Pi^2 Closure report

Implementation of a decentralized inter-campus network

Brief description: This project aims to design and prepare the deployment of a decentralized inter-campus communication network capable of operating without Internet connectivity or centralized infrastructure. Based on a comparative study of existing decentralized networking solutions, a LoRa-based mesh approach was selected as the most suitable for low-bandwidth, resilient communications between campuses. The project resulted in a complete state of the art and a deployment roadmap detailing the technical steps required to implement such a network.

Team Number: Project 61 — Team 5301

Project Partner: IFT (Institute For Future Technologies) / PTCC (Programme de Transfert au Campus Cyber), led by Aline Becq

Project Team:

Team Member	**Role**
Fadilatou Anem	Project Manager
Inès Kaci	Research Lead
Killian Fournier	Prototyping Lead
Nicolas Renoir	Security Lead
Yanis Baouche	Use Case & Demonstration Lead
Samy Achache	Use Case & Demonstration Co-Lead

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1 Objectives Set versus Results Achieved

1.1 Project Initial Objectives

The initial objectives of the project, defined during the kickoff phase, were the following:

- Design a decentralized communication network capable of operating without Internet access or centralized servers.
- Ensure resilience against network outages and single points of failure.
- Study and compare existing decentralized networking solutions, both software-only and hardware-assisted.
- Select a solution adapted to an inter-campus context, taking into account range, cost, deployment complexity, and security.
- Define a concrete use case, consisting of sending short text messages or lightweight JSON messages (less than 10 KB) between campuses. Then,proceed with sending a file
- Deploy a proof of concept (POC) based on the selected solution.

During the project, the objectives evolved due to external constraints. The final implementation objective was adjusted from a full POC deployment to the delivery of a complete technical deployment roadmap. This adjustment was justified by the delayed reception of the hardware equipment, which prevented physical experimentation within the academic semester.

1.2 Results Achieved

The project successfully achieved the following results:

- A comprehensive state of the art covering decentralized networking solutions, including Retroshare, IPFS, Meshtastic, LibreMesh, AREDN, and OpenWRT-based mesh networks.
- A technical and financial comparison of these solutions, focusing on topology, bandwidth, security, accessibility, required technologies, performance, and cost.
- Identification of the strengths and limitations of each approach, particularly the trade-off between bandwidth and autonomy.
- Selection of Meshtastic as the most suitable solution for the defined use case, due to its off-grid capabilities, resilience, low cost, and compatibility with lightweight messaging.
- Definition of a detailed operational roadmap describing all the steps required to deploy the Meshtastic network once the hardware is received.
- Procurement of three Meshtastic-compatible hardware kits based on the Seeed XIAO ESP32-S3 and SX1262 LoRa module, intended for the future deployment and testing of the network. The selected kit integrates an ESP32-S3 microcontroller and a LoRa transceiver, enabling low-power, long-range, off-grid mesh communications (`https://www.gotronic.fr/art-xiao-esp32s3-mash-lora-40055.htm`).

However, the following objectives could not be fully achieved:

- Physical deployment and testing of the network.
- Performance measurements, such as range, latency, and packet loss, under real campus conditions.

These deviations are explained by the late delivery of the LoRa hardware kits, which occurred after the end of the academic semester. Consequently, the project focus was shifted toward documentation, analysis, and reproducibility rather than practical implementation.

1.3 List of Deliverables

The deliverables produced during the project are the following:

- **State of the Art Report**
  Detailed analysis of decentralized networking solutions.
  Accepted by the partner.
- **Comparative Analysis Table**
  Technical and financial comparison of all studied solutions.
  Accepted by the partner.
- **Deployment Roadmap for Meshtastic**
  Step-by-step guide covering firmware flashing, serial configuration, Bluetooth pairing, and network configuration.
  Intended to ensure reproducibility and future deployment.
- **Project Poster**
  Visual synthesis of the project objectives, methodology, and selected solution, intended for presentation and dissemination purposes.
- **Project Presentation Video**
  Short video (approximately two minutes) presenting the project context, objectives, and main results.
- **Final Project Report (this document)**
  Consolidation of all project data and analysis for academic and operational reuse.

2 Methodological Review

The project was conducted using a structured methodology combining role allocation, planning, and iterative validation with the project partner.

First, the team defined clear responsibilities by assigning a reference role to each student (project management, research, prototyping, security, and use case/demonstration). These roles did not mean that only one person worked on a given topic; instead, each role acted as a coordinator and point of reference for the corresponding workstream, ensuring consistency and follow-up.

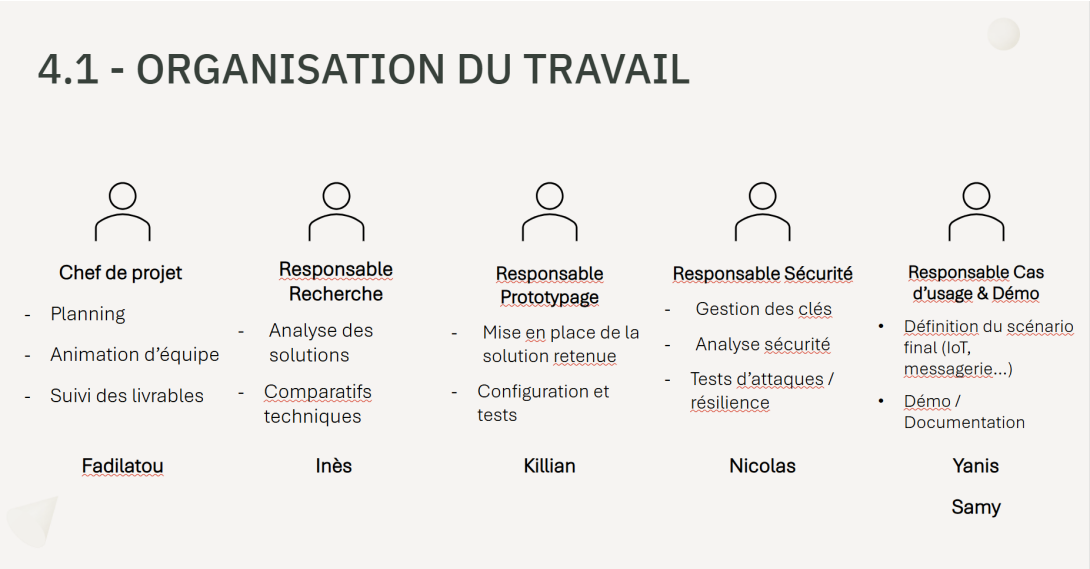

Figure 1: Distribution of roles and responsibilities within the project team

Second, planning was established early through a global Gantt chart presented from the first partner meeting. Even though the initial schedule could not be fully respected, it provided a framework, milestones, and shared objectives.

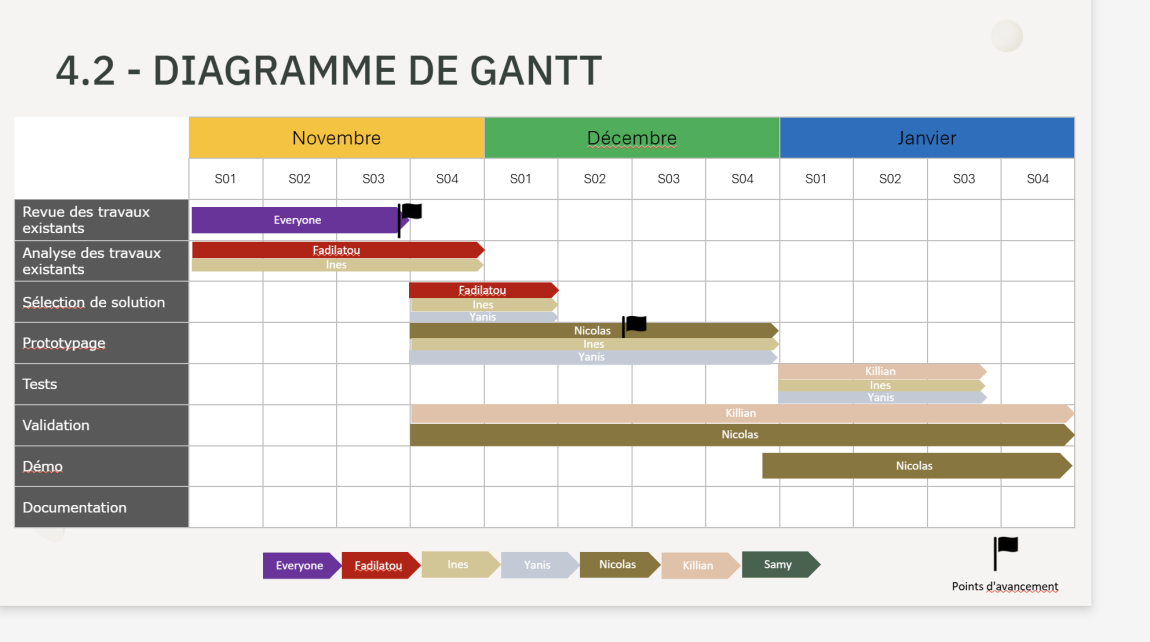

Figure 2: Initial global Gantt chart presenting the main project phases and milestones

A second and more detailed planning was later produced using GanttPRO, an online tool used to build Gantt charts, assign tasks to team members, and support follow-up through email notifications.

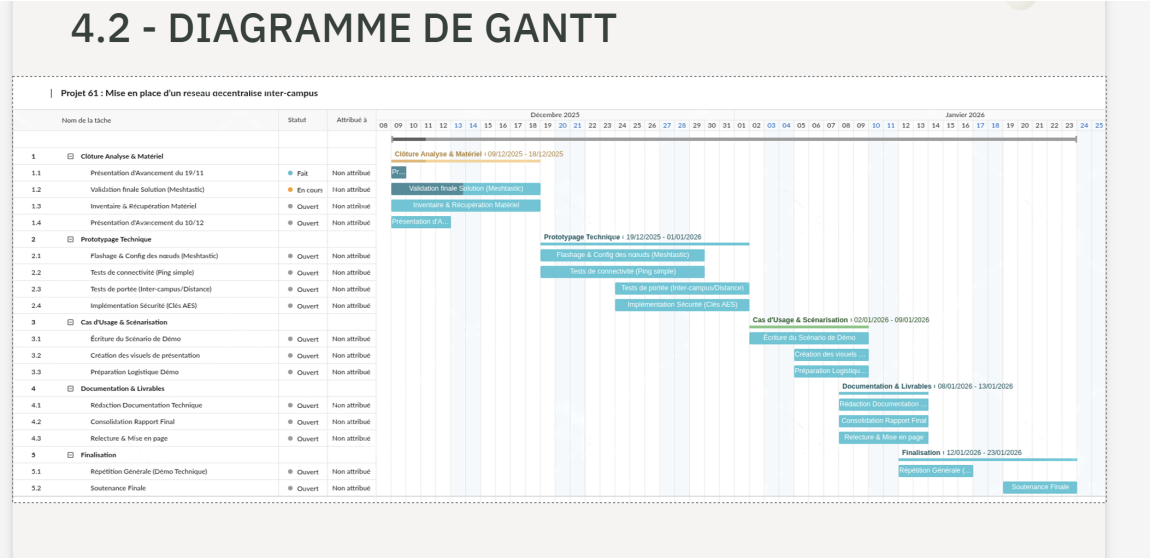

Figure 3: Detailed project planning produced with GanttPRO, including task allocation and scheduling

Gantt

Third, the work progressed through iterative exchanges with the partner. An initial meeting with Aline Becq was organized as soon as the project was assigned in order to obtain context and documentation. A first version of the state of the art was then produced and discussed during a follow-up meeting. The feedback highlighted missing details and led to a strengthened and more complete version. A third meeting was used to present the final state of the art and to justify the selected solution.

Finally, the team maintained internal coordination before and after each partner meeting to agree on task allocation and deadlines. When blocking points occurred, the team also contacted the partner through Microsoft Teams to clarify requirements and resolve issues quickly. Overall, this organization enabled steady progress and ensured that the deliverables remained aligned with the project objectives despite external constraints.

3 Risk Management

Several major risks were identified during the project:

- **Hardware delivery delays:** risk of preventing physical deployment.
- **Technical infeasibility:** insufficient range or bandwidth for inter-campus communication.
- **Security risks:** improper management or misconfiguration of encryption keys in a decentralized environment.
- **Over-complexity:** solutions requiring excessive configuration or expertise.

Mitigation actions included:

- Focusing early on documentation and roadmap creation to preserve project value.
- Selecting a solution (Meshtastic) with strong community support and proven field usage.

- Limiting the use case to low-bandwidth messaging compatible with LoRa constraints.

The hardware delivery risk materialized, but its impact was partially mitigated by the production of a complete deployment guide.

4 Constraints

The project was developed under several constraints that influenced both the technical choices and the final outcomes.

Time Constraint

- The project was conducted within a single academic semester, which was incompatible with the late delivery of the hardware equipment.

Technical Constraints

- Very low bandwidth imposed by LoRa technology.
- Limitation to a single active Bluetooth connection per node.

Operational Constraints

- Requirement for off-grid operation, without reliance on Internet connectivity.
- Need for minimal infrastructure and low deployment cost.

Security Constraints

- Ensuring the confidentiality of exchanged messages.
- Secure management of shared encryption keys in a decentralized environment.

Organizational Constraints

- All team members were apprentice students, present at the school only three days per week.
- Team members were enrolled in four different academic classes, making the organization of common meetings and work sessions challenging.

Reproducibility Constraint

- The solution had to be easily redeployable and reusable by future student teams or Lab-Cyber members.

These constraints directly influenced the final choice of Meshtastic and justified the focus on documentation, analysis, and deployment preparation rather than physical implementation.

5 Technical Review

5.1 Appropriateness of Technical Options

We selected **Meshtastic** as our primary technical solution because it directly addressed the specific requirements of our inter-campus context. While we studied other options like LibreMesh or OpenWRT, we found that they rely on WiFi frequencies which have a limited range in dense urban environments like La Défense.

- **Our Choice of LoRa Technology:** We opted for **LoRa** (Long Range) technology on the 868 MHz band. We concluded that this choice is technically superior for connecting distant buildings (e.g., Pôle Léonard de Vinci to Campus Cyber) because it can penetrate obstacles and cover several kilometers with very low power consumption.
- **Meshtastic Firmware:** We chose Meshtastic for its mature "off-grid" messaging ecosystem and its built-in support for **AES-256 encryption**. It allows us to form a self-healing mesh network without any centralized server.

5.2 Resources Dedicated to the Project

To complete this project, we mobilized the following resources:

- **Human Resources:** We organized ourselves into specialized coordination poles (Research, Prototyping, Security, Use Case) to optimize our 3-day weekly presence as apprentices.
- **Financial Resources:** We planned a budget of approximately **100 €** for the acquisition of 4 hardware kits.
- **Technical Resources:** We selected hardware kits based on the **Seeed XIAO ESP32-S3** and the **SX1262 LoRa** module. We also used tools like **PuTTY** for our technical roadmap.

5.3 Schedule and Implementation Gaps

We must highlight a significant gap between our initial schedule and the actual implementation status:

- **Status of Physical Testing:** As previously stated, **we performed no physical tests or network deployments** during the semester. This was entirely due to external hardware delivery delays beyond our control.
- **Our Mitigation Strategy:** To compensate for this, we shifted our efforts toward high-quality documentation. We transformed our "Proof of Concept" into a **detailed Deployment Roadmap** to ensure that our technical research can be implemented immediately once the hardware arrives.

6 Engineering standards

In our project, we adhered to several international engineering standards to ensure interoperability and security:

- **ISO/IEC 18033-3 (AES-256):** We used this standard for symmetric data encryption to guarantee the confidentiality of campus communications.
- **LoRa Physical Layer:** We respected the standards for long-range, low-power radio communication on the 868 MHz ISM band.
- **IEEE 802.15.1 (Bluetooth LE):** We used this for the secure interface between mobile devices and the mesh nodes.
- **JSON (RFC 8259):** We chose this format for exchanging lightweight alert messages.

7 "Post-project" tasks

To ensure a successful handover to the LabCyber team, we have identified the following operational steps that must be completed according to our technical guide:

1. **Hardware Flashing:** Apply our roadmap to flash the Meshtastic firmware onto the Seeed XIAO modules using the official web flasher.
2. **Serial Configuration:** Connect the nodes via USB-C and use PuTTY (Baud rate: 115200) to retrieve the **nodenum** (Node ID) and set the default password to **123456**.
3. **Application Pairing:** Pair the nodes with the mobile application via Bluetooth and configure the correct LoRa region (EU_868) for all devices.
4. **Field Tests:** Conduct the physical range tests we planned between the Campus Cyber and the Pôle buildings to determine optimal node placement.

8 Project Completion Recommendations

- **Early Procurement:** We strongly recommend that future teams place hardware orders during the very first week of the project to avoid the delivery delays we encountered.
- **Documentation Reliance:** We recommend that future users strictly follow our technical roadmap and user guide to ensure the reproducibility of the network setup.
- **Network Expansion:** To maximize coverage, we recommend placing "Repeater" nodes on rooftops to take full advantage of the mesh network's multi-hop capability.

9 Annexes to the closure report

We have included the following documents as appendices to this report:

1. **Meshtastic User Guide:** Our detailed guide for firmware flashing and software configuration.
2. **Comparative Analysis Table:** Our technical and financial summary of the studied solutions.
3. **Operational Roadmap:** Our step-by-step action plan for physical testing.
4. **Project Poster:** The visual synthesis we created for the final showroom.