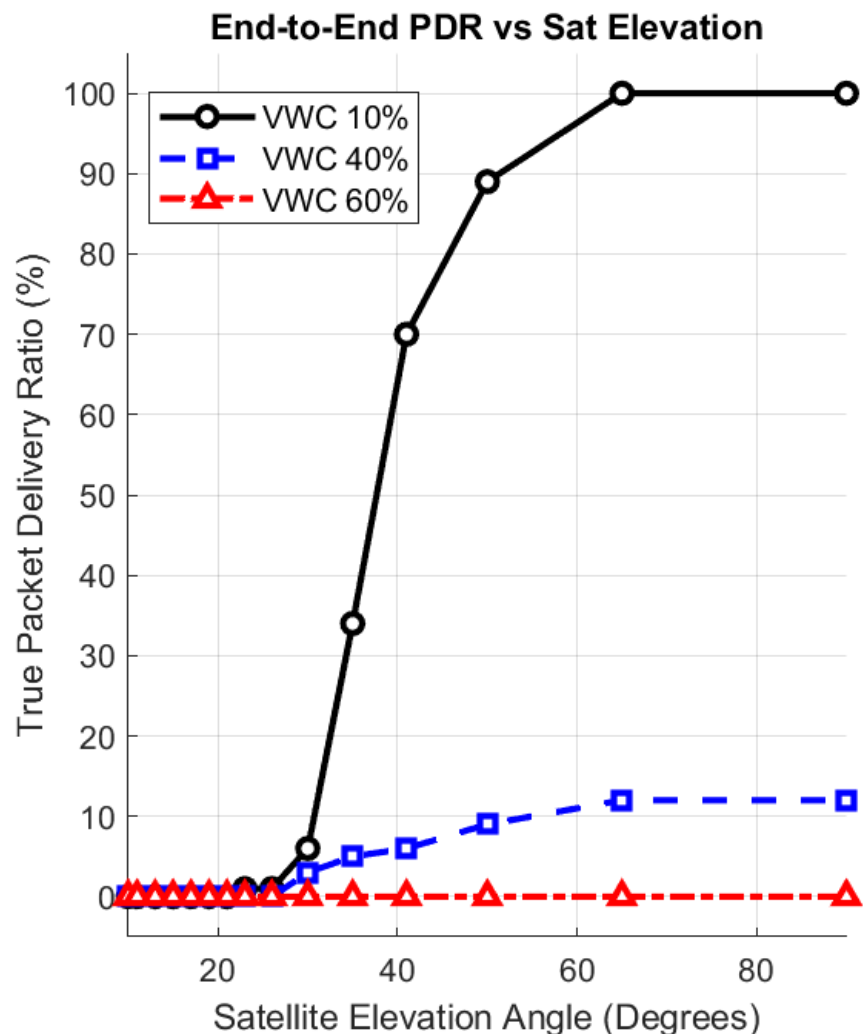
Graph 4: Interval Influence - Scenario 3 (Surface, 33dBm)



VEV-16. Delay Comparison for Scenario 3

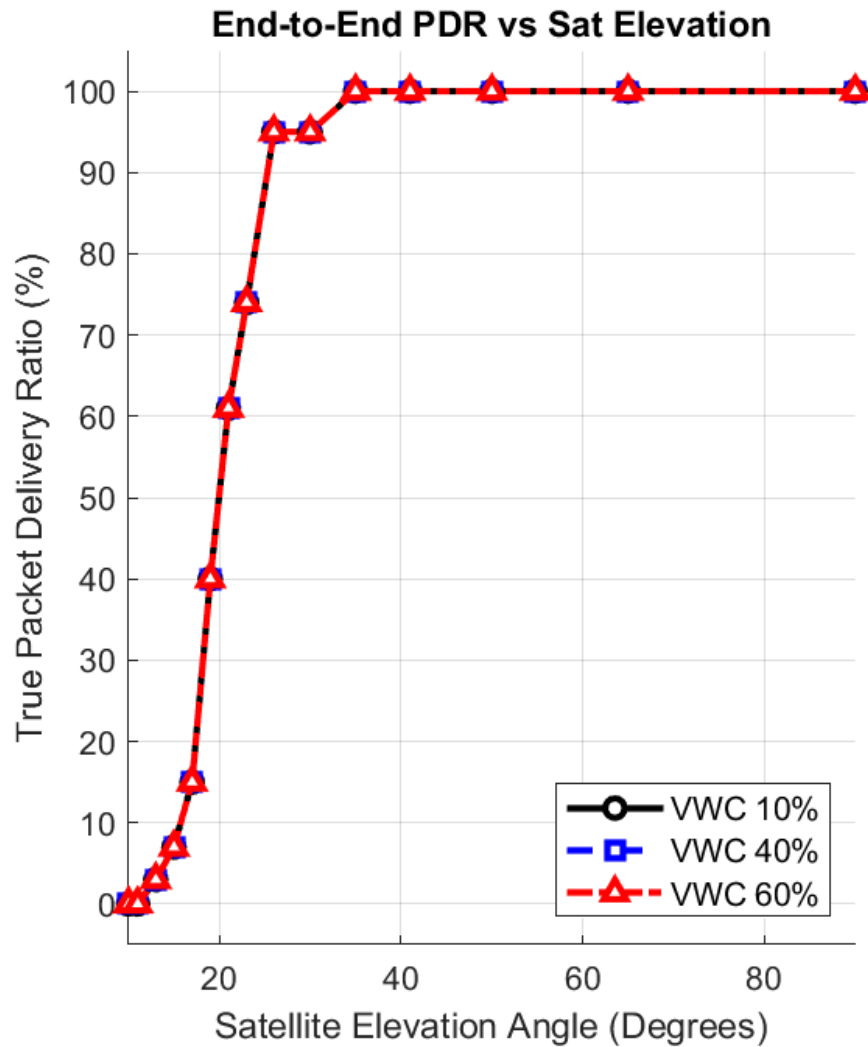
Description: Figures illustrate how certain number of packets were sent with different delays for Scenario 3 (Surface, LoRa = 33dBm)

- **Sending a single packet:** For a range of 0-900 meters, each PDR = 100%. Range 900-1150, PDR with delays of 30 seconds and 10 seconds are similar (88%). The PDRs for rest ranges are greater than others as delay timers more than others.
- **Sending 3 packets burst:** For a range of 0-900 meters, each PDR = 100%. Range 900-1150, PDR with delays of 30 seconds and 10 seconds are similar (73%). The PDRs for rest ranges are greater than others as delay timers more than others.
- **Sending 5 packets burst:** For a range of 0-900 meters, each PDR = 100%. Range 900-1150, the PDR trends. The PDRs for rest ranges are greater than others as delay timers more than others.



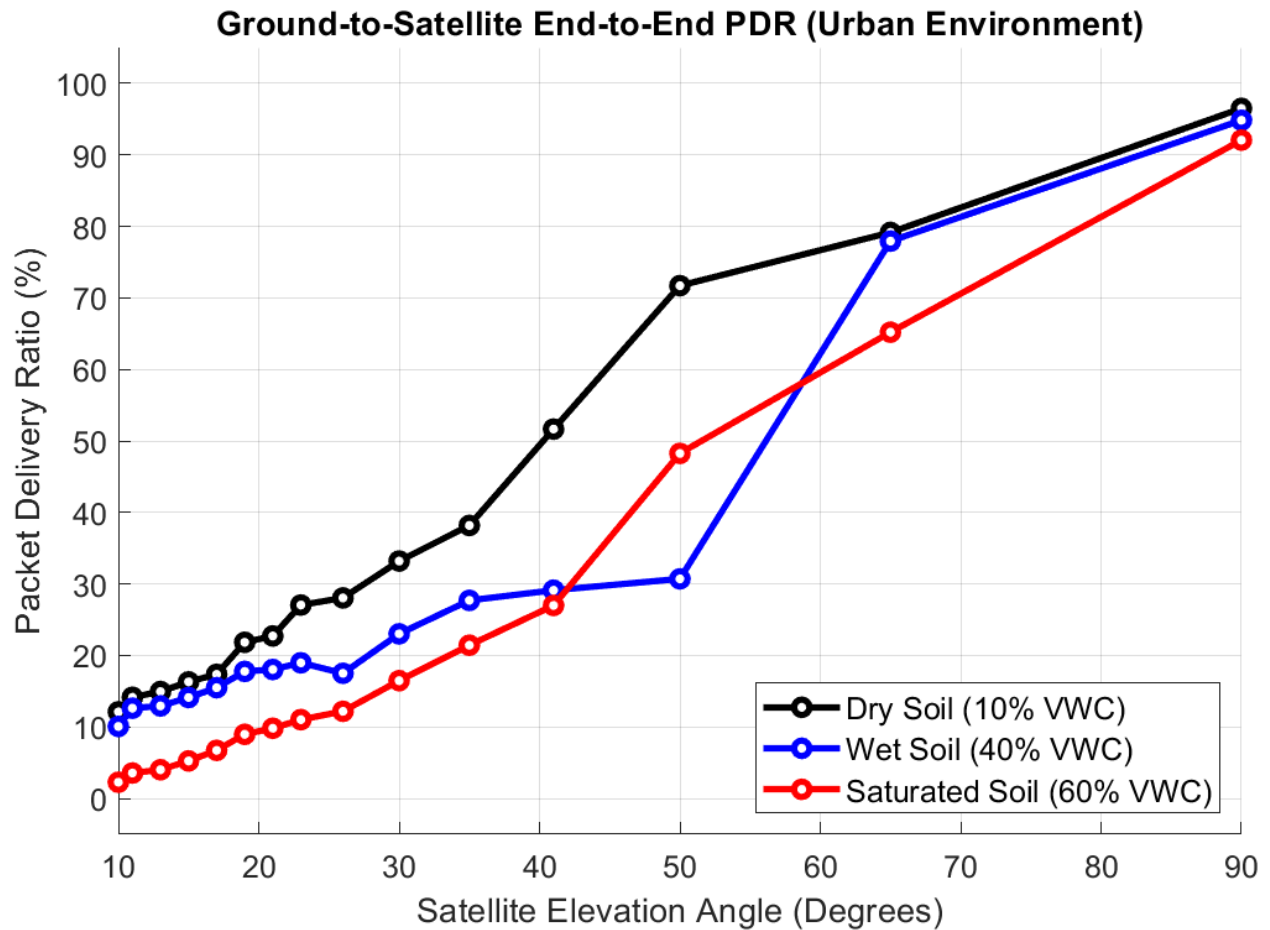
VEV-17. End-to-end PDR of the Hybrid relay against elevation angles at 1000 km orbital distance, 0.8 burial depth (at harsh conditions).

Description: When satellite elevation angle is less than 30 degrees, PDR is close to 0% for every VWC level. Each VWC line reaches its peak at 65 degree, dry (0.1) hitting 100%, wet (0.4) hitting 11% and saturated (0.6) is 0%.



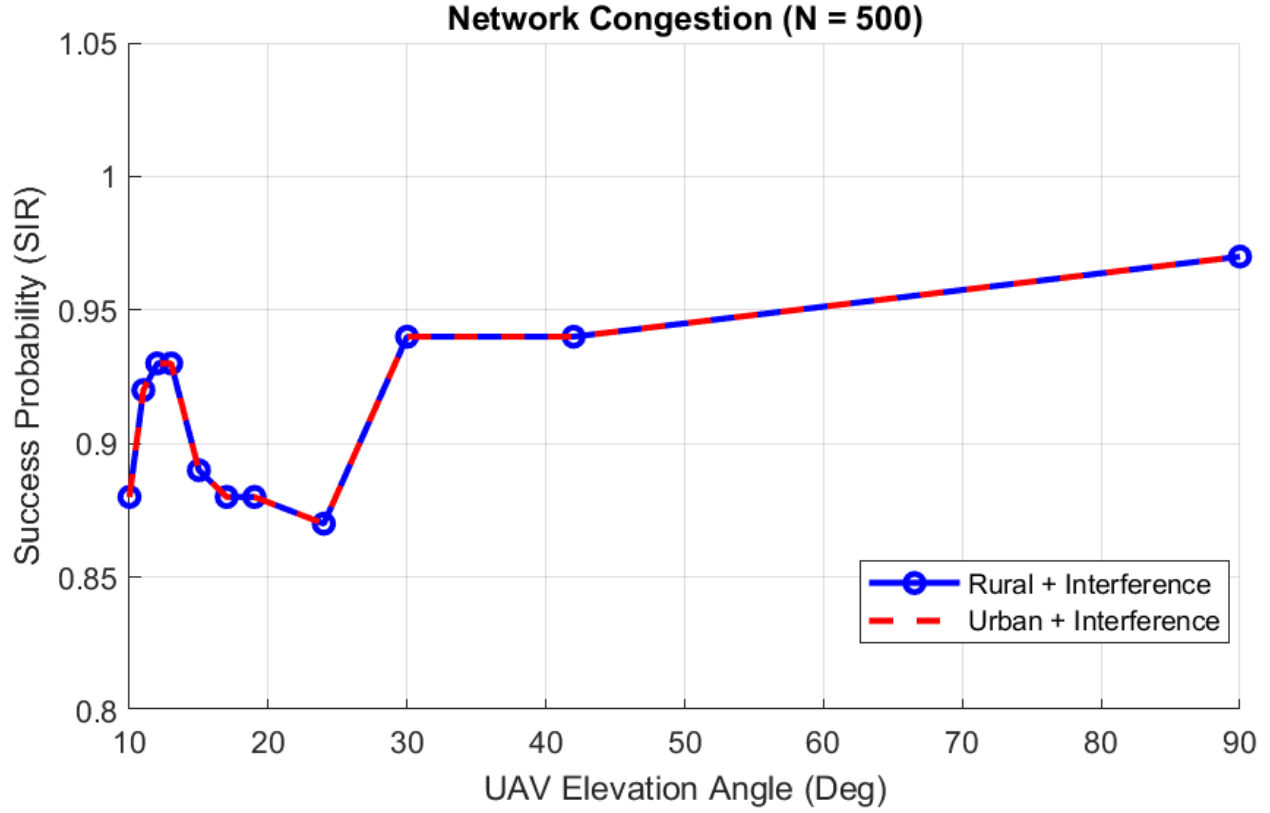
VEV-18. End-to-end PDR of the Hybrid relay against elevation angles at 600 km orbital distance, 0.2 burial depth.

Description: The lines for each VWC level follow the same PDR at different elevation angles. At 20 degree PDR is 50%, from 35 degree PDR is 100%.



VEV-19. Ground-to-satellite PDR against elevation angles at 600 km orbital distance, 35 dB satellite antenna gain at different VWC levels at 0.2 m depth, 1000 iterations.

Description: Dry soil shows the best PDR hitting 95-96% at 90 degree elevation angle, wet soil hits 94-95% PDR at the same value, saturated soil has 90-91% PDR at the same value. PDR proportional to the elevation angle.



VEV-20. Network congestion at 500 nodes and 3600 seconds report period.

Description: Success probability lowers from 93% to 88% between 13 to 24 elevation angle degrees. It hits a peak of 97% at 90 degrees.

$$P_t + G_t - \text{air loss} - \text{soil loss} = -137 \text{ dB} \quad (1)$$

$$10 \text{ dBm} + 2 \text{ dBi} - \text{air loss} - \text{soil loss} = -137 \text{ dB}$$

$$\text{air loss} + \text{soil loss} = 149 \text{ dB}$$

$$L(d, \theta)[\text{dB}] = L_f(d) + L_3(\theta) \quad \text{for } \theta > 10^\circ \quad (2)$$

$$L_3(\theta)[\text{dB}] = \eta_0 - \eta_1 e^{-(90-\theta)/v} \quad (3)$$

$$f = 200 \text{ MHz}; \eta_0 = 9.08, \eta_1 = 6.4058, v = 12.01$$

$$L_3(10^\circ)[\text{dB}] = 9.07 \text{ dB}$$

$$L_f(d) = 20 \log_{10}(4\pi df/c) \quad (4)$$

For $d = 40$ meters: $L_f(40) = 57.22 \text{ dB}$

$L(40, 10^\circ) = 57.22 + 9.07 = 66.29 \text{ dB}$

$\text{soil loss} = 149 - 66.29 = 82.71 \text{ dB}$

function:

clay_input=45;

vwc_input=[0.1 0.4 0.6];

Depth=0.4;

for i = 1:length(vwc_input)

 [RealSoilDielectric, ImagSoilDielectric] = clc_die(clay_input, vwc_input(i), Frequency);

 Ls(i) = U2Aloss(RealSoilDielectric, ImagSoilDielectric, Depth, Frequency)

end

Ls(2) = 56.67 dB

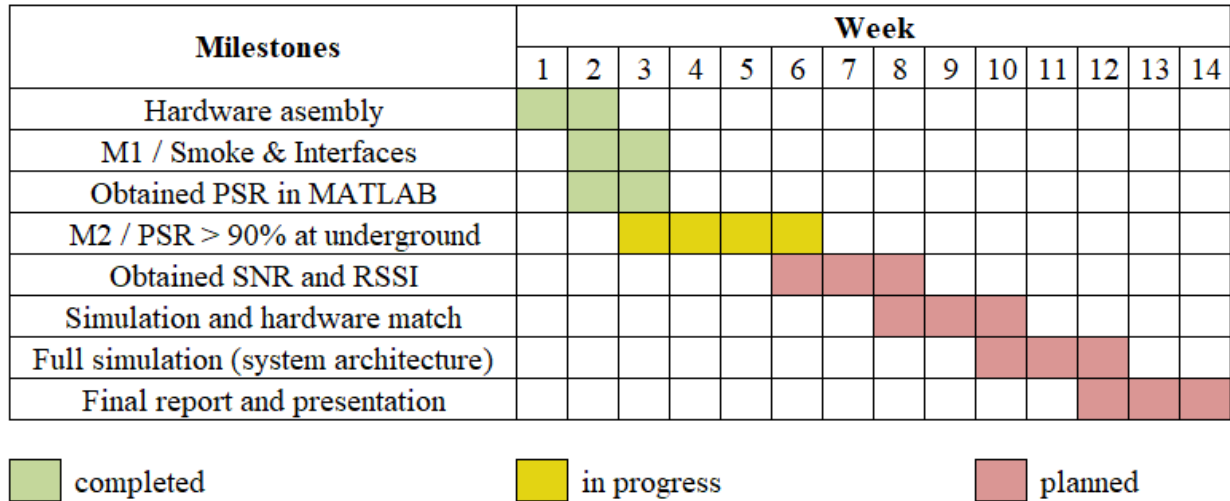
Mismatch: $82.71 - 56.67 = 26 \text{ dB}$

VEV 21. Soil loss calculation

Appendix F. Project Management Evidence

[Attach Gantt chart, task board snapshot, meeting summary table, BOM details, and procurement notes.]

Gantt chart



PMEV-1. Gantt chart from the Spring semester.

BOM details

The money spent on the materials for the capstone project was thoroughly calculated.

[illegible]

PMEV-2. Screenshot of the Excel file where the expenses are calculated.

	5546 9546 1811 5532 СОЗДАН Привезём до 2 декабря Доставка на почту	\$ 33.08
	5546 2661 4491 5532 СОЗДАН Привезём до 1 декабря Доставка на почту	\$ 12.37
	5546 2661 4503 5532 СОЗДАН Привезём до 30 ноября Доставка на почту	\$ 0.92
	5546 2661 4497 5532 СОЗДАН Привезём до 1 декабря Доставка на почту	\$ 0.90
	5546 2661 4489 5532 СОЗДАН Привезём до 30 ноября Доставка на почту	\$ 1.62

PMEV-3. One of the screenshots of the order from Aliexpress marketplace.



Покупка успешно совершена!

6,440 ₸

Ampermarket.Kz Shop

Детали операции

Номер операции	4891527494
Адрес покупки	ASTANA, KZ
Дата и время операции	29.01.2026 16:26
ФИО плательщика	АРМАН Ж.
Оплачено с	Super Card - **4472
Сумма	6,440 ₸
Итого	6,440 ₸



FREEDOM SUPERAPP

PMEV-4. One of the receipts of the purchase from the local electronics store.

The screenshots of the order, the receipts were collected to be used as evidence when asking to return the money. The reimbursement payment method was chosen.