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TITLE:

PORTABLE SOLAR-POWERED LOCAL MESH COMMUNICATION AND CHARGING KIOSK

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SUPERVISOR: Mr. M. Marufu

A project submitted in fulfillment of the Bachelor of Science (BSc) in Electronic Engineering as a requirement of the final year project.

DECLARATION

I hereby certify that the work which is being presented in the project entitled PORTABLE SOLAR-POWERED LOCAL MESH COMMUNICATION AND CHARGING KIOSK FOR RURAL ZIMBABWE in partial fulfilment of the requirements for the award of the degree of BACHELOR OF SCIENCE and submitted in the DEPARTMENT OF ELECTRONIC ENGINEERING, BINDURA UNIVERSITY OF SCIENCE EDUCATION, is an authentic record of my own work carried out during the period from August 2019 to June 2026 under the supervision of Mr. M. Marufu, Lecturer, Electronic Engineering Department.

The matter presented in this project has not been submitted by me for the award of any other degree of this or any other institute.



19 June 2026

Signature of the student with date

(TAKUDZWA MUTAMBURIGWA)

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.



7 July 2026

Signature of the Supervisor with date

(MOTION MARUFU)

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DEDICATION

I dedicate this project to my family, whose support, encouragement and patience gave me the strength to complete this work. I also dedicate it to rural communities in Zimbabwe, whose communication and energy-access challenges inspired the development of DunhuConnect.

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I would like to express my sincere gratitude to my project supervisor, Mr M Marufu, for guidance, technical direction and academic support throughout the development of this project. I also acknowledge the Department of Electronic Engineering at Bindura University of Science Education for providing the academic environment and support needed to carry out this work.

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ABSTRACT

Rural communities in Zimbabwe continue to face a combined communication and energy-access challenge. Mobile coverage may exist in some areas, but weak backhaul, high data costs, unstable power, and limited phone-charging opportunities still prevent reliable digital participation. This study designed and implemented DunhuConnect, a portable solar-powered local mesh communication and charging kiosk developed to provide useful community services even when external internet connectivity is unavailable or unreliable.

The system was built around a local-first architecture consisting of ESP32 communication nodes, a Raspberry Pi super node, a captive portal, a local communication service, router-based backhaul, and a solar-battery charging subsystem. The main aim was not simply to provide internet access, but to preserve local communication, account-based access, and phone charging as practical services for rural deployment. The project followed an engineering design and prototyping approach in which the communication, control, portal, backhaul, and power subsystems were developed, integrated, and tested as one working prototype.

Testing confirmed that users could connect to the DunhuConnect network, create accounts through the captive portal, communicate locally through the system, and remain connected while moving between implemented nodes. Router backhaul was validated, showing that the kiosk can support external connectivity when an upstream link is available while retaining its local-first service model. The hardware implementation also showed that the Raspberry Pi super node, ESP32 nodes, and charging subsystem could operate together as a single kiosk platform. The super node charging function was validated, confirming the value of treating energy access as part of the communication service rather than as a separate accessory.

The results show that DunhuConnect achieved its core objectives of local communication, node-based access extension, captive portal operation, router backhaul integration, and basic charging support. However, the prototype remains a Version 1 system. Further work is recommended to develop DunhuConnect Version 2 with a rugged enclosure, improved solar autonomy, stronger security, better monitoring, larger field trials, optimised antenna placement, and a more scalable node-management framework. Overall, the project demonstrates that a portable local-first communication and charging kiosk can be a realistic engineering response to rural connectivity and power-access challenges in Zimbabwe.

Keywords: DunhuConnect, rural communication, mesh network, ESP32, Raspberry Pi, captive portal, solar-powered kiosk, local-first communication, router backhaul, device charging.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
AC	Alternating Current
ADC	Analogue-to-Digital Converter
AP	Access Point
BUSE	Bindura University of Science Education
DC	Direct Current
ESP32	Espressif Systems 32-bit microcontroller
GSM	Global System for Mobile Communications
ICT	Information and Communication Technology
IP	Internet Protocol
LED	Light Emitting Diode
LoRa	Long Range
LPWAN	Low-Power Wide-Area Network
MPPT	Maximum Power Point Tracking
PCB	Printed Circuit Board
PV	Photovoltaic
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
SD	Secure Digital
SSID	Service Set Identifier
TCP	Transmission Control Protocol
USB	Universal Serial Bus
WAN	Wide Area Network
Wi-Fi	Wireless Fidelity

CHAPTER 1

INTRODUCTION AND BACKGROUND TO THE STUDY

Portable Solar-Powered Local Mesh Communication and Charging Kiosk for Rural Zimbabwe

DunhuConnect

1.1 Background of the Study

This study focuses on the design and development of DunhuConnect, a portable solar-powered local communication and charging kiosk intended for rural Zimbabwean operating conditions. Earlier project notes referred to the system as ZimMesh; however, the final project identity adopted in this report is DunhuConnect. The name reflects the central intention of the project: to connect a local community first, then extend that connection outward when a backhaul link is available.

The project was motivated by a practical observation rather than by a purely theoretical networking problem. In many rural settings, communication does not fail only because there is no internet signal. It also fails because mobile data is expensive, backhaul quality is inconsistent, phones run out of charge, and communities do not always have a shared local point for announcements, messaging, and access to basic digital services. A system designed for this environment therefore has to deal with communication and power together. A Wi-Fi signal without useful local services is not enough, and a charging box without communication value does not address the wider digital-access problem. (GSMA, 2023; POTRAZ, 2024).

DunhuConnect is proposed as a local-first system. In this context, local-first means that the kiosk should continue to provide useful services at the deployment site even when external internet access is unavailable or unreliable. When router backhaul or another upstream link is working, the system can extend selected services beyond the local site. When that upstream path fails, the kiosk should not become useless. Users should still be able to connect to the local network, access the captive portal, communicate within the local service, receive announcements, and charge mobile devices. This distinction is important because the project is not merely a small rural internet hotspot; it is an integrated resilience platform for local communication and energy support. (Guo et al., 2007).

The architecture combines four main elements. The first is the energy subsystem, which uses solar input, battery storage, voltage regulation, and protected charging outputs. The second is the embedded access layer, built around ESP32-based nodes that provide local wireless access and support node-to-node coverage extension. The third is the super-node layer, where a Raspberry Pi hosts the captive portal, local services, account management, and control logic. The fourth is the backhaul layer, where a router or later satellite/mobile interface can provide upstream connectivity when available. These elements are designed to work as one system rather than as isolated modules.

The current direction of the project is also shaped by implementation experience. The local communication function has been demonstrated, users can communicate on the system, the hardware has been implemented, node handover has been validated, router backhaul has been shown to work, the super node supports charging, the captive portal is operational, and accounts can be created. These achievements strengthen the relevance of the project because they show that the system is no longer only a proposal. At the same time, the introduction chapter remains careful not to present future field hardening as if it were already a production deployment. The system is treated as a working prototype whose next stage is wider validation and Version 2 refinement.

1.1.1 Rural Communication and Power-Access Context

Rural connectivity is often described through network coverage, but coverage alone does not guarantee usable digital access. A mobile network may exist in an area while still being too weak, too congested, too expensive, or too unreliable for daily communication tasks. Users may also own phones but fail to use them effectively when charging is irregular. In practice, the digital gap in rural areas is therefore not only a signal problem. It is a combined problem of service quality, affordability, device readiness, and power access. (GSMA, 2023; ZIMSTAT, 2026).

This combined problem is especially relevant in Zimbabwe, where rural communities may experience weaker broadband capacity, unstable power supply, and longer distances from technical support infrastructure. In such a setting, a rural communication solution should not assume the stable conditions of an urban internet cafe, office router, or household broadband line. It should assume that power may drop, backhaul may disappear, users may need to share infrastructure, and local operators may require simple maintenance procedures. (POTRAZ, 2024; Surana et al., 2008).

The charging requirement is central to the project because the phone is the main digital device for many users. A person can be near a communication point and still be disconnected if the phone battery is flat. For this reason, DunhuConnect treats user charging as part of the system's main

service package. The kiosk identity is justified not only by wireless communication but also by visible, user-facing utility. The charging subsystem increases the likelihood that users will approach the kiosk, understand its value, and use the communication services it provides.

The rural operating context also changes the meaning of resilience. In a city, losing internet for a short time may be inconvenient because alternative networks and charging points are nearby. In a rural community, the same outage may affect school messages, local coordination, health communication, mobile-money activity, church announcements, or family contact. A local communication point that remains available during an outage can therefore have practical value even if it does not provide full broadband at that moment.

1.1.2 Need for a Local-First Communication Kiosk

The central design idea behind DunhuConnect is that a community should not lose every digital service simply because the upstream link is down. Conventional hotspot thinking places almost all value on the internet connection. If the router has no internet, users see the network as broken. The local-first approach used in this project is different. It asks what the kiosk can still provide when the backhaul path is weak, absent, or expensive.

A local-first kiosk can preserve short-message communication, notices, local information pages, account access, and basic coordination inside the coverage area. This does not remove the need for external connectivity. Rather, it changes the dependency relationship. Backhaul becomes an extension of the local system, not the only reason the system exists. When router backhaul is validated and available, the system can provide wider connectivity. When it is not available, the Raspberry Pi-hosted local platform and ESP32 access layer should still preserve the local service experience.

This approach is aligned with the way rural communities often use shared infrastructure. Schools, clinics, churches, business centres, and ward offices can all benefit from a communication point that gives people a place to receive notices, exchange short messages, charge phones, and access selected services. The kiosk therefore becomes a shared utility point rather than a private networking appliance. (Guo et al., 2007; UN IGF DC3/APC, 2017).

Rural constraint	Effect on users	DunhuConnect design response
Unstable or expensive backhaul	Users may lose external internet access even when a local Wi-Fi network is visible.	Keep local portal, messaging, and announcements available without relying fully on the upstream link.
Irregular charging opportunities	Phones may be unusable when communication is needed most.	Include protected charging outputs as part of the kiosk service.

Limited technical support nearby	Faults may remain unresolved for long periods.	Use modular ESP32 nodes, a Raspberry Pi super node, logs, and clear subsystem boundaries.
Wide or uneven user locations	One access point may not cover the useful area.	Use distributed nodes and handover to support local movement between coverage zones.
Need for community-level information	Announcements may fail when mobile networks are weak.	Use captive portal and local notice or communication functions.

Table 1.1 Rural constraints and the corresponding DunhuConnect design response.

1.1.3 Evolution of the Project Concept

The project concept developed from a broad rural connectivity idea into a more focused local communication and charging system. In early discussions, the backhaul path received strong attention because mobile broadband or satellite connectivity is an obvious need in remote areas. However, the project became stronger when the communication problem was narrowed. The most important question became: can a portable kiosk continue to support useful local communication and charging even when external infrastructure is unreliable?

This shift made the project more realistic. Satellite or mobile broadband can improve the system, but these services have cost, regulation, power, and availability constraints. If the project depended entirely on a satellite link, it would be vulnerable to procurement limitations and licensing conditions. By treating router backhaul as a validated but modular extension, the design protects the core contribution: local access, local communication, user charging, and graceful degradation.

The same shift also improved the engineering structure of the project. Instead of building a one-purpose hotspot, DunhuConnect is organised as a layered system. The ESP32 nodes create the local wireless edge. The Raspberry Pi acts as the super node and local service host. The captive portal provides the user interface. The backhaul link extends service when available. The solar-battery subsystem supports operation in weak-grid or off-grid conditions. Each layer has a defined responsibility, which makes the system easier to test and explain.

1.1.4 Local-First System Architecture

The proposed architecture can be understood as a stack of cooperating layers. At the bottom is the energy layer, consisting of solar input, battery storage, charge control, voltage regulation, and user charging outputs. Above it is the access layer, where ESP32 nodes provide local wireless coverage and allow client devices to connect to the kiosk network. Above the access layer is the super-node layer, where the Raspberry Pi hosts the local control platform, captive portal, user

account features, and local communication services. The backhaul layer sits above the local platform as an optional or modular link to external services.

The most important architectural decision is that the Raspberry Pi remains the local authority for the kiosk. This means the local platform can host services and make decisions even when the external link is weak. If the system relied completely on a cloud server for every service decision, it would fail during the exact conditions the project is trying to address. Keeping control local allows the kiosk to degrade gracefully (Guo et al., 2007; Pentland et al., 2004).

In the implemented direction, users connect to the local network and interact through the captive portal. The captive portal is more than a login page. It is the first user-facing layer of the kiosk and can provide access to accounts, local messages, announcements, and service status. When a router backhaul path is available, external connectivity can be included. When the backhaul is absent, the local functions should remain accessible.

Layer	Main components	Role in the project
Energy layer	Solar input, battery, regulators, charging outputs	Provides operating power and user charging support.
Access layer	ESP32 root and mesh/access nodes	Provides local wireless access and coverage extension.
Super-node layer	Raspberry Pi, local services, captive portal	Hosts control logic, accounts, messaging, and local service pages.
Backhaul layer	Router or future mobile/satellite interface	Provides external connectivity when available.
User-service layer	Phones, portal, local chat, notices, charging ports	Turns the technical system into a useful community service.

Table 1.2 Layered view of the DunhuConnect architecture.

1.1.5 Hardware Implementation Direction

The hardware implementation is based on affordable and modular components. The Raspberry Pi is used as the super node because it can run Linux-based services while consuming less power than a laptop or desktop computer. ESP32 boards are used for the node layer because they provide Wi-Fi capability, embedded programmability, low cost, and wide availability. The router backhaul interface is kept modular so that the system can use a working router during prototype validation and later support other upstream links where appropriate.

The charging and power sections require careful design because they carry the user-facing load of the kiosk. Unlike a normal embedded prototype that only powers a microcontroller, DunhuConnect must supply the controller, nodes, and mobile-device charging outputs. This creates

a design trade-off: communication services must remain protected while users charge devices. The system should therefore prioritise the core controller and communication layer before allocating remaining energy to charging.

The final hardware must also be understandable and maintainable. A rural kiosk that can only be repaired by the original developer is not a strong deployment design. For that reason, the hardware direction emphasises labelled connectors, clear subsystem separation, test points, protected outputs, modular nodes, and a rugged enclosure. These decisions may appear small compared with the software stack, but they strongly affect whether the system can survive practical use.

1.1.6 Software and User-Service Direction

The software side of the project is organised around the Raspberry Pi local platform. The super node hosts the portal and local services, while the ESP32 nodes provide the access layer. The portal supports user access to the system, and the account-creation function demonstrates that the kiosk can manage users rather than operating as an uncontrolled open hotspot. This is important because public shared systems need some form of access control, accountability, and service management.

Local communication is the most visible proof of the project's purpose. Users have been able to communicate through the local system, which confirms the practical value of the local-first approach. The communication feature means that even when external mobile services are weak, users on the same kiosk network can still exchange information. This supports the project's central argument that resilience should not be measured only by internet availability.

Seamless handover between nodes is another important part of the user experience. In a practical deployment, users may move between coverage zones around the kiosk, between a charging area and a notice area, or between nearby buildings. If movement immediately breaks the service, the network becomes frustrating to use. Handover validation therefore supports the claim that the system can function as a small local coverage network rather than as a single static access point.

1.1.7 Operating Modes of the Kiosk

DunhuConnect is designed around operating modes rather than around a single ideal condition. This is important because rural deployment rarely provides perfect conditions all the time. The first mode is normal assisted operation, where the local kiosk is powered and the router backhaul is available. In this mode, the system can provide local communication, captive portal services, account access, charging, and selected external connectivity.

The second mode is local-only operation. In this mode, the backhaul path is unavailable, but the Raspberry Pi and ESP32 access layer remain active. Users should still access the portal, local messages, notices, and charging services. This mode is central to the value of the project because it proves that the kiosk does not fail completely when the upstream link fails.

The third mode is constrained-power operation. In this mode, solar input or battery capacity may be limited, and the system must protect essential communication functions. User charging may need to be limited or delayed if the battery becomes low. This mode connects the communication design to the energy design and prevents the charging service from draining the system to the point where communication becomes unavailable.

The fourth mode is maintenance and commissioning. In this mode, the operator or developer checks node status, verifies the portal, confirms backhaul, tests charging, and resolves faults. This mode matters because rural systems must be inspectable. A kiosk that works during a demonstration but provides no clear maintenance path will not be suitable for real deployment.

Operating mode	Condition	Expected service behaviour
WAN-assisted mode	Power available and router backhaul active	Local services, account access, charging, and selected internet access are available.
Local-only mode	Power available but backhaul unavailable	Portal, local communication, notices, and charging remain available.
Constrained-power mode	Battery or solar input is limited	Core communication is prioritised; charging may be controlled.
Maintenance mode	Operator checks or repairs the system	Logs, node status, power paths, and portal access are inspected.

Table 1.3 Main operating modes expected for DunhuConnect.

1.1.8 Conceptual Design Logic

The conceptual logic of DunhuConnect begins with the community problem and ends with a layered engineering response. The community problem is not only lack of internet. It is the combined difficulty of communicating locally, keeping phones charged, and depending on unstable external infrastructure. The engineering response is therefore not one component but a combination of local wireless access, local computing, modular backhaul, and off-grid power.

A useful way to understand the system is to follow the user path. A user approaches the kiosk with a phone. The phone connects to the DunhuConnect local network. The captive portal appears and allows the user to access the service. The user may create or use an account, communicate locally, view notices, and charge the phone. If the router backhaul is available, selected external

access may also be possible. If it is not available, the local services continue. This user path is simple, but it represents several engineering layers working together.

The project therefore uses a service-continuity definition of success. It does not ask only whether a link can be established under perfect conditions. It asks whether the kiosk remains useful when the real environment is imperfect. This definition is more appropriate for rural Zimbabwean deployment because it reflects the conditions under which the system is expected to operate.

Community need	Technical response	Expected outcome
Local messaging during weak network conditions	Raspberry Pi-hosted local communication service	Users can communicate inside the local coverage area.
Access without complex phone configuration	Captive portal through local Wi-Fi	Users can interact with the system using normal mobile devices.
Power support for phones	Protected charging outputs from the kiosk energy subsystem	Users can charge devices at the service point.
Coverage around the kiosk area	ESP32 node layer with handover between nodes	Users can move across local coverage zones with less service interruption.
Internet access when available	Router backhaul as modular upstream link	External connectivity can be added without replacing local-first design.

Table 1.4 Conceptual link between community needs and technical responses.

1.2 Problem Statement

Rural communities in Zimbabwe continue to face a combined communication and energy-access problem. Users may have mobile phones but still struggle to communicate reliably because of weak network quality, data affordability, power cuts, limited charging points, and dependence on external infrastructure. Existing hotspot-style solutions often assume that internet backhaul is always available and that users already have charged devices. In practice, these assumptions are often not reliable in the rural environment targeted by this project. (GSMA, 2023; POTRAZ, 2024).

When conventional backhaul is unavailable, many access systems collapse into uselessness even though some local services could still be provided. A community may not always need full internet access to remain coordinated. It may need local messaging, notices, emergency information, account access, and phone charging. A system that fails to preserve these basic services during upstream interruption does not fully address the rural resilience problem. (Guo et al., 2007).

There is therefore a need for a portable, solar-powered, local-first communication and charging kiosk that combines same-network communication, local service hosting, mesh-based coverage extension, controlled user access, modular router backhaul, and user device charging. The key

problem addressed by this study is the absence of an integrated system that treats communication continuity and energy access as one practical engineering challenge for rural Zimbabwean deployment.

The problem is not solved by providing a router alone, a solar charger alone, or a software portal alone. These components become useful only when they are integrated into a service point that can operate under real constraints. DunhuConnect responds to that integration gap by placing the Raspberry Pi super node, ESP32 access nodes, captive portal, router backhaul, and solar-powered charging subsystem into one prototype architecture. (Guo et al., 2007; Feron, 2016).

1.3 Aim of the Project

The aim of this study is to design, implement, and evaluate a portable solar-powered local mesh communication and charging kiosk for rural Zimbabwe, using a Raspberry Pi super node, ESP32-based access nodes, captive portal services, modular router backhaul, and protected charging outputs to provide local communication, user access, and device charging under constrained infrastructure conditions.

1.4 Specific Objectives

The project is guided by three specific objectives. These objectives were kept deliberately focused so that the study remains achievable and defensible within a final-year engineering project.

- To develop a local communication and captive portal system that allows users connected to the DunhuConnect network to create accounts, access the local portal, and exchange messages or information within the same kiosk network.
- To design and implement the local network architecture of the kiosk, including the Raspberry Pi super node, ESP32 root node, ESP32 access or mesh nodes, router backhaul interface, and node handover behaviour required for resilient intra-community communication.
- To design and implement the power and charging subsystem required to support the Raspberry Pi platform, ESP32 nodes, router backhaul interface, and user-facing charging outputs from a solar-battery energy system.

These objectives reflect the revised identity of the project. The priority is not to present DunhuConnect as a satellite-first internet product. The priority is to prove that a local

communication and charging kiosk can remain useful under rural operating constraints while still supporting upstream backhaul when available.

1.5 Research Questions

The study is also guided by research questions that translate the objectives into testable engineering concerns. These questions help connect Chapter 1 to the design, methodology, implementation results, and recommendations that follow.

- How can a portable rural kiosk provide local communication services to users even when external backhaul is unavailable or unstable?
- How can a Raspberry Pi super node and ESP32-based nodes be organised to support local access, captive portal operation, user accounts, and handover between local coverage points?
- How can the power subsystem be designed so that communication equipment and user charging outputs can coexist without compromising the core operation of the kiosk?
- What practical limitations remain after the first working prototype, and how should these inform the development of DunhuConnect Version 2?

1.6 Scope of the Study

The scope of the study covers the design and prototype implementation of a portable solar-powered local mesh communication and charging kiosk. The system includes a Raspberry Pi-based super node, ESP32-based node hardware, captive portal functionality, user account creation, local communication, router backhaul validation, and user charging through the super-node service point.

The communication scope includes local Wi-Fi access, local service delivery, captive portal interaction, local messaging or information exchange, and handover between nodes. The study therefore includes both the user-facing service experience and the embedded access architecture that supports it. The router backhaul is included as a validated upstream path, but the system is not defined only by the backhaul. The local services remain the centre of the project.

The power scope includes the solar-battery design basis, voltage regulation, supply of the Raspberry Pi and ESP32 nodes, and user charging outputs. The charging function is included because it directly affects whether the kiosk can serve real users. It also affects energy budgeting, load prioritisation, enclosure design, and Version 2 recommendations.

The software scope includes the captive portal, account creation, local service hosting, and system control logic on the Raspberry Pi. The study does not attempt to build a full commercial social-media platform or a nationwide communication service. It focuses on the local service features needed to demonstrate the viability of a rural communication kiosk.

The hardware scope includes the implemented prototype and the engineering pathway for a more rugged Version 2 design. The first version proves the feasibility of the architecture. Version 2, discussed later in the dissertation, should improve enclosure strength, power autonomy, security, monitoring, field maintainability, and larger-scale coverage testing.

1.6.1 Scope Boundaries

Several boundaries are necessary to keep the study academically honest. The project does not claim to provide nationwide rural connectivity. It does not claim that a commercial-scale production kiosk has already been certified, mass-produced, or tested across many villages. It also does not claim that every future backhaul option, including satellite, has already been permanently deployed. Instead, the study focuses on a working prototype architecture and the evidence needed to support continued development.

The study also does not attempt to replace mobile network operators or public telecommunications infrastructure. DunhuConnect is better understood as a shared local service point that can complement existing infrastructure. Its value is strongest when the existing network is weak, expensive, unavailable, or insufficient for immediate local communication and charging needs.

The local communication service is treated as a prototype-level communication platform. The system demonstrates that users can communicate locally, but future work should strengthen moderation, retention policies, privacy controls, and administrative tools before larger community deployment. This distinction keeps the claims proportional to the current prototype maturity.

1.6.2 Assumptions

The first assumption is that the intended deployment environment has at least intermittent solar availability sufficient to recharge the system over time. The design does not assume perfect sunlight or continuous power, but it assumes that solar energy can contribute meaningfully to daily operation.

The second assumption is that most users will access the kiosk using mobile phones rather than laptops or desktop computers. This assumption influences the use of Wi-Fi access, captive portal interaction, simple account flows, and phone charging outputs.

The third assumption is that the Raspberry Pi super node can remain the local service authority during normal operation. This assumption is important because it allows local communication and portal access to continue even if the external backhaul path is not available.

The fourth assumption is that the kiosk will be deployed in a shared environment where simplicity and visibility matter. Users should not need specialised equipment to understand the system. They should be able to connect, access the portal, communicate locally, and charge their phones using familiar devices.

1.6.3 Constraints

The project is constrained by prototype resources, time, component availability, power budget, and the limits of low-cost embedded hardware. ESP32 nodes are suitable for local access and embedded networking tasks, but they are not equivalent to industrial access points. The Raspberry Pi provides a practical local service platform, but it also has power and storage limits that must be respected.

The power subsystem is constrained by the need to support both system operation and user charging. Charging can increase community value, but it can also drain the energy system if not controlled. For this reason, the design must treat charging as a managed service rather than as an unlimited output.

The project is also constrained by regulatory and deployment realities. Public communication systems and backhaul services must operate within lawful conditions. The prototype can validate router backhaul and local communication, but larger deployment must consider licensing, service-provider relationships, and site-level permission (POTRAZ, 2023; Reuters, 2024).

Finally, the dissertation is constrained by evidence. Claims must match what has been implemented and tested. This is especially important because the project has moved through several naming and design refinements. The final report uses DunhuConnect as the project identity and presents the working prototype as Version 1, with Version 2 reserved for the rugged and field-ready continuation of the work.

1.7 Significance of the Study

1.7.1 Social Significance

The social significance of DunhuConnect lies in its ability to support basic community communication where ordinary infrastructure is weak or interrupted. A working local kiosk can help users exchange information, receive notices, and keep phones charged. This may be useful at schools, clinics, churches, growth points, ward offices, community meetings, or emergency-response locations.

The system is also socially relevant because it recognises that charging is part of digital inclusion. A communication service is not useful to a user whose phone cannot stay powered. By combining communication and charging, the kiosk addresses a more complete version of the rural access problem. (GSMA, 2023; Khan, 2023).

The project also supports community-level coordination. Local announcements, event updates, emergency information, and short user messages can continue through the local system even when external networks are unreliable. This makes the kiosk useful not only as a technology demonstration but as a practical community service point.

1.7.2 Technical Significance

The technical significance of the project lies in its integration of embedded systems, wireless communication, edge computing, solar power, user-interface design, and power management. Each of these areas is common in engineering, but the value of the project comes from making them work together under constrained conditions.

The use of ESP32 nodes allows the project to explore low-cost local access and coverage extension. The Raspberry Pi super node allows local services to run without relying on a remote cloud server. The captive portal gives users a practical interface. The router backhaul demonstrates modular upstream connectivity. The charging subsystem connects the technical network to a visible user need.

The project therefore contributes a working example of a local-first rural communication architecture. It does not claim to be the final answer to rural connectivity, but it does show how a small, affordable, and portable system can preserve useful service value even under imperfect infrastructure conditions.

1.7.3 Academic Significance

From an academic perspective, the project is suitable for an Electronic Engineering dissertation because it requires system-level design rather than isolated circuit construction. The work involves defining a real problem, reviewing relevant technologies, developing a system architecture, implementing hardware and software subsystems, testing the prototype, and recommending a Version 2 path based on observed limitations.

The project also encourages honest engineering reporting. A strong dissertation should not exaggerate the prototype into a finished commercial product. Instead, it should clearly show what has been implemented, what has been validated, what remains limited, and what future work is necessary. This study follows that approach by treating the current implementation as Version 1 and positioning Version 2 as the next development stage.

1.7.4 Economic and Sustainability Significance

The economic value of DunhuConnect is linked to shared access. A single kiosk can serve several users rather than requiring every household to purchase separate infrastructure. This does not remove all cost barriers, but it can reduce the cost per user and provide a practical starting point for community digital services (Guo et al., 2007; UN IGF DC3/APC, 2017).

The sustainability value lies in the combination of solar power, modular hardware, and local maintainability. A system that depends completely on grid power or distant cloud infrastructure is less suitable for rural resilience. By using local computing and renewable energy input, the kiosk is better aligned with the conditions it is meant to serve. (Feron, 2016; Esmaili et al., 2018).

The charging service may also support sustainability because it provides an immediate service that users understand. In future versions, charging could form part of a small operating model that helps cover maintenance, data, or replacement costs. This business aspect is outside the main technical scope of this dissertation, but it is relevant to future deployment.

1.8 Justification of the Study

The study is justified because it responds to a real integration gap. Existing solutions often address only part of the problem. A router provides connectivity only when backhaul is working. A solar charger provides energy but not communication. A chat application requires a network and device power. A mesh network may extend access but does not automatically provide a local service

platform or charging support. DunhuConnect combines these elements into one local-first kiosk architecture. (Guo et al., 2007; Kanwal and Imran, 2015; Feron, 2016).

The project is also justified by the practical progress already achieved. The local communication function has been shown to work, users have communicated through the system, handover between nodes has been demonstrated, router backhaul has been validated, the captive portal works, accounts can be created, hardware has been implemented, and the super node supports charging. These results confirm that the project is technically plausible and worth documenting as a complete engineering study.

The study is further justified because it creates a clear path for future work. The Version 1 prototype proves feasibility. Version 2 can now focus on stronger hardware, better power autonomy, improved security, field testing, monitoring, enclosure design, and larger-scale deployment. This progression is academically valuable because it links implementation results to realistic recommendations rather than ending with a one-time demonstration.

1.9 Limitations of the Study

The first limitation is that the prototype represents a controlled first implementation rather than a full rural field deployment across many sites. Laboratory and small-area testing can prove technical feasibility, but wider village deployment would introduce additional variables such as weather, terrain, user load, vandalism risk, long-term battery ageing, and maintenance behaviour.

The second limitation is that the first version uses available prototype hardware rather than a fully rugged production enclosure. This affects environmental protection, cable management, connector durability, and public-use safety. These issues are important, but they are more appropriately addressed in Version 2 after the core system has been proven.

The third limitation is that local communication has been validated at prototype level, but larger user numbers and longer traffic sessions still need further testing. Future evaluation should measure message delay, user load, handover performance under movement, and system behaviour when several users charge devices and communicate at the same time.

The fourth limitation is that router backhaul has been validated, but the system should not be interpreted as permanently tied to one backhaul device. The design remains modular so that future versions can integrate stronger mobile broadband, satellite, or other upstream links if resources and regulatory conditions allow.

The fifth limitation is that security and administration require further hardening before public deployment. Account creation is working, but a real deployment would require stronger password handling, administrator roles, abuse control, session management, and data privacy rules. These are included as future work rather than overstated as complete production features.

1.10 Definition of Key Terms

Term	Meaning in this study
DunhuConnect	The final name used for the portable solar-powered local mesh communication and charging kiosk developed in this project.
Local-first	A design principle in which useful local services remain available even when external backhaul is absent.
Super node	The Raspberry Pi-based local controller and service host for the kiosk.
ESP32 node	An embedded wireless node used for local access, coverage extension, or communication support.
Captive portal	The local web interface presented to users when they connect to the kiosk network.
Backhaul	The upstream connection from the local kiosk to external networks through a router or future wide-area link.
Handover	The ability for user access to remain usable as movement occurs between local node coverage areas.
Version 2	The next development stage intended to make the current prototype more rugged, secure, scalable, and field-ready.

Table 1.5 Definition of key terms used in the study.

1.11 Structure of the Dissertation

The dissertation is organised into five chapters. Chapter 1 introduces the study, explains the background, defines the problem, states the aim and objectives, describes the scope, and justifies the significance of the project. It also sets the local-first direction that guides the rest of the report.

Chapter 2 reviews the literature related to rural digital inclusion, shared-access systems, wireless mesh networking, backhaul technologies, off-grid solar power, user charging, and community communication systems. The chapter identifies the integration gap that DunhuConnect addresses.

Chapter 3 presents the methodology used to design and implement the system. It describes the research design, system requirements, architecture, flow of operation, hardware design, software design, implementation procedure, testing plan, and ethical considerations.

Chapter 4 presents the experimental results and analysis. It reports the implementation results, local communication tests, captive portal operation, account creation, handover validation, router backhaul validation, charging behaviour, and interpretation of the results against the objectives.

Chapter 5 presents the conclusion, recommendations, and future work. The chapter uses the results from Version 1 to recommend a Version 2 development path focused on field readiness, rugged hardware, stronger power autonomy, security, monitoring, scalability, and long-term rural deployment.

1.12 Chapter Summary

This chapter introduced DunhuConnect as a portable solar-powered local mesh communication and charging kiosk for rural Zimbabwe. The chapter explained that the project is motivated by a combined communication and power-access problem rather than by internet connectivity alone. It argued that rural users need a system that can provide local communication, account-based access, notices, charging, and backhaul support when available, while still remaining useful when external connectivity is unavailable.

The chapter also clarified the local-first identity of the project. DunhuConnect is not defined only by router backhaul or future satellite access. Its main contribution is the integration of a Raspberry Pi super node, ESP32-based nodes, captive portal services, local communication, user accounts, modular backhaul, and a solar-supported charging subsystem into one community-facing prototype.

The aim, objectives, research questions, scope, assumptions, constraints, significance, justification, and limitations were presented to define the boundaries of the study. The chapter also introduced the idea of Version 2, which will be used later in the dissertation to describe the future work needed to move from a successful prototype to a more rugged, secure, and field-ready rural communication platform.

Overall, Chapter 1 provides the conceptual foundation for the rest of the dissertation. Chapter 2 builds on this foundation by reviewing the literature and technical evidence relevant to the design. Chapter 3 then translates the problem into a detailed methodology, Chapter 4 evaluates the

implemented system, and Chapter 5 recommends the Version 2 pathway required for practical deployment.

CHAPTER 2

LITERATURE REVIEW

Portable Solar-Powered Local Mesh Communication and Charging Kiosk for Rural Zimbabwe

DunhuConnect

2.1 Introduction

This chapter reviews the literature that informs the design of DunhuConnect, a portable solar-powered local mesh communication and charging kiosk intended for rural Zimbabwean conditions. The review is written from the position established in Chapter 1: the project is not only an internet-access proposal. It is a local-first communication and charging system in which router backhaul, mobile broadband or future satellite backhaul can extend service, but should not be the single point on which the whole service depends. Research on rural networks has repeatedly shown that useful systems must be designed around intermittent connectivity, limited local support and imperfect power conditions rather than ideal urban assumptions (Surana et al., 2008; Zennaro et al., 2007).

The central argument is that rural digital access is a coupled engineering problem. GSMA (2023) distinguishes the coverage gap from the much larger usage gap, showing that the presence of mobile broadband coverage does not itself guarantee meaningful use. Affordability, device access, digital readiness and relevant services also affect participation. For a rural kiosk, energy adds another constraint: off-grid communication equipment and user devices must remain powered for connectivity to have practical value (Feron, 2016). The literature is therefore reviewed across rural digital inclusion, shared-access kiosks, wireless mesh networking, local service resilience, backhaul, off-grid solar power, charging and field reliability.

The review is deliberately selective. It focuses on the technologies and system principles that directly influence the present prototype: Raspberry Pi-based local control, ESP32-class access nodes, captive portal services, same-network messaging, modular backhaul, solar-battery operation and protected user charging. This approach follows the systems perspective advocated by Surana et al. (2008), who argue that rural deployments succeed or fail through the interaction of power, networking, monitoring, maintenance and local operational conditions rather than through a single high-performing component.

The literature also provides a basis for the Version 2 direction. The present prototype has demonstrated local communication, node handover, router backhaul, captive portal operation, account creation, hardware integration and super-node charging. The role of the literature is therefore twofold: to justify the design decisions already made and to identify the measurements, protections and operational improvements required before wider field deployment.

This distinction between proof of concept and sustainable deployment is important. Patra et al. (2007) and Surana et al. (2008) show that rural wireless systems require deliberate RF planning, monitoring and maintenance if they are to remain useful beyond a demonstration. DunhuConnect Version 2 is therefore treated as an engineering progression from a working prototype toward a more measurable, rugged and maintainable rural service platform.

2.1.1 Structure of the Chapter

The chapter first establishes the theoretical background of local-first rural communication systems and then discusses the Zimbabwean connectivity and energy context. The review proceeds to related systems and technologies, including KioskNet, DakNet, WiLDNet, community networks, Wi-Fi mesh, LoRa, satellite and mobile backhaul, and off-grid photovoltaic systems. These systems are not treated as interchangeable. Instead, each is examined for the specific design lesson it contributes to DunhuConnect.

Traceability is a key requirement of the review. Guo et al. (2007) and Pentland, Fletcher and Hasson (2004) inform the kiosk and intermittent-connectivity logic; Patra et al. (2007) and Kanwal and Imran (2015) inform the wireless and mesh aspects; Feron (2016) and El-Khozondar et al. (2016) inform solar-energy design; Berto, Napoletano and Savi (2021) and Cotrim and Kleinschmidt (2020) define the realistic role of LoRa; and Michel et al. (2022) and Tirmizi et al. (2022) inform the treatment of satellite backhaul as an optional upstream layer rather than the identity of the system.

Review area	Reason for inclusion	Link to DunhuConnect
Rural digital inclusion	Shows why coverage alone does not solve access	Supports local-first communication and charging
Shared-access kiosks	Explains why community service points remain relevant	Supports the kiosk model instead of household-only access
Wireless mesh networking	Explains coverage extension, routing and handover	Supports the ESP32 node layer and local mobility
Backhaul systems	Explains router, mobile and satellite upstream options	Supports modular WAN-assisted operation
Off-grid PV and batteries	Explains energy autonomy and load budgeting	Supports solar operation and charging
Charging services	Shows why device power is part of usable access	Justifies protected user charging
Field reliability	Explains maintenance and monitoring constraints	Supports rugged Version 2 hardware and diagnostics

Table 2.1 Main literature areas reviewed in relation to the DunhuConnect design.

2.2 Theoretical Background

2.2.1 Rural Digital Inclusion and the Limits of Coverage-Based Thinking

Rural digital inclusion cannot be reduced to whether a radio signal is present. GSMA (2023) reports a substantial global usage gap among people who live within mobile broadband coverage but do not use mobile internet, and identifies infrastructure, affordability, consumer readiness, devices and relevant content or services as interacting enablers. This distinction is directly relevant to DunhuConnect: nominal coverage may coexist with weak service quality, expensive data, uncharged devices or a need for communication that is local rather than internet-based.

For that reason, the project does not begin from the assumption that rural users simply need a stronger upstream link. Backhaul is valuable, but it does not by itself provide local messaging, community notices, account access or device power. A shared service point can concentrate these functions in one location and make personal mobile phones more useful by providing Wi-Fi access, local services and charging even when the wider network is degraded (Guo et al., 2007; GSMA, 2023).

The literature therefore supports a service-continuity interpretation of digital inclusion. In this interpretation, a system is judged not only by peak bandwidth but also by whether users can still perform useful tasks when the network or power environment is imperfect. This is consistent with rural deployment studies that place reliability, low operating cost and maintainability alongside connectivity performance (Surana et al., 2008).

2.2.2 Local-First Resilience

Local-first resilience means that the site retains useful services when upstream connectivity is unavailable. KioskNet was explicitly designed around low-cost kiosks and intermittent transport of data, demonstrating that local access can remain useful even when continuous internet connectivity is not available (Guo et al., 2007). DakNet similarly showed that asynchronous and store-and-forward communication can deliver value in developing-region settings without requiring an always-on high-speed link (Pentland, Fletcher and Hasson, 2004).

DunhuConnect applies the same resilience principle with a different architecture. The Raspberry Pi acts as a local service authority for the portal, accounts, messages and status information, while the router or later satellite/mobile link acts as an enhancement. When the backhaul is present, the kiosk can expose selected external services; when it is absent, the local service should continue. The design therefore follows the broader lesson of KioskNet and DakNet without reproducing their older hardware or data-mule mechanisms (Guo et al., 2007; Pentland, Fletcher and Hasson, 2004).

This approach does not reject the internet. It changes the failure mode of the kiosk. Instead of becoming useless when the WAN disappears, the kiosk degrades to a local-only state. Surana et al. (2008) show why such graceful operation matters in rural systems, where faults, power quality and delayed technical support can make dependence on a single external path operationally fragile.

2.2.3 Shared-Access Kiosk Theory

Shared-access kiosks are relevant where individual ownership of infrastructure is uneconomic or where community services are easier to maintain at a common point. Guo et al. (2007) describe a kiosk model intended to lower the cost of access and tolerate intermittent connectivity. For DunhuConnect, the kiosk is not merely a housing for electronics; it is a visible service point that combines access, local communication, charging and basic user support.

Pentland, Fletcher and Hasson (2004) further demonstrate that the usefulness of rural digital infrastructure can come from the way services are organised around real constraints rather than from continuous high-speed access. This leads to three design implications for DunhuConnect: the interface must be phone-facing and simple, local services must remain accessible without WAN connectivity, and charging must be treated as part of the core user service.

2.2.4 Wireless Mesh Networking and Handover

Wireless mesh and multi-hop networking can extend coverage beyond a single access point, but the literature makes clear that mesh behaviour must be engineered rather than assumed. AODV discovers routes reactively, OLSR maintains routes proactively, and RPL and Babel address other constrained or dynamic network conditions (RFC 3561, 2003; RFC 3626, 2003; RFC 6550, 2012; RFC 8966, 2021). The practical choice depends on traffic patterns, node capability, link quality and energy constraints.

For rural wireless systems, radio placement and link behaviour are equally important. Patra et al. (2007) demonstrated through WiLDNet that long-distance rural Wi-Fi requires careful attention to antenna alignment, MAC behaviour and link conditions. Kanwal and Imran (2015) likewise discuss community wireless mesh networking as a possible rural-connectivity approach, but one whose usefulness depends on appropriate topology and deployment conditions.

DunhuConnect does not attempt to turn Chapter 2 into a protocol competition. The project-level question is whether users can reach the local service across the intended coverage area and remain usable while moving between implemented nodes. The successful handover observed in the current prototype is therefore meaningful, but the literature indicates that Version 2 should add quantitative RF evidence such as RSSI, packet loss, handover delay, node spacing and obstacle effects (Patra et al., 2007).

2.2.5 Off-Grid Energy and Load-Aware Communication

Off-grid photovoltaic systems combine generation, charge control, storage, conversion, protection and loads. Feron (2016) shows that the sustainability of rural off-grid PV systems depends not only on initial technical performance but also on reliability, maintenance and long-term operating conditions. For DunhuConnect, the load is mixed and time-varying: it includes the Raspberry Pi, ESP32 nodes, router backhaul, conversion losses and user charging.

This mixed load creates a design hierarchy. Communication and control are priority loads, while user charging must be managed so that it does not collapse the core service during weak solar input or low battery state. Research on PV maximum-power-point tracking illustrates the importance of extracting available solar energy efficiently, while battery and protection design remain necessary for safe operation (El-Khozondar et al., 2016). Khan (2023) also illustrates the practical relevance of solar-powered phone charging for rural contexts.

Version 2 should therefore move beyond a simple battery-voltage indication toward energy telemetry. The operator should be able to determine whether solar input is present, whether the battery is charging, how much current the system is drawing, and whether user charging threatens the communication load. This makes energy management part of network resilience rather than a separate electrical subsystem.

2.3 Zimbabwean Rural Connectivity and Energy Context

2.3.1 Connectivity Conditions

The Zimbabwean context strengthens the case for separating nominal coverage from effective access. GSMA (2023) shows that Sub-Saharan Africa continues to face a large mobile-internet usage gap even where coverage exists, while POTRAZ sector reporting documents a communications market in which coverage, service quality, traffic and infrastructure conditions vary over time (POTRAZ, 2024). For a rural engineering design, the important implication is that an upstream signal cannot be assumed to be continuously affordable, strong or available at every site.

A shared kiosk can therefore reduce dependence on continuous external data for basic local functions. Users can connect to a local network, register, exchange messages, view notices and charge devices. When a router or mobile broadband link is available, the kiosk can extend selected services outward; when it is absent, the local functions remain. This architecture addresses the difference between connectivity as a radio condition and connectivity as a usable service.

The user interface should also be mobile-first. GSMA (2023) treats handset access and device capability as part of the mobile-internet adoption problem. DunhuConnect consequently prioritises ordinary smartphones, a lightweight captive portal and simple account flows rather than assuming that users have laptops, specialised terminals or complex configuration skills.

2.3.2 Energy and Charging Context

Energy access is one of the strongest reasons to integrate charging with communication. Feron (2016) identifies technical sustainability, maintenance and system reliability as central concerns for off-grid rural PV systems. In a communications kiosk, these concerns extend to the user device: a phone cannot use a local or external service if its battery is depleted. The charging function therefore supports digital access rather than merely adding convenience.

The present prototype has already shown that the super node can support charging. Literature on solar phone charging, including Khan (2023), supports the practicality of treating phone power as a visible rural service. The engineering requirement is to provide that service with current limiting, protection and load prioritisation so that charging demand does not jeopardise the Raspberry Pi, nodes or backhaul equipment.

2.3.3 Regulatory and Deployment Context

Backhaul is not only a technical issue; it is also shaped by regulation, equipment availability and service-provider conditions. Zimbabwe's approval of Starlink licensing in 2024 illustrates that satellite options are subject to national regulatory decisions rather than being automatically deployable at any time (Reuters, 2024). POTRAZ notices and sector reports likewise make regulation part of the deployment environment (POTRAZ, 2023; POTRAZ, 2024).

This supports a modular backhaul strategy. The project can validate the local network, portal, accounts, charging and handover using a router while leaving future mobile or satellite links as replaceable upstream interfaces. Michel et al. (2022) show that low-Earth-orbit satellite systems can offer substantially different performance from older geostationary systems, while Tirmizi et al. (2022) emphasise the wider technical complexity of hybrid satellite-terrestrial networking. Neither source justifies making satellite connectivity the sole measure of project success.

Contextual factor	Effect on rural users	Design response in DunhuConnect
Uneven broadband quality	External communication may be unreliable	Keep local communication active without backhaul
Data affordability pressure	Users may avoid continuous internet use	Provide local notices and same-network messaging
Irregular charging access	Phones may be unavailable even where signal exists	Include protected phone-charging outputs
Mobile-first access	Users mainly reach services from phones	Use captive portal and lightweight mobile interface
Regulatory limits on backhaul	Not every upstream path can be assumed	Keep router/mobile/satellite backhaul modular

Table 2.2 Zimbabwean rural context and its influence on the DunhuConnect design.

2.4 Review of Related Systems and Technologies

2.4.1 KioskNet and Local Kiosk Architectures

KioskNet is directly relevant because it was designed to provide very low-cost internet access through rural kiosks under intermittent-connectivity conditions. Guo et al. (2007) proposed a system in which kiosk users could access services locally while data was transported opportunistically. The contribution to DunhuConnect is the service philosophy: a rural kiosk should preserve useful local functions and tolerate disruption instead of assuming a continuously available WAN.

DunhuConnect does not copy KioskNet's implementation. Modern users expect direct smartphone access, mobile-friendly web interfaces and near-immediate local interaction. The project therefore adapts the kiosk principle to a Raspberry Pi local controller, Wi-Fi-capable embedded nodes and a captive portal. What remains from Guo et al. (2007) is the more durable lesson that interruption should be treated as a normal design condition, not an exceptional fault.

2.4.2 DakNet and Store-and-Forward Thinking

DakNet provides an earlier example of useful connectivity under asynchronous conditions. Pentland, Fletcher and Hasson (2004) used mobile access points and store-and-forward transfer to move data between remote communities and connected locations. Although DunhuConnect does not use the same transport mechanism, DakNet demonstrates that digital services can remain meaningful without an always-on broadband path.

For DunhuConnect, this supports keeping messages, notices, account information and service status available inside the local network. Backhaul can later synchronise or extend selected services, but loss of the WAN should not erase the local user experience. The project therefore translates store-and-forward resilience into a local-first edge-service model.

2.4.3 WiLDNet and Long-Distance Wi-Fi Lessons

WiLDNet demonstrates that rural Wi-Fi cannot be engineered by simply extending urban assumptions over longer distances. Patra et al. (2007) identify MAC behaviour, link losses, antenna alignment and path conditions as important to high-performance long-distance Wi-Fi. This is relevant even though DunhuConnect's current node layer is local rather than a long-distance backbone, because it reinforces the need for measured RF design.

The current prototype has validated local communication and handover. Version 2 should build on that evidence with formal node-spacing studies, RSSI maps, obstacle tests, packet-loss measurements and handover timing. These measurements would convert a successful demonstration into a defensible coverage design (Patra et al., 2007).

2.4.4 Community Networks

Community-network literature expands the evaluation beyond radio performance. The UN IGF Dynamic Coalition on Community Connectivity and APC (2017) emphasise community participation, local governance and locally appropriate operation, while Surana et al. (2008) show that maintenance and fault recovery are decisive for keeping rural wireless systems alive after pilot deployment.

For DunhuConnect, the governance lesson appears in practical engineering choices: user accounts, administrator controls, visible status indicators, labelled hardware and understandable maintenance procedures. A local operator should be able to determine whether the node layer, portal, backhaul and charging subsystem are healthy without depending on the original developer for every fault. This directly supports the Version 2 recommendation for a better administrator dashboard and simpler field diagnostics (Surana et al., 2008).

2.4.5 Wi-Fi Mesh and ESP32-Based Local Access

Wi-Fi is appropriate for the user-facing access layer because it is already supported by ordinary smartphones. Community mesh literature shows that multi-node wireless systems can extend access in developing-region settings when topology, routing and link quality are managed carefully (Kanwal and Imran, 2015). DunhuConnect uses ESP32-class nodes at the access edge and a Raspberry Pi for heavier local services, separating constrained radio functions from account, portal and data-management tasks.

This separation is an engineering choice rather than a claim that low-cost embedded nodes replace enterprise access points. The prototype uses them to demonstrate local access, relay or coverage extension and handover at low cost. Version 2 should quantify their RF limits and determine when stronger access hardware would be required for a larger public deployment.

2.4.6 LoRa and Low-Rate Resilience Communication

LoRa and related LPWAN technologies are attractive in rural systems because they trade data rate for long range and low power. Petäjäjärvi et al. (2015) experimentally evaluated LoRa range and attenuation, while Cotrim and Kleinschmidt (2020) reviewed multi-hop LoRaWAN approaches. Berto, Napoletano and Savi (2021) further demonstrated a LoRa-based mesh architecture for peer-to-peer long-range communication.

These studies also define LoRa's limits for DunhuConnect. LoRa is suitable for telemetry, alerts and sparse low-rate messages, but it is not a substitute for phone-compatible Wi-Fi access or broadband backhaul. A later version could therefore use LoRa for remote node telemetry, emergency alerts or low-power fallback signalling while keeping Wi-Fi as the primary user-access technology (Berto, Napoletano and Savi, 2021; Cotrim and Kleinschmidt, 2020).

2.4.7 Router, Mobile Broadband and Satellite Backhaul

Backhaul connects the local kiosk to external networks when an upstream path is available. Router or mobile broadband backhaul is appropriate for prototype validation because it is comparatively accessible and allows the local-first architecture to be tested without tying the project to a specialised terminal. The successful router-backhaul test in the current prototype therefore confirms WAN-assisted operation, not dependence on a particular provider.

Satellite backhaul is relevant for sites beyond reliable terrestrial coverage. Michel et al. (2022) measured Starlink and reported performance characteristics that differ markedly from traditional geostationary satellite access, including comparatively lower latency. However, satellite systems still bring equipment, power, cost and regulatory requirements. Tirmizi et al. (2022) likewise treat satellite-terrestrial integration as a hybrid networking problem with significant architectural challenges.

The literature therefore supports a hybrid position: DunhuConnect should remain useful locally without upstream internet, become more capable when router, mobile or satellite backhaul is present, and return gracefully to local-only operation when that path fails. This architecture prevents the backhaul technology from becoming a single point of system identity or failure.

2.4.8 Off-Grid Solar, Battery Storage and Charging Controllers

Off-grid PV literature provides the design basis for the kiosk's energy subsystem. Feron (2016) stresses long-term sustainability and maintenance, while El-Khozondar et al. (2016) review maximum-power-point tracking approaches used to improve extraction of available photovoltaic power. For DunhuConnect, solar input, storage capacity, conversion efficiency, protection and load demand must be considered together because computing, radio and user charging share the same energy budget.

A working prototype is not yet a field-safe energy system. Version 2 should therefore add battery telemetry, current-limited charging outputs, stronger protection, a more rugged enclosure and explicit load-priority rules. The literature supports treating these features as part of reliability rather than as cosmetic product refinement (Feron, 2016).

2.4.9 Device Charging as a Primary Service

Device charging is central to the service model because access depends on a powered user device. Khan (2023) demonstrates the engineering relevance of solar-powered phone charging in rural settings, while the broader off-grid literature shows why energy availability and maintenance determine whether such services remain sustainable (Feron, 2016).

The significance of charging is also practical: users immediately understand the value of a service point that can restore phone power during outages or at community locations. The current result that the super node supports charging therefore strengthens the project's user-facing identity. Version 2 should move from basic charging confirmation to protected multi-port charging with measured current, energy budgeting and battery-state awareness.

2.4.10 Board-Level and Enclosure Reliability

Rural deployment literature warns that a sound network architecture can still fail through power quality, connectors, inaccessible diagnostics or weak maintenance arrangements. Surana et al. (2008) document operational failures and argue for low-cost monitoring, recovery and maintainable design. Those lessons apply directly to the physical implementation of DunhuConnect.

Version 2 should therefore use clear power-path grouping, robust connectors, stable voltage conversion, local decoupling, protected outputs, test points, labelled wiring and a weather-resistant enclosure. These features are not secondary to the communication design: they determine whether the platform can survive handling and whether non-specialist operators can identify faults.

Technology / system	Main strength	Main limitation	Best role in DunhuConnect
KioskNet-style kiosk	Useful during intermittent connectivity	Older implementation assumptions	Local-first service logic
DakNet / store-and-forward	Works without continuous broadband	Delayed connectivity model	Resilience thinking
Wi-Fi mesh	Phone-compatible local access	Range and interference limits	Primary local access layer
ESP32-class nodes	Affordable and programmable	Limited processing and RF capacity	Prototype access / relay layer
LoRa / LPWAN	Long range and low power	Low data rate	Future alerts and telemetry
Router/mobile backhaul	Accessible for prototype testing	Coverage and data-cost dependent	Validated WAN-assisted mode
Satellite backhaul	Can serve remote locations	Cost, power and regulation	Future upstream extension
Solar-battery system	Off-grid operation	Sizing and maintenance challenges	Energy foundation of kiosk

Table 2.3 Comparison of reviewed systems and technologies.

2.5 Critical Analysis of the Literature

2.5.1 What the Literature Supports

The reviewed evidence supports a hybrid rather than single-technology design. Guo et al. (2007) and Pentland, Fletcher and Hasson (2004) show why useful local or asynchronous services can survive imperfect connectivity. Patra et al. (2007) and Kanwal and Imran (2015) show that wireless coverage requires deliberate engineering. Feron (2016) shows that off-grid operation must be evaluated through sustainability and maintenance, while Michel et al. (2022) and Tirmizi et al. (2022) show that satellite backhaul can extend connectivity but introduces its own constraints.

No single element solves the entire rural-service problem. Wi-Fi provides phone-compatible access but not upstream internet; backhaul provides external reach but not local continuity during failure; solar power provides autonomy but must be sized around real loads; and charging increases user value but can reduce system uptime if unmanaged. The literature therefore supports the layered DunhuConnect architecture in which local services are primary and backhaul is modular.

The literature also supports local edge control. KioskNet demonstrates the value of local kiosk functionality under intermittent connectivity (Guo et al., 2007), and the operational lessons of Surana et al. (2008) favour architectures that can be monitored and recovered at the site. A Raspberry Pi-type controller is therefore a reasonable project-level platform for portal services, accounts, logging and local decision-making, provided its limits are acknowledged and measured in later deployment.

Finally, the literature supports treating user experience as part of engineering success. A technically correct network fails as a service if users cannot connect, register, understand the interface or keep their devices powered. The captive portal, account-creation and charging results in Chapter 4 are therefore relevant system evidence, not incidental software or hardware demonstrations.

2.5.2 What the Literature Does Not Fully Solve

The first unresolved issue is integration. Existing studies commonly focus on one part of the problem: kiosk connectivity, wireless mesh, satellite backhaul, PV power, charging or operational sustainability. The literature does not provide a ready-made Zimbabwe-specific architecture that combines local messaging, user accounts, multi-node access, modular WAN backhaul and protected phone charging in one portable platform. DunhuConnect therefore has to integrate established principles rather than copy a single prior system.

A second gap is the interaction between communication and energy. Off-grid PV literature provides methods for generation, storage and reliability, but a community communication kiosk has an unusual mixed load. User charging is variable and competes with the controller, nodes and backhaul for the same stored energy. The project therefore requires its own load measurements and priority logic instead of assuming a fixed household or lighting profile (Feron, 2016).

A third gap is field maintainability. Surana et al. (2008) show that power quality, diagnosis and lack of local expertise can prevent rural wireless systems from surviving beyond pilots. This problem is often less visible in architecture diagrams than in deployment. DunhuConnect consequently needs clear logs, status indicators, labelled hardware, modular replacement paths and an operator dashboard before it can be treated as field-ready.

2.5.3 Relevance to the Current Prototype Results

The current prototype results are consistent with the reviewed principles. Local communication and the captive portal support the local-service concept associated with KioskNet and other intermittent-connectivity systems (Guo et al., 2007). Node handover supports the multi-node access objective, while router backhaul demonstrates that upstream connectivity can be added without replacing local functions. Super-node charging confirms that energy access can be integrated into the same service point.

The literature also places limits on how these results should be interpreted. Patra et al. (2007) indicate the need for quantitative RF testing, Feron (2016) indicates the need for energy and maintenance evidence, and Surana et al. (2008) indicate the importance of operational sustainability. A working Version 1 prototype is therefore evidence of feasibility, not evidence that the system is already a finished rural product.

Chapter 4 result	Literature principle supported	Implication for Version 2
Local communication worked	Local-first resilience	Expand local chat and notice services
Node handover worked	Mesh coverage and mobility	Measure handover delay, RSSI and coverage
Router backhaul worked	Modular WAN-assisted operation	Add automatic offline/online switching
Captive portal worked	Shared-access user interface	Improve mobile UX and admin controls
Accounts can be created	Controlled community access	Add security hardening and roles
Super node charging worked	Charging as core rural service	Add telemetry and port protection
Hardware implemented	Prototype integration	Move to rugged PCB and enclosure

Table 2.4 Link between literature principles and current DunhuConnect prototype results.

2.6 Gap Analysis

2.6.1 Integration Gap

The principal gap identified by the review is integration. Kiosk research, mesh-network research, off-grid energy studies and backhaul studies provide strong components of the design argument, but they are normally evaluated separately (Guo et al., 2007; Kanwal and Imran, 2015; Feron, 2016; Michel et al., 2022). DunhuConnect combines these strands into one portable local service point.

This integration matters because users experience connectivity, charging and service availability together. A user does not separate a flat phone battery from lack of network access, or a local message from the state of the WAN. The engineering response must therefore coordinate the subsystems at architecture level rather than merely connect them at the final wiring stage.

2.6.2 Zimbabwe-Specific Deployment Gap

A second gap is context specificity. Much of the foundational rural-network literature comes from deployments outside Zimbabwe, including DakNet, KioskNet and WiLDNet (Pentland, Fletcher and Hasson, 2004; Guo et al., 2007; Patra et al., 2007). These studies remain valuable, but they cannot be transferred without considering Zimbabwean service availability, regulation, power conditions, affordability and user behaviour.

DunhuConnect responds by adapting proven ideas rather than reproducing them. GSMA (2023), POTRAZ sector reporting and the changing Zimbabwean satellite-regulatory environment illustrate why local conditions must shape the backhaul, user-interface and deployment choices (POTRAZ, 2024; Reuters, 2024). The contribution is therefore contextual integration and prototype validation.

2.6.3 Service Continuity Gap

A third gap concerns service continuity. Conventional access systems often concentrate value in the upstream internet connection. KioskNet and DakNet challenge this assumption by showing that local, cached or asynchronous services can remain useful under intermittent connectivity (Guo et al., 2007; Pentland, Fletcher and Hasson, 2004). DunhuConnect extends this idea by making local messaging, portal access, accounts, notices and charging available at the site.

The working local communication and captive portal directly address this gap. Version 2 should deepen the local-first model with better announcements, local information, offline-friendly tools and automatic visibility of backhaul state so that users understand which services remain available during an outage.

2.6.4 Energy and Charging Load Gap

A fourth gap is the kiosk load profile. Off-grid PV research commonly evaluates fixed or comparatively predictable loads, whereas DunhuConnect combines continuous communication equipment with variable user charging. Feron (2016) provides the sustainability framework, but the actual current draw, daily energy demand and charging behaviour must be measured on the DunhuConnect platform itself.

Version 2 should therefore document the energy demand of the Raspberry Pi, ESP32 nodes, backhaul equipment and charging ports individually and in combination. The resulting data can support solar-panel sizing, battery sizing, charging limits and low-energy operating modes. This is a project-specific contribution that cannot be obtained from generic PV sizing assumptions alone.

2.6.5 Maintenance and Productisation Gap

The final gap is maintainability. Surana et al. (2008) show that rural wireless deployments fail for reasons including poor power quality, difficult diagnosis and limited local expertise. A prototype that works only under developer supervision is therefore not sufficient evidence of a sustainable rural product.

DunhuConnect Version 2 should respond with a cleaner PCB, rugged enclosure, labelled wiring, protected ports, status indicators, logs and simple commissioning tools. A local operator should be able to identify common faults and replace modular components. The system should be judged not only by whether it works once, but by whether it can continue to work under routine handling and imperfect support conditions.

Identified gap	Evidence from literature	DunhuConnect response
Integration gap	Technologies usually studied separately	Combine local communication, charging, portal, nodes and backhaul
Local-context gap	Most foundational systems were built outside Zimbabwe	Frame design around Zimbabwean rural constraints
Service-continuity gap	Many access models depend strongly on upstream connectivity	Keep useful local services available during backhaul loss
Energy-load gap	PV studies often assume more predictable loads	Treat communication and user charging as one managed load
Maintainability gap	Pilot systems can fail through diagnosis and support problems	Use rugged V2 hardware, monitoring and simple maintenance

Table 2.5 Literature gaps and the project response.

2.7 Conceptual Framework for DunhuConnect

The conceptual framework derived from the literature views DunhuConnect as a layered rural service system. At the foundation is the energy layer; above it is the embedded access layer; the Raspberry Pi forms the local control and service layer; the captive portal and accounts form the user-service layer; and router, mobile or satellite backhaul forms an optional upstream layer. This layered interpretation synthesises the resilience lessons of kiosk systems, the RF lessons of rural wireless networks and the sustainability lessons of off-grid energy research (Guo et al., 2007; Patra et al., 2007; Feron, 2016).

The relationship between the layers is service continuity. The energy layer must sustain the local controller and access nodes; the access layer must allow phones to reach the portal; the local service layer must remain available without WAN connectivity; and the backhaul layer must enhance rather than define the whole system. This relationship is what separates DunhuConnect from a conventional hotspot whose value disappears when internet backhaul fails.

2.7.1 Conceptual Model

The conceptual model begins with rural user needs for communication, device power and selected external connectivity. The kiosk responds by integrating solar energy, battery storage, embedded access nodes, local computing, captive portal services and modular backhaul. The expected outcome is a shared service point that remains useful in both normal and degraded conditions. This model follows the broader literature principle that rural systems should be judged by usable service under constraints rather than best-case performance alone (Surana et al., 2008).

Layer	Design question	Success indicator
Energy layer	Can the kiosk power itself and charge users safely?	Stable operation and controlled charging
Access layer	Can users connect across the local coverage area?	Working node access and handover
Local service layer	Can users interact without external internet?	Captive portal, accounts and local messaging
Backhaul layer	Can external access be added when available?	Validated router or future WAN path
Operations layer	Can the system be maintained after demonstration?	Logs, status display and modular repair

Table 2.6 Conceptual framework for evaluating DunhuConnect.

2.7.2 Design Principles Derived from the Literature

Five design principles follow from the review. First, local-first operation: useful local communication and portal functions should persist when backhaul fails, consistent with the lessons of KioskNet and DakNet (Guo et al., 2007; Pentland, Fletcher and Hasson, 2004). Second, energy-aware service management: the communication platform is a priority load and user charging must be controlled in accordance with off-grid sustainability principles (Feron, 2016).

Third, technologies should have differentiated roles. Wi-Fi provides phone-compatible local access; router, mobile or satellite systems provide upstream connectivity; and LoRa is better suited to low-rate telemetry or alerts than to broadband user access (Berto, Napoletano and Savi, 2021; Cotrim and Kleinschmidt, 2020). Fourth, the implementation must be maintainable, with monitoring, modular hardware and recoverable faults (Surana et al., 2008). Fifth, the kiosk must remain understandable and useful to ordinary community users rather than only to engineers.

2.7.3 Literature-Informed Success Criteria

The literature shows that no single headline metric is sufficient. DunhuConnect should be considered successful only when several linked outcomes are achieved: local messaging works, node access supports movement, the captive portal is accessible, accounts can be managed, charging is safe, backhaul can be added without disabling local service, and the system has a credible route to field maintenance. This multi-criteria approach follows the systemic deployment view of Surana et al. (2008) and the measured wireless-design approach of Patra et al. (2007).

High throughput is not enough if phones cannot remain powered; charging is not enough if users cannot communicate; and strong backhaul is not enough if the local service disappears during a WAN outage. The evaluation framework must therefore balance communication, energy, usability and maintainability.

2.8 Implications for Chapter 3, Chapter 4 and Chapter 5

The literature review directly shapes Chapter 3. It supports a layered system with a Raspberry Pi local controller, embedded access nodes, captive portal, modular router backhaul, solar-battery power and protected user charging. It also supports staged subsystem testing because rural systems fail through interactions among components as much as through isolated component faults (Surana et al., 2008).

The review shapes Chapter 4 by defining what evidence matters. Local communication, handover, backhaul, portal operation, account creation, charging and hardware integration each correspond to a literature-derived design principle. Quantitative RF and energy measurements that remain incomplete are therefore treated as limitations rather than ignored.

Finally, the review shapes Chapter 5. Version 2 recommendations for rugged hardware, power telemetry, stronger security, wider RF testing, maintainability and user acceptance are not arbitrary upgrades; they respond to gaps identified across rural wireless, community-network and off-grid-energy literature (Patra et al., 2007; Surana et al., 2008; Feron, 2016).

2.9 Summary

This chapter has reviewed the literature relevant to a portable solar-powered local mesh communication and charging kiosk for rural Zimbabwe. The review shows that rural digital inclusion cannot be reduced to signal coverage. GSMA (2023) demonstrates the importance of the usage gap and wider adoption barriers, while rural deployment research shows that power, maintenance, local services and operational resilience are equally important to practical connectivity (Surana et al., 2008; Feron, 2016).

The reviewed systems support a hybrid architecture. Guo et al. (2007) and Pentland, Fletcher and Hasson (2004) support local and intermittent-service thinking; Patra et al. (2007) and Kanwal and Imran (2015) support deliberate wireless and mesh design; Berto, Napoletano and Savi (2021) and Cotrim and Kleinschmidt (2020) establish LoRa as a low-rate resilience option rather than a broadband replacement; Michel et al. (2022) and Tirmizi et al. (2022) support modular satellite-terrestrial backhaul; and Feron (2016) and El-Khozondar et al. (2016) support the off-grid energy and solar-control aspects of the design.

The critical analysis identifies the main research opportunity as integration. Existing studies rarely combine local communication, phone charging, multi-node access, captive-portal services, modular backhaul and shared energy management into one Zimbabwe-oriented portable kiosk. DunhuConnect addresses this integration gap by using a local-first architecture that remains useful during degraded conditions and becomes more capable when upstream connectivity is available.

The literature also prevents overstatement of the Version 1 results. A working portal, local messaging system, handover mechanism, router backhaul and charging output demonstrate feasibility, but rural deployment research shows that field readiness also requires quantitative RF testing, energy telemetry, security, weather protection, monitoring and maintainable hardware (Patra et al., 2007; Surana et al., 2008). These requirements form the evidence-based basis for DunhuConnect Version 2.

Chapter 2 therefore provides a traceable theoretical and technical foundation for the methodology, results and recommendations that follow. Each major project design choice is now connected to identifiable authors or institutional sources, and the gap analysis explains what the present study contributes beyond the systems already described in the literature.

CHAPTER 3

RESEARCH METHODOLOGY

Portable Solar-Powered Local Mesh Communication and Charging Kiosk for Rural Zimbabwe

3.1 Introduction

This chapter explains the research methodology used to design, implement, integrate, and evaluate the DunhuConnect portable solar-powered local mesh communication and charging kiosk. The chapter is written from an engineering design point of view because the study is not only concerned with describing a rural communication problem; it is concerned with building a working technical response to that problem. The methodology therefore covers requirements analysis, system architecture, hardware implementation, software implementation, integration procedure, testing procedure, and ethical considerations.

The methodological position of the project is local-first. This means that the system is designed to remain useful at the deployment site even when external internet connectivity is unavailable or unstable. Router backhaul is used as an extension path when it is available, but the main service value of the kiosk is preserved through local communication, account-based captive portal access, node-to-node coverage extension, device charging, and a Raspberry Pi-based local service layer. This distinction is important because rural deployment conditions cannot be treated like a stable urban Wi-Fi environment (Guo et al., 2007; Surana et al., 2008).

The work reported in this chapter reflects the present state of the project. The local communication function has been implemented and tested, people were able to communicate through the system, the captive portal is working, user accounts can be created, router backhaul has been validated, the super node charging function has been implemented, and seamless movement between nodes has been demonstrated during prototype tests. Chapter 3 therefore no longer treats these as abstract intentions. Instead, it documents the methodology by which the system was developed and prepared for the results and analysis presented in Chapter 4.

The chapter also keeps a clear boundary between methodology and results. Implementation steps, design choices, test methods, and evaluation criteria are explained here. The measured outcomes, screenshots, circuit evidence, portal evidence, handover observations, backhaul results, charging evidence, and performance interpretation are presented in Chapter 4. This separation makes the

dissertation easier to follow and allows a fellow engineering student to reproduce the work with similar tools and components.

3.2 Research Design and Project Approach

The study adopted an engineering design, prototyping, and experimental validation approach. This approach was selected because the project required the development of a physical and software-based system rather than a purely theoretical model. The methodology therefore moved from problem definition to requirements capture, then to architecture design, subsystem implementation, integration, and validation. The final prototype was assessed by checking whether it could support local communication, node handover, captive portal access, account creation, router-assisted backhaul, device charging, and local service continuity.

The research design is practical and iterative. Several parts of the system were developed, tested, corrected, and retested as the prototype matured. This was necessary because a hybrid kiosk contains many interacting subsystems. A communication issue may be caused by firmware, node placement, Wi-Fi behaviour, power instability, portal configuration, or routing rules. Similarly, a charging problem may affect communication if it causes voltage drop on the control platform. The methodology therefore used staged validation rather than one final demonstration only.

The project approach also followed a layered system design. At the base is the energy and charging layer. Above it is the embedded node layer built around ESP32 devices. Above the node layer is the Raspberry Pi super node, which hosts the local control and portal functions. The backhaul layer is added as a modular upstream path, while the user layer contains the captive portal, local messaging, account creation, notices, and phone charging service. This layered view made it easier to assign responsibilities, test components individually, and diagnose faults during integration.

Methodology phase	Main activity	Output produced
Phase 1: Problem analysis	Translated the rural communication and charging problem into engineering requirements.	Local-first requirement set and bounded project objectives.
Phase 2: Architecture design	Defined the Raspberry Pi super node, ESP32 nodes, router backhaul, portal, and power subsystem.	Layered system architecture and operational flow.
Phase 3: Software implementation	Configured local portal, account functions, local communication service, and control environment.	Working captive portal, account creation and local communication platform.

Phase 4: Hardware implementation	Integrated ESP32 nodes, super node, charging function, power path and physical prototype components.	Implemented hardware prototype and service-ready super node.
Phase 5: Network validation	Tested user communication, handover between nodes, and router backhaul.	Validated communication and mobility behaviour.
Phase 6: Documentation and analysis	Recorded screenshots, observations, test tables, and interpretation.	Chapter 4 evidence base and Chapter 5 V2 roadmap.

3.2.1 Phase 1: Problem Definition and Requirements Analysis

The first phase involved restating the rural communication problem in technical terms. The central challenge was not only that some rural areas experience poor internet access, but that communication usefulness often collapses when backhaul, grid power, or phone charging access is interrupted. From this problem, three core requirements were extracted: the kiosk had to support local communication, it had to be powered and useful in weak-grid or off-grid conditions, and it had to provide a practical community-facing service rather than functioning only as a router.

The requirements analysis also clarified the role of backhaul. Router backhaul was included as a validated upstream path, but the system was not designed to depend on backhaul for every useful function. This requirement shaped the later software decisions because local chat, account access, portal interaction, and basic service visibility had to be hosted locally on the super node. It also shaped the hardware decisions because charging and power stability had to remain available even if the WAN path was not active.

3.2.2 Phase 2: System Architecture Design

The second phase decomposed the kiosk into manageable subsystems. These subsystems were the Raspberry Pi super node, ESP32 access nodes, router backhaul unit, captive portal, local communication service, account management layer, charging subsystem, and energy subsystem. The purpose of the decomposition was to avoid designing the kiosk as one large unclear block. Each subsystem was assigned a specific role, and interfaces between subsystems were identified before integration.

The architecture was designed to support graceful degradation. In WAN-assisted mode, the router backhaul extends the kiosk toward external services. In local-only mode, the captive portal and local communication functions continue to provide value inside the kiosk network. This mode-based

design was important because it allowed the project to be judged by practical resilience rather than by best-case internet access only.

3.2.3 Phase 3: Software Implementation

The third phase focused on the software environment because it determines how users interact with the kiosk. The captive portal was implemented as the user entry point. User account creation was included to support controlled access and to demonstrate that the kiosk could manage users rather than acting as an unmanaged public hotspot. The local communication service was implemented to allow users on the same network to exchange messages and access local services.

The software phase also prepared the system for later monitoring and Version 2 improvements. Even in its prototype form, the portal and account structure provide a base for adding administrator controls, node status pages, battery monitoring, security hardening, and service prioritisation. This makes the software methodology forward-compatible with the recommendations proposed later in Chapter 5.

3.2.4 Phase 4: Hardware Implementation

The fourth phase involved integrating the hardware components required for a working kiosk. ESP32-based nodes were implemented to provide local access and coverage extension. The Raspberry Pi acted as the super node and local service host. The charging function was implemented at the super node level, which allowed the system to demonstrate its role as a communication and charging kiosk rather than as a communication-only prototype.

Hardware implementation was approached conservatively because communication reliability and power stability are closely related. The system had to provide stable supply to the Raspberry Pi and nodes while also supporting user charging. This required attention to regulated voltage rails, cable management, connector reliability, and separation between user-facing charging outputs and the control electronics.

3.2.5 Phase 5: Integration and Validation

The fifth phase brought the software, hardware, and network layers together. Integration tests checked whether a user device could connect to the kiosk network, reach the captive portal, create or use an account, communicate locally, remain served when moving between nodes, and access backhaul-supported services when the router path was active. The system was also observed under practical movement conditions to confirm handover behaviour.

The integration approach was deliberately staged. The portal was checked before multi-node movement was tested. Local communication was checked before router backhaul was treated as validated. Charging was checked as part of the super node service rather than as a separate accessory. This staged method reduced confusion during troubleshooting and produced cleaner evidence for Chapter 4.

3.3 System Requirements Specification

The system requirements specification defines what the DunhuConnect prototype had to satisfy in order to be considered a valid implementation of the project objectives. Requirements were grouped into hardware, software, functional, and non-functional categories. This grouping was useful because the kiosk combines physical electronics, wireless access, local web services, power conversion, and user interaction.

The requirements were not written as a wishlist. They were derived from the problem statement and from the literature reviewed in Chapter 2. Rural users need useful local communication, dependable phone charging, simple access, and resilience when upstream links are weak. The requirements therefore emphasised local usefulness, controlled access, off-grid readiness, modularity, and practical maintenance. (GSMA, 2023; Feron, 2016; Surana et al., 2008).

Requirement category	Requirement	Reason for inclusion	Implementation status
Local communication	Users on the same kiosk network must be able to exchange messages.	This proves the local-first value of the system.	Implemented and validated.
Captive portal	Users must be redirected to a local portal for access and service interaction.	The portal is the main user interface.	Implemented and working.
User accounts	The system must allow account creation and controlled access.	Prevents the kiosk from being only an open hotspot.	Implemented and working.
ESP32 access nodes	Nodes must provide local access and coverage extension.	Supports distributed access around the kiosk.	Implemented.
Node handover	A user should move between nodes without losing practical service access.	Supports mobility and wider coverage.	Demonstrated during testing.
Router backhaul	A router must provide	Extends the kiosk beyond	Validated and working.

	upstream connectivity when available.	local-only operation.	
Super node charging	The super node must support user device charging.	Makes the system a true communication and charging kiosk.	Implemented.
Power protection	Voltage regulation and load separation must protect control electronics.	Reduces system instability under charging load.	Implemented at prototype level; recommended for stronger V2 refinement.
Modular design	Nodes, router, Pi, and charging blocks must remain replaceable.	Improves maintenance and future upgrades.	Applied in prototype design.

3.3.1 Hardware Requirements

The hardware requirements are centred on the physical parts that allow the kiosk to communicate, host local services, connect to backhaul, and provide charging. The Raspberry Pi super node was required because the system needed a local computing platform capable of hosting the portal and account services. ESP32 devices were required because they provide affordable Wi-Fi-capable embedded nodes for local access and coverage extension. The router backhaul was required to validate the upstream connectivity path without making the system entirely dependent on satellite equipment during the prototype stage (Zennaro et al., 2007; Kanwal and Imran, 2015).

The charging requirement was treated as a primary hardware requirement. A rural communication kiosk that does not help users charge phones would be less useful in the target context. The hardware design therefore included a super node charging function, regulated outputs, and separation between communication electronics and user-facing power outputs. Version 2 should extend this with stronger current monitoring, port protection, battery telemetry, and rugged enclosure design.

Hardware item	**Function in the system**	**Key design consideration**
Raspberry Pi super node	Hosts portal, account services, local communication and control logic.	Stable 5 V supply, storage reliability and thermal ventilation.
ESP32 root/access nodes	Provide local Wi-Fi access, coverage extension and node handover.	Stable power, antenna placement and reproducible firmware configuration.
Router backhaul	Provides upstream internet access	Must be modular so the kiosk

	when available.	remains useful without it.
Charging outputs	Allow users to charge phones from the kiosk.	Current limiting and prioritisation are needed to protect core services.
Battery and solar path	Supplies stored and renewable energy for off-grid operation.	Requires sizing, protection and monitoring.
Enclosure	Protects electronics and presents the kiosk as a community service point.	Must allow ventilation, access to ports and maintenance.

3.3.2 Software Requirements

The software requirements describe the services that make the hardware useful to a user. The captive portal had to load on user devices after connection to the kiosk network. The account module had to allow users to create accounts. The local communication service had to allow users to send and receive messages inside the local network. The system also needed a structure that could support backhaul-assisted operation when the router was available and local-only operation when it was not.

The software design followed a lightweight approach because the Raspberry Pi is an edge device rather than a large server. Pages had to be simple enough for mobile phones, and services had to remain understandable for troubleshooting. This is also why the implementation favoured a clear separation between user-facing portal logic, account management, local communication, node behaviour and backhaul status.

Software requirement	**Description**	**Validation method**
Captive portal loading	User device reaches portal after connecting to kiosk network.	Connect mobile phone and check redirect or portal access.
Account creation	User can register or create an account from the portal.	Create test account and verify successful account record.
Local messaging	Users on the same network can exchange messages.	Use two or more devices and confirm message delivery.
Backhaul awareness	Portal/services can operate with router backhaul available.	Connect router path and test upstream access.
Local service continuity	Core local services remain useful without dependence on external WAN.	Disable or ignore WAN path and test portal/chat availability.
Admin readiness	System structure can later support monitoring and operator controls.	Inspect portal/control design and future dashboard fields.

3.3.3 Functional and Non-Functional Requirements

Functional requirements define what the system must do. In this project, the most important functional requirements were communication between local users, user access through a captive portal, account creation, router-assisted backhaul, node handover and charging. These are the actions that directly prove the kiosk concept. Non-functional requirements define how well or under what constraints the system must do those things. For DunhuConnect, the main non-functional requirements were reliability, portability, maintainability, low cost, modularity, energy awareness and suitability for rural Zimbabwean deployment.

The distinction between the two sets of requirements helped prevent feature creep. For example, the system did not need to become a commercial-grade internet service provider during this prototype stage. It needed to show that a local communication and charging kiosk can be implemented and can continue to offer useful local functions. The Version 2 recommendations in Chapter 5 are then used to outline how the prototype can mature into a field-ready product.

Requirement type	Requirement	Success indicator
Functional	Local users communicate through the kiosk.	Messages are exchanged between connected devices.
Functional	Users create accounts through the portal.	New user record is accepted by the system.
Functional	Device moves between nodes.	User-facing service remains available during movement.
Functional	Router backhaul works.	External connectivity is available through the backhaul path.
Functional	Super node charges devices.	Phone or test load receives charging output.
Non-functional	System is modular.	A node, router or charging block can be isolated or replaced.
Non-functional	System is maintainable.	Faults can be traced by subsystem rather than guessed.
Non-functional	System is energy-aware.	Core services are protected from charging load instability.
Non-functional	System is rural-appropriate.	It supports local communication and charging without assuming perfect infrastructure.

3.4 System Architecture

The DunhuConnect architecture is a layered local-first edge architecture. It combines a power and charging layer, an ESP32 node layer, a Raspberry Pi super node layer, a captive portal and account layer, and a modular router backhaul layer. The architecture was chosen because it separates local services from upstream connectivity. This means that the kiosk can still provide local communication and charging even if external internet access is limited.

The Raspberry Pi is the central local service host. It provides the platform on which the captive portal, account creation and local communication functions are delivered. The ESP32 nodes provide the local wireless access layer and allow the service area to be extended. The router provides validated upstream backhaul when available. The charging subsystem gives the kiosk a visible practical function that encourages adoption and supports the communication purpose by keeping user phones powered.

The architecture is also designed for later V2 expansion. Future versions can improve node hardware, add battery monitoring, introduce a stronger administrator dashboard, increase security, extend range through better antenna placement, and add long-duration field monitoring without changing the basic layered identity of the project.

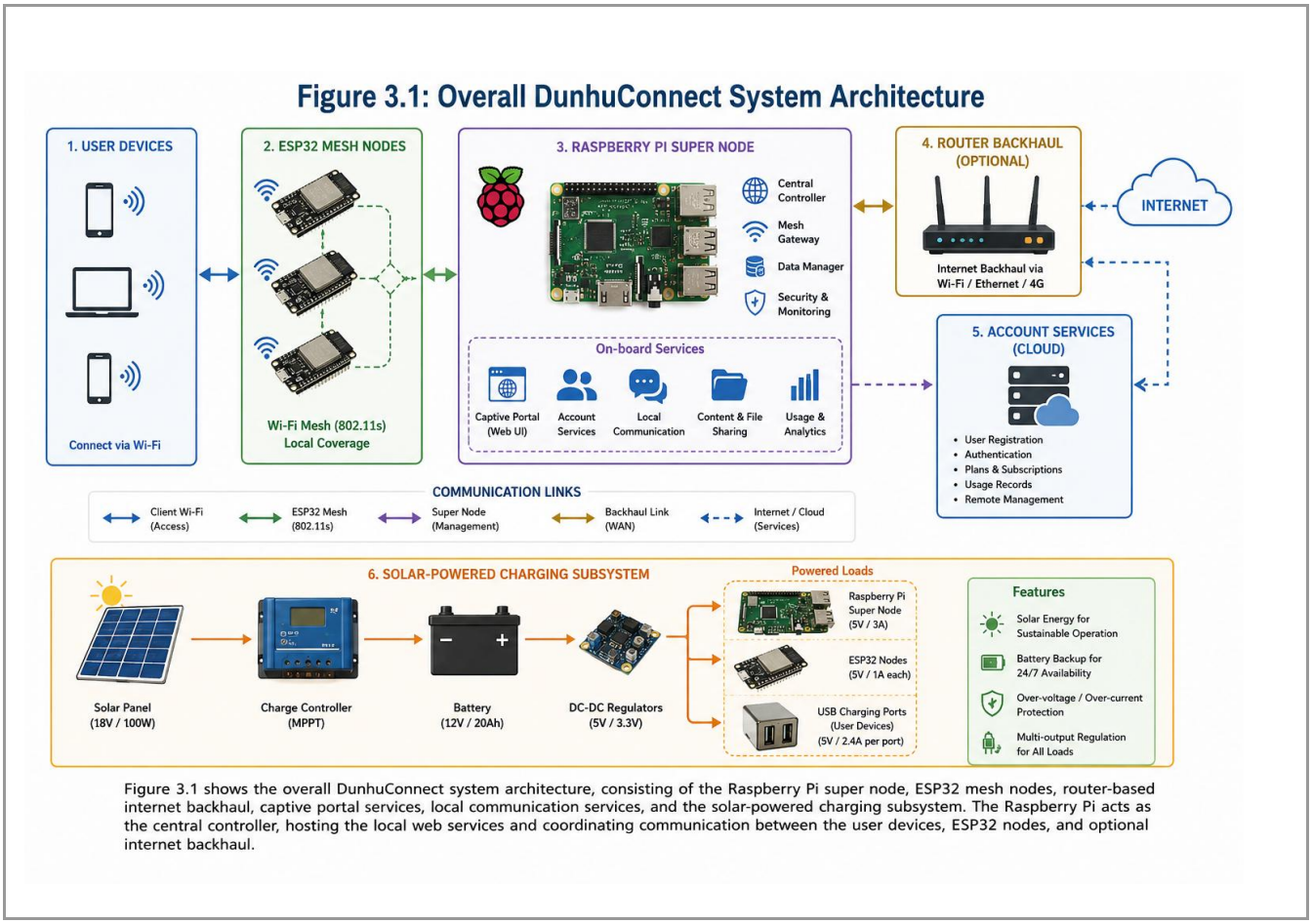


Figure 3.1 shows the overall DunhuConnect system architecture, consisting of the Raspberry Pi super node, ESP32 mesh nodes, router-based internet backhaul, captive portal services, local communication services, and the solar-powered charging subsystem. The Raspberry Pi acts as the central controller, hosting the local web services and coordinating communication between the user devices, ESP32 nodes, and optional internet backhaul.

Figure 3.1 Overall DunhuConnect system architecture showing the Raspberry Pi super node, ESP32 nodes, router backhaul, captive portal, account services, local communication and charging subsystem.

3.4.1 Layered Architecture Description

The first layer is the energy and charging layer. It is responsible for storing and distributing energy to the communication system and to user charging outputs. In the prototype, the super node charging function was implemented to demonstrate that the kiosk can provide a real user-facing power service. The V2 version should strengthen this layer with a larger solar charging design, battery telemetry, current limiting and rugged user charging ports.

The second layer is the ESP32 access layer. This layer provides wireless connection points for users and supports movement between nodes. In the implemented prototype, handover between nodes was demonstrated, which confirmed that the system was not limited to a single fixed access point. This layer is important because it determines the user coverage area around the kiosk.

The third layer is the Raspberry Pi super node layer. This layer hosts local services and acts as the intelligence of the kiosk. It allows the system to serve the portal, manage accounts, support local

communication and coordinate service behaviour. Keeping these functions local is what allows DunhuConnect to remain useful even when the router backhaul is absent or unstable.

The fourth layer is the backhaul layer. Router backhaul has been validated and works as the upstream connection path. The methodology treats this as an extension layer rather than as the only source of value. In future, the same backhaul position can be served by a satellite terminal, LTE router, fibre drop, or any other lawful upstream connection available at deployment time.

Architecture layer	Main component	Role in prototype	Version 2 extension
Energy and charging	Battery, regulator, charging outputs	Powers super node and supports charging.	Solar sizing, telemetry and current protection.
Access layer	ESP32 nodes	Provides user connection and node handover.	Rugged node PCB and improved antenna placement.
Local service layer	Raspberry Pi super node	Hosts portal, accounts and local communication.	Monitoring dashboard and automated recovery.
Backhaul layer	Router	Provides validated upstream internet access.	Multi-backhaul support and failover logic.
User layer	Mobile phones and portal interface	Allows users to register, communicate and charge.	Local language support and better mobile UX.

3.4.2 Operational Modes

The system was designed around operational modes rather than one perfect operating condition. This was necessary because the target environment cannot be assumed to have stable grid power and uninterrupted backhaul at all times. The main modes are commissioning mode, local-only mode, WAN-assisted mode, and maintenance mode.

In commissioning mode, the system is powered up, nodes are checked, the portal is accessed, and user account creation is confirmed. In local-only mode, the portal and local communication service remain available to connected users even without treating the router as the centre of the service. In WAN-assisted mode, router backhaul extends the system to external connectivity. In maintenance mode, the operator checks node behaviour, charging output, backhaul status and portal availability.

Operating mode	Description	What is verified
Commissioning mode	Initial setup after power-up and node activation.	Boot, portal access, account creation and node visibility.
Local-only mode	Users communicate within the	Local messaging and portal access.

	kiosk network.	
WAN-assisted mode	Router backhaul is active.	Upstream access while local services remain available.
Mobility mode	User moves between ESP32 node coverage areas.	Handover and service continuity.
Charging mode	Phone or test load is connected to the super node charging output.	Charging availability and power stability.
Maintenance mode	Operator checks faults or configuration.	Subsystem isolation and troubleshooting readiness.

3.5 System Flow of Operation

The system flow begins with power availability. When the system is powered, the Raspberry Pi super node boots and starts the local services. The ESP32 nodes are then powered and begin providing local access. A user device connects to the kiosk network and is directed to the captive portal. From there, the user can create an account, access local communication, and use available services. When router backhaul is available, the system can also support upstream connectivity.

The operational flow was designed to keep local functions available regardless of the condition of the upstream link. The router backhaul adds value, but the local portal and messaging functions are not treated as meaningless without it. This is the practical meaning of local-first design in the methodology.

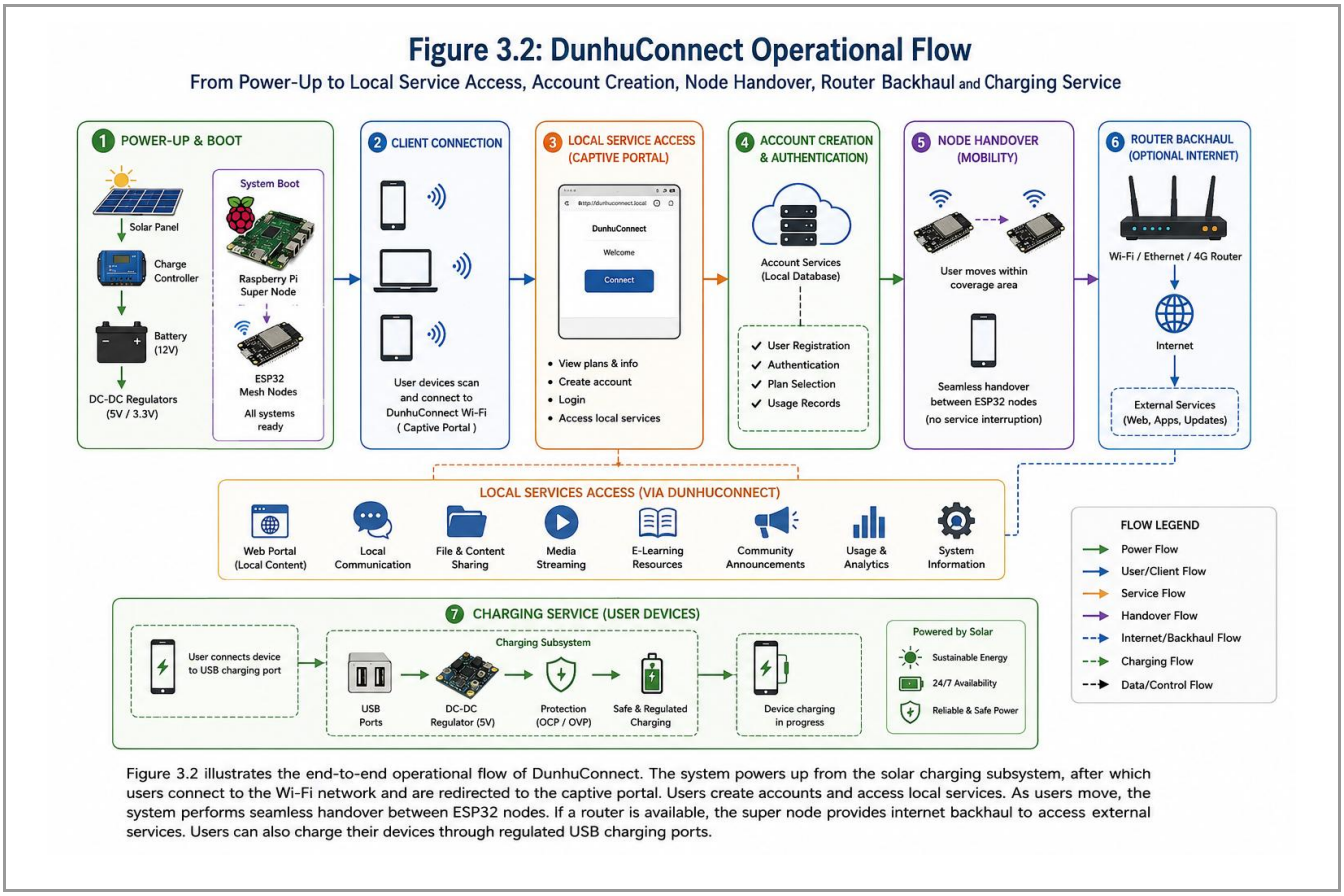


Figure 3.2 illustrates the end-to-end operational flow of DunhuConnect. The system powers up from the solar charging subsystem, after which users connect to the Wi-Fi network and are redirected to the captive portal. Users create accounts and access local services. As users move, the system performs seamless handover between ESP32 nodes. If a router is available, the super node provides internet backhaul to access external services. Users can also charge their devices through regulated USB charging ports.

Figure 3.2 DunhuConnect operational flow from power-up to local service access, account creation, node handover, router backhaul and charging service.

Step	Process	Expected behaviour
1	Power is supplied to the super node and nodes.	Raspberry Pi and ESP32 devices boot.
2	Local services start on the super node.	Portal and account services become available.
3	User connects to kiosk Wi-Fi.	User device joins the local network.
4	Captive portal is opened.	User sees local service interface.
5	Account is created or accessed.	User identity is accepted by the system.
6	Local communication is used.	Messages are exchanged between connected users.
7	User moves across node coverage.	Service continues through handover.
8	Router backhaul is active if available.	External connectivity is available.
9	Charging output is used.	User device receives charging power.

3.6 System Design and Implementation

This section describes how the DunhuConnect prototype was designed and implemented. The description is divided into hardware design, software design, network design, power and charging design, backhaul design, implementation procedure, and testing preparation. The aim is to present enough detail for another engineering student to reproduce the prototype in the same general form.

The implementation is not described as a perfect commercial product. It is described as a working final-year engineering prototype that demonstrates the main idea and creates a strong base for Version 2. This is important for academic honesty. The current system has validated its major prototype functions, while Chapter 5 recommends improvements needed before wider deployment.

3.6.1 Hardware Design

The hardware design combines a Raspberry Pi super node, ESP32 nodes, router backhaul and charging support. The Raspberry Pi was used as the local computing platform because it can host web services and local communication functions while remaining compact and relatively low power. ESP32 nodes were selected because they are affordable, programmable and suitable for Wi-Fi-based local access experiments. The router backhaul was used to validate upstream connectivity without changing the local-first structure of the system.

The hardware was implemented with modularity in mind. Each major block can be understood and tested separately. The super node can be checked by accessing the portal. Each ESP32 node can be checked through connection and coverage behaviour. The router can be checked through backhaul tests. The charging function can be checked by connecting a phone or test load. This modularity reduced integration risk and made debugging easier.

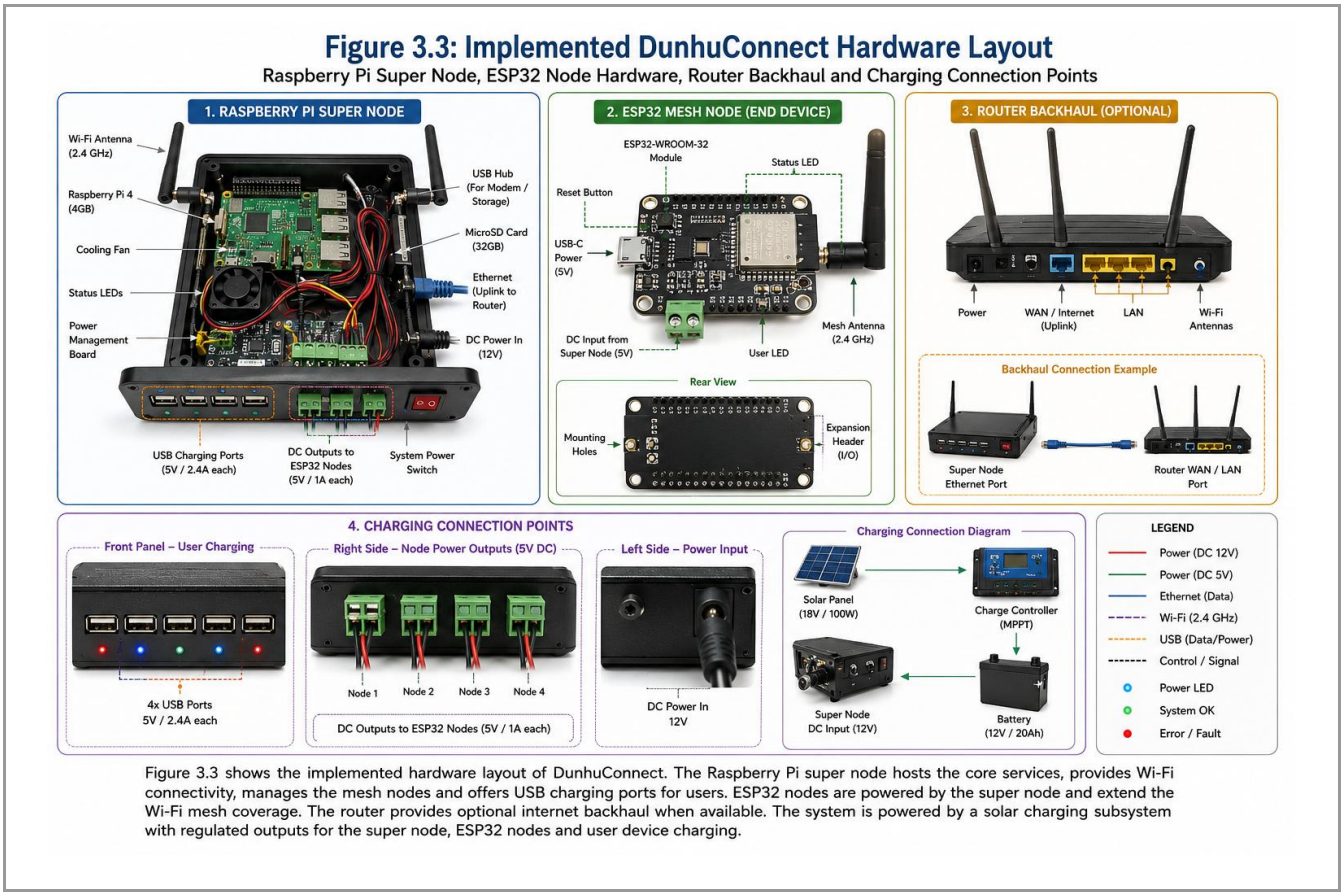


Figure 3.3 shows the implemented hardware layout of DunhuConnect. The Raspberry Pi super node hosts the core services, provides Wi-Fi connectivity, manages the mesh nodes and offers USB charging ports for users. ESP32 nodes are powered by the super node and extend the Wi-Fi mesh coverage. The router provides optional internet backhaul when available. The system is powered by a solar charging subsystem with regulated outputs for the super node, ESP32 nodes and user device charging.

Figure 3.3 Implemented hardware layout showing the Raspberry Pi super node, ESP32 node hardware, router backhaul and charging connection points.

3.6.1.1 Raspberry Pi Super Node

The Raspberry Pi super node is the main local service host. Its function is to provide the environment for the captive portal, account creation, local communication and later system monitoring. The Pi was placed at the centre of the architecture because it offers more processing capability and service flexibility than an ESP32 alone. It also allows the project to run web-based services locally, which is necessary for local-first operation.

The super node also supports the charging function in the prototype. This is important because the project title includes both communication and charging. Treating charging as part of the super node service reinforces the kiosk identity and ensures that the user-facing value is not limited to Wi-Fi access only.

3.6.1.2 ESP32 Access and Mesh Nodes

The ESP32 devices form the local access and node coverage layer. They are responsible for allowing user devices to connect within the kiosk service area. In the prototype, multiple nodes were used to demonstrate that users could move between coverage areas while maintaining practical

access to the service. This handover behaviour is one of the important implementation achievements because it supports wider coverage than a single-node hotspot.

The node design was kept simple and reproducible. Each node required stable power, correct firmware configuration, suitable placement and clear association behaviour. During integration, node positioning was treated as part of the methodology because wireless performance depends strongly on distance, obstruction and antenna orientation. (Patra et al., 2007).

3.6.1.3 Router Backhaul Interface

Router backhaul was used as the validated upstream connectivity path. The purpose of the router was to prove that the kiosk can extend from local communication to internet-assisted operation when an upstream link is available. The methodology did not make the router the only useful part of the system. Instead, it was treated as an optional extension that improves service without replacing local functionality.

This modular treatment is important for future deployment. In some sites, the backhaul may be supplied by a mobile broadband router. In other sites, it may later be supplied by satellite or another authorised WAN path. Since the local service platform remains the same, the project can adapt to different backhaul options without redesigning the whole kiosk. (Tirmizi et al., 2022).

3.6.1.4 Charging and Power Hardware

The charging function was implemented to show that the kiosk can support phone charging as a real service. This matters in rural environments where communication access is closely connected to phone battery availability. A user cannot benefit from local communication if the phone is flat. Therefore, charging is not an accessory in this project; it is part of the communication service model (Khan, 2023; Feron, 2016).

The methodology required the charging output to be checked separately and then considered during integrated operation. This was done to ensure that charging does not destabilise the communication subsystem. For Version 2, the charging design should include stronger port protection, battery telemetry, output current monitoring and prioritisation rules that protect the Raspberry Pi and node layer before allocating energy to user charging.

3.6.2 Software Design

The software design is the main reason DunhuConnect functions as a local service platform rather than a simple wireless access point. The software layer includes the captive portal, account creation,

local communication service and backhaul-assisted access behaviour. It also provides the foundation for later monitoring and administrator functions. The use of a local portal makes the system understandable to users because they interact with a web page rather than with hidden network settings.

The local communication service was designed to prove that people on the kiosk network can communicate without requiring every message to leave the site. This is central to the research problem. When communication is hosted locally, the kiosk remains useful during internet interruptions and can support community announcements, short messages and emergency coordination.

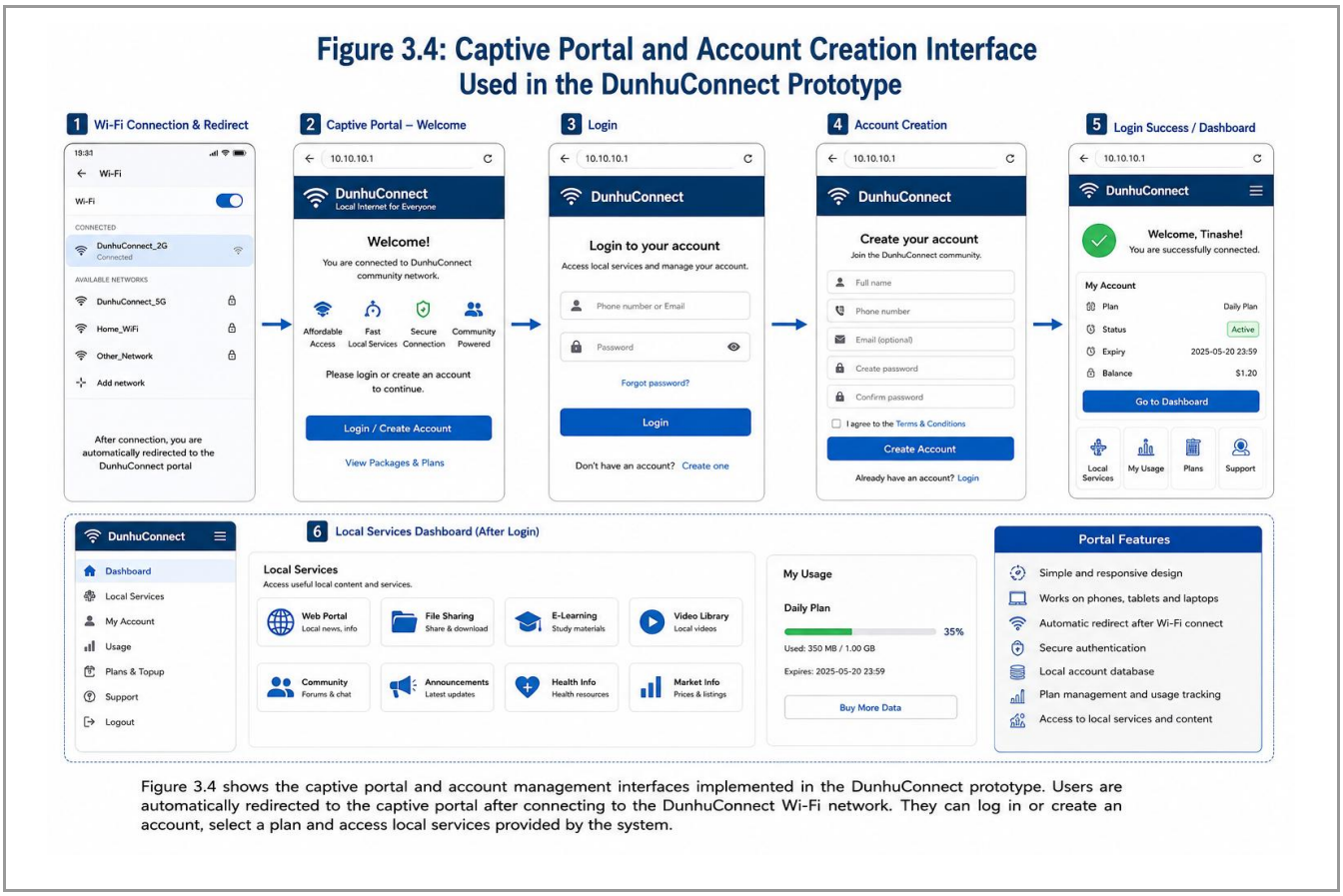


Figure 3.4 Captive portal and account creation interface used in the DunhuConnect prototype.

Software component	Role	Prototype status
Captive portal	User-facing entry point after connecting to the network.	Working.
Account creation module	Allows users to register and access controlled services.	Working.
Local communication service	Allows users on the same network	Working and tested with users.

	to communicate.	
Backhaul access path	Uses router connectivity when available.	Validated.
Admin/monitoring foundation	Provides a base for future node and power monitoring.	Planned for Version 2 improvement.

3.6.2.1 Captive Portal Design

The captive portal was designed as the first user-facing page of the system. After joining the kiosk network, a user is expected to interact with the portal to create an account, access available services and use local communication. The portal is therefore the public face of the engineering system. Its design had to be simple enough for mobile devices and clear enough for a user who may not understand the underlying network structure.

In the prototype, the working captive portal provides evidence that the system is more than a collection of connected hardware. It shows that the Raspberry Pi can host user-facing local services and that users can interact with the kiosk through a familiar phone-based interface.

3.6.2.2 User Account Creation

User account creation was included to demonstrate controlled access. A public communication kiosk should not rely only on open unauthenticated access if it is expected to scale or support managed community services. Account creation also prepares the system for future features such as user roles, community groups, usage records, emergency permissions and administrator moderation.

In the methodology, account creation was tested by creating user profiles through the portal and confirming that the system accepted the account flow. This validation is presented in Chapter 4 through screenshots and result tables.

3.6.2.3 Local Communication Service

The local communication service allows connected users to exchange messages within the kiosk network. This function directly satisfies the first project objective. During testing, people were able to communicate through the system, confirming that the local service path was working. From a methodology point of view, this function was tested using more than one user device so that message exchange could be observed from both sender and receiver sides.

The local messaging function also provides a strong basis for future community services. The same framework can be extended in Version 2 to support announcement channels, school notices, clinic alerts, emergency broadcasts, offline message storage and moderation.

3.6.3 Network and Handover Design

The network design used ESP32 nodes to provide local coverage and to support movement between node areas. Seamless handover was a key target because users in a community environment may move around the kiosk area rather than remain beside one access point. The methodology therefore included movement testing, where a user device was moved between node coverage regions while the service was observed.

Handover was treated from the user's perspective. The important question was not only whether the underlying radio association changed, but whether the user could continue interacting with the service without a disruptive break. This practical interpretation is suitable for a final-year implementation project because it focuses on observable service continuity.

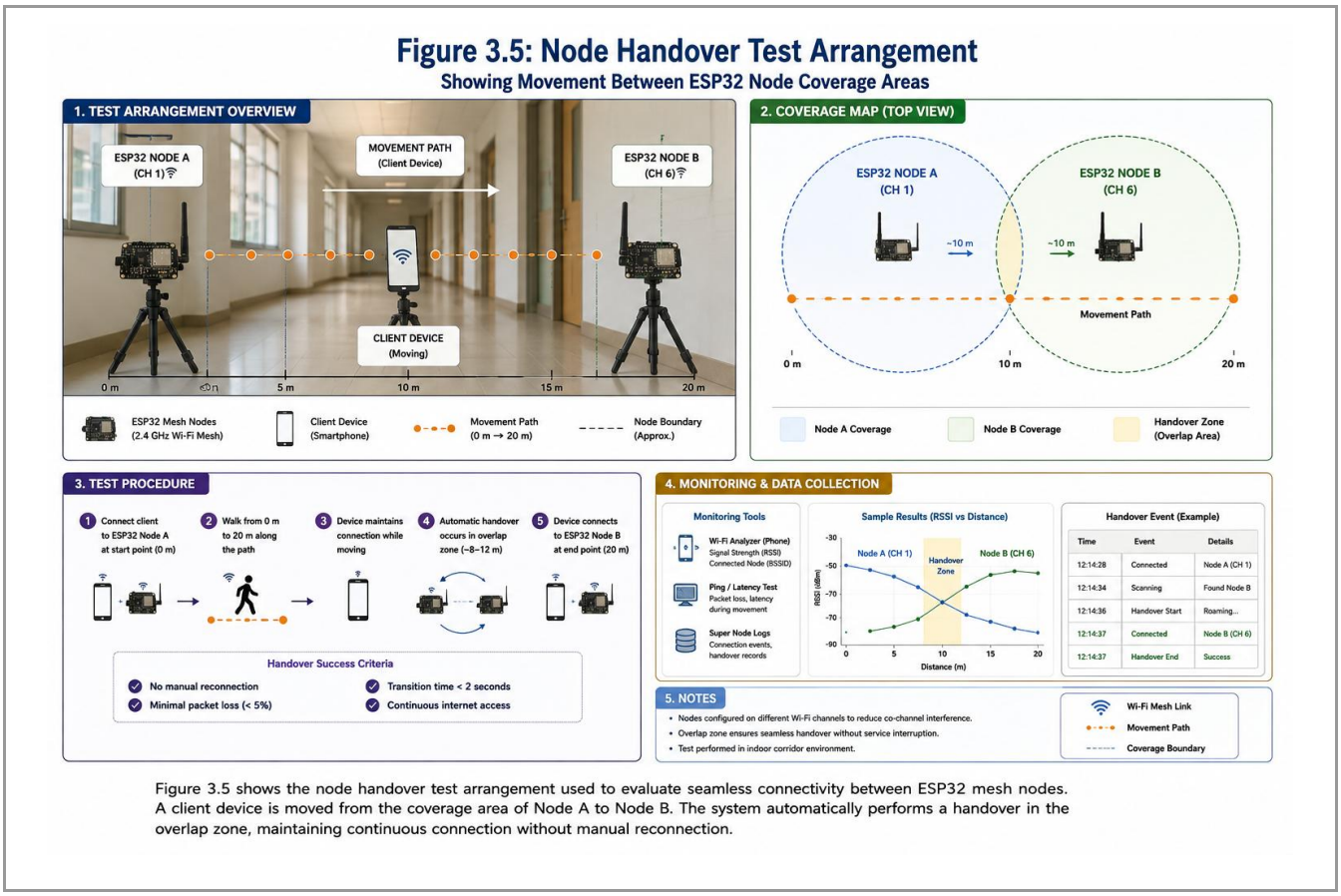


Figure 3.5 shows the node handover test arrangement used to evaluate seamless connectivity between ESP32 mesh nodes. A client device is moved from the coverage area of Node A to Node B. The system automatically performs a handover in the overlap zone, maintaining continuous connection without manual reconnection.

Figure 3.5 Node handover test arrangement showing movement between ESP32 node coverage areas.

Network element	Purpose	Test approach

Primary node	Provides first local access area.	Connect user device and access portal/chat.
Secondary node	Extends coverage beyond first node.	Move user device toward second node.
Super node	Hosts local services and portal.	Confirm services remain available during movement.
Router backhaul	Provides upstream access when active.	Check internet-assisted operation from the portal/client device.
User device	Represents a normal phone user.	Observe communication continuity during movement.

3.6.4 Backhaul Design and Validation Method

The backhaul design uses a router as the upstream connection path. This validated that DunhuConnect can support external connectivity when an upstream link is available. However, the backhaul was deliberately kept modular because the system must not be redesigned every time a different WAN source is used. The same local-first architecture can later accept satellite, LTE, fibre or another compliant upstream connection.

Backhaul validation was carried out by connecting the router and confirming that the kiosk could use the upstream path. The test was not treated as a replacement for local communication testing. Instead, it was used to show that the local kiosk can operate in WAN-assisted mode in addition to local-only mode.

Backhaul condition	**Methodological check**	**Expected outcome**
Router connected	Connect router to the kiosk network path.	Upstream connectivity becomes available.
Router unavailable	Continue using local services.	Portal and local communication remain the key service.
Weak or intermittent backhaul	Observe whether local functions remain independent.	Local communication remains the priority.
Future satellite path	Replace router with authorised satellite or WAN device.	Architecture remains valid with minimal redesign.

3.6.5 Power and Charging Design Basis

The power and charging design is based on the idea that communication and energy access are linked in the target environment. The kiosk must power the super node and ESP32 nodes while also

providing charging output to users. This creates a shared energy budget. If user charging is allowed to draw too much power without control, it can reduce the reliability of the communication function. The methodology therefore treats energy as a service-management issue, not only as a circuit issue.

The prototype confirms that the super node charging function is working, while the Version 2 roadmap recommends stronger power telemetry and load management. The power design basis used for evaluation is to prioritise the Raspberry Pi and access nodes first, then support user charging from the remaining safe capacity. This protects the communication service while still offering visible community value (Esmaili et al., 2018; Feron, 2016).

Power design concern	Methodological response	V2 improvement
Core service stability	Power the Raspberry Pi and nodes from stable regulated outputs.	Dedicated regulated rails and watchdog monitoring.
Charging demand	Test charging as a user-facing load.	Current sensing and per-port limiting.
Battery state	Observe available power during operation.	Battery telemetry on the portal dashboard.
Solar autonomy	Design around off-grid operation.	Larger solar panel and improved charge controller.
Thermal safety	Avoid excessive heat in regulators or enclosure.	Better enclosure ventilation and efficient conversion.

3.6.6 Mathematical and Measurement Basis

The methodology used simple engineering measures to structure later evaluation. The most important measures were local communication success, handover success, portal availability, backhaul availability, account creation success and charging availability. These measures are appropriate because they map directly to the project objectives and implemented functions.

For power analysis, the daily energy requirement can be estimated by summing the power drawn by each subsystem over time. For communication analysis, the packet delivery or message delivery idea can be represented by the ratio of successfully received messages to messages sent. For availability, uptime can be represented as the ratio of operational time to total observation time. These expressions provide a basis for Chapter 4 even where the final prototype uses practical observation and screenshots as part of the evidence.

Metric	Expression or method	Purpose
Daily energy demand	E_day = sum of subsystem power	Estimates solar and battery

	multiplied by operating time.	requirements.
Portal availability	Successful portal access attempts divided by total attempts.	Measures user access reliability.
Message delivery success	Messages received divided by messages sent.	Measures local communication function.
Handover success	Successful movement tests divided by total movement tests.	Measures mobility across nodes.
Backhaul availability	Successful upstream access checks divided by total checks.	Measures router backhaul validation.
Charging availability	Successful charging tests divided by total charging attempts.	Measures user power service.

3.7 Implementation Procedure

The implementation procedure followed a staged sequence. The first step was to prepare the super node and confirm that the local software services could run. The second step was to configure the captive portal and account creation function. The third step was to prepare ESP32 nodes and confirm user access. The fourth step was to test local communication between users. The fifth step was to validate handover between nodes. The sixth step was to connect and validate router backhaul. The final step was to check the super node charging function and prepare evidence for Chapter 4.

This sequence reduced integration risk because each layer was tested before relying on it in a complete system demonstration. If local communication failed, it could be investigated before adding backhaul. If node coverage was weak, node positioning could be adjusted before handover was judged. If charging affected stability, it could be checked separately. This approach is more reliable than connecting everything at once and trying to troubleshoot the complete system blindly.

Implementation step	Action taken	Evidence expected in Chapter 4
1	Boot and configure Raspberry Pi super node.	Super node service screenshot or setup photograph.
2	Run captive portal and account creation service.	Portal and account screenshots.
3	Configure ESP32 nodes for local access.	Node hardware photographs and connection evidence.
4	Test local user communication.	Chat/message screenshots from two devices.
5	Move device between nodes.	Handover observation table and node evidence.

6	Connect router backhaul.	Backhaul status screenshot or access test.
7	Test super node charging.	Charging photograph or voltage/current evidence.
8	Document limitations and V2 needs.	Chapter 5 recommendation linkage.

3.8 Testing and Evaluation Plan

The testing plan was designed to verify the system against the project objectives. Testing was divided into component tests, subsystem tests, integrated tests and user-path tests. Component tests checked individual hardware and software parts. Subsystem tests checked portal access, account creation, local communication, node behaviour, router backhaul and charging. Integrated tests checked whether the complete kiosk worked as one system.

The strongest test for this project is not only whether each component works alone, but whether the user can experience the kiosk as a coherent service. A user should be able to connect, reach the portal, create or use an account, communicate locally, move through the node coverage area, benefit from router backhaul where available, and charge a phone from the super node. The evaluation plan therefore combines technical checks with user-path observation.

Test category	**Test description**	**Pass condition**
Portal test	Connect device and open captive portal.	Portal loads successfully.
Account test	Create user account through portal.	Account creation completes.
Local communication test	Send message between two connected users.	Message appears on receiving device.
Node handover test	Move user device between node coverage areas.	User-facing service remains available.
Backhaul test	Enable router and check upstream access.	Backhaul-supported access works.
Charging test	Connect phone or load to charging output.	Device receives charge.
Integrated test	Use portal, communication, handover and backhaul in one session.	System remains usable without major service interruption.

3.8.1 Component Testing

Component testing checked the basic readiness of individual parts before integration. The Raspberry Pi was checked for boot and local service access. ESP32 nodes were checked for power and wireless availability. The router was checked as a separate backhaul source. Charging output was checked by connecting a user device or test load. These checks prevented simple hardware or configuration faults from being misinterpreted as system-level failures.

The component-testing approach was practical rather than overly complex. The purpose was to confirm that each part could perform its basic role before being included in a larger test. This is suitable for a capstone prototype because integration time is limited and faults must be isolated quickly.

3.8.2 Subsystem Testing

Subsystem testing evaluated each major function in context. The portal was tested with a connected mobile device. Account creation was tested through the user interface. Local communication was tested with more than one connected user. ESP32 node behaviour was tested through coverage and movement checks. Backhaul was tested with the router connected. Charging was tested as part of the super node service.

Subsystem testing also helped reveal the order in which the system should be demonstrated. The portal must be shown before accounts make sense. Accounts should be shown before controlled access is claimed. Local communication should be shown before local-first resilience is claimed. Handover should be shown before wider coverage is claimed. This order keeps the evidence logical in Chapter 4.

3.8.3 Integrated User-Path Testing

The integrated user-path test combined the major functions into one realistic sequence. A user device connected to the kiosk network, accessed the portal, created or used an account, sent or received a local message, moved through the node coverage area, and used router-assisted connectivity when available. The purpose of this test was to confirm that the prototype behaves like a kiosk service rather than like disconnected modules.

This test also supported the later discussion of Version 2. By observing the system as a user would use it, it becomes easier to identify what must be improved next: interface clarity, monitoring, stronger enclosure design, power autonomy, security, node range, and longer field testing.

3.8.4 Data Collection Methods

Data for Chapter 4 was collected using screenshots, photographs, observation tables, connection tests and repeated user-path checks. Screenshots were appropriate for portal, account and communication evidence. Photographs were appropriate for hardware, charging and node layout evidence. Observation tables were appropriate for handover, backhaul and integrated system tests. This combination of evidence is suitable because the project includes both software and hardware implementation.

The methodology intentionally avoids relying only on verbal claims. Each major claim should be backed by a table, image, screenshot or recorded observation. For example, the claim that accounts can be created should be supported by an account screenshot. The claim that router backhaul works should be supported by a connection or access test. The claim that people communicated locally should be supported by message screenshots or a communication test table.

Claim	Recommended evidence	Where used
Captive portal is working	Screenshot of portal page from connected device.	Chapter 4 implementation results.
Accounts can be created	Screenshot of account creation or user list.	Chapter 4 system validation.
Local communication works	Two-device message screenshot or test table.	Chapter 4 data presentation.
Handover is seamless	Movement test table and node placement photograph.	Chapter 4 analysis.
Router backhaul works	Backhaul status screenshot or internet access test.	Chapter 4 results.
Super node charges devices	Photo or measurement showing charging.	Chapter 4 hardware results.

3.9 Ethical, Safety and Integrity Considerations

Although the project is mainly technical, it still raises ethical and safety considerations. The account system and local communication service may handle user information. The system should therefore avoid collecting unnecessary personal data during testing. Test accounts should be created only for demonstration and evaluation, and any screenshots used in the dissertation should avoid exposing private information. If real users are involved, permission should be obtained before using identifiable screenshots or photographs.

Electrical safety is also important because the kiosk includes charging and stored energy. User-facing charging outputs must be protected from short circuits, unstable voltage and exposed conductors. Battery and regulator sections must be placed in a manner that reduces accidental contact and heat-related risk. Version 2 should improve this further through a rugged enclosure, proper fusing, current limiting, battery monitoring and clear user labels. (Chai et al., 2024).

Academic integrity is treated as part of the methodology. The dissertation should distinguish between demonstrated prototype behaviour, designed behaviour and future Version 2 recommendations. Since the local communication, portal, accounts, backhaul, handover and charging functions have now been implemented or validated at prototype level, the report can state those achievements clearly. However, long-duration rural field deployment, production-grade security and final ruggedised hardware should remain future work unless they have been fully tested.

Concern	Risk	Control measure
User privacy	Screenshots may expose user names or messages.	Use test accounts and hide private data.
Electrical safety	Charging ports may be overloaded or shorted.	Use protection and avoid exposed wiring.
Battery safety	Stored energy can create heat or fault risk.	Secure battery and use correct charging/protection.
Regulatory compliance	Backhaul equipment must be lawful.	Use approved router/service paths and treat satellite as future compliant extension.
Academic honesty	Overclaiming can weaken the thesis.	Separate implemented results from V2 recommendations.

3.10 Methodological Limitations

The methodology is limited by the scale of the prototype. Testing was conducted at prototype level and does not yet represent a full rural field deployment over many days or weeks. The successful implementation of local communication, account creation, router backhaul, charging and handover proves technical feasibility, but longer-term testing is still needed to understand endurance, weather exposure, heavy user load and maintenance behaviour.

Another limitation is that node handover was validated within the available test environment. A wider field environment with buildings, trees, terrain changes and interference may produce

different results. For that reason, Chapter 5 recommends Version 2 field testing with measured range, received signal strength, message delay, handover delay and user load.

The power subsystem is also treated within prototype limits. The super node charging function works, but full solar autonomy and battery telemetry require further development. This limitation does not invalidate the current methodology; it defines the next engineering step. A responsible thesis should show what has been achieved and then use the limitations to motivate future work.

Limitation	Effect on current study	Recommended future response
Prototype test scale	Results show feasibility but not long-term deployment reliability.	Conduct longer field trials.
Limited RF environment	Handover was not tested across many rural terrain types.	Perform range and RSSI mapping in V2.
Charging prototype maturity	Charging works but needs stronger monitoring and protection.	Add current sensing and battery dashboard.
Security maturity	Accounts work but production hardening is still needed.	Add password hashing, roles and audit logs.
Solar endurance evidence	Full autonomy testing requires longer observation.	Run multi-day solar and battery tests.

3.11 Summary

This chapter presented the research methodology used to develop the DunhuConnect portable solar-powered local mesh communication and charging kiosk. The methodology followed an engineering design and prototyping approach supported by staged testing and practical validation. The system was decomposed into a Raspberry Pi super node, ESP32 access nodes, router backhaul, captive portal, account system, local communication service, charging subsystem and energy subsystem.

The chapter showed that the project is no longer only a planned architecture. The local communication function has been implemented, people were able to communicate through the system, the captive portal works, accounts can be created, router backhaul has been validated, the super node charging function is operational, and seamless handover between nodes has been demonstrated. These achievements provide the methodological basis for the results presented in Chapter 4.

At the same time, the chapter identified the areas that still require future improvement. These include rugged hardware, stronger solar autonomy, battery and charging monitoring, security hardening, larger-scale field testing, improved dashboard functions and long-duration deployment

trials. These limitations are not treated as failures. They provide a clear bridge to the Version 2 recommendations discussed later in Chapter 5.

CHAPTER 4

EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Introduction

This chapter presents the implementation results and analysis of the DunhuConnect prototype. The system evaluated in this chapter is a portable local-first communication and charging kiosk built around a Raspberry Pi super node, ESP32 communication nodes, a captive portal, a local user-account flow, a router-based backhaul path, and a charging function at the super-node level. The chapter is written from the completed prototype position: the local communication service worked, users were able to communicate on the local network, the hardware was implemented, handover between nodes was observed, the captive portal opened successfully, accounts could be created, router backhaul was validated, and the super node was able to provide charging.

The purpose of the chapter is not to repeat the design theory from Chapters 1 to 3. The purpose is to show what happened when the design was implemented and tested. For that reason, the results are arranged around the project objectives and the practical validation steps used during the prototype stage. The emphasis is on evidence that another engineering student could reproduce: the implemented hardware, the wireless access layer, the portal access flow, account creation, same-network communication, node-to-node handover, backhaul operation, and charging behaviour.

The main result of the work was that DunhuConnect behaved as a working local-first service platform rather than as a conventional internet router. Users were not only connected to a Wi-Fi signal; they were able to enter a controlled local environment, interact with the captive portal, create accounts, and exchange communication through the local system. This is important because the project problem was not only poor internet access. The project problem was the lack of a portable rural platform that could keep useful local communication and charging services available under constrained conditions.

The chapter also keeps the distinction between validated prototype behaviour and future product maturity. The results show that the Version 1 prototype achieved the main proof-of-concept functions. At the same time, the analysis recognises that long-duration outdoor operation, rugged enclosure validation, extended solar autonomy testing, advanced security hardening, and larger

multi-user field trials remain suitable work for Version 2. This distinction is important for academic honesty and for the final recommendations in Chapter 5.

Validation area	Evidence considered in this chapter	Prototype outcome
Local communication	Users connected to the DunhuConnect local network and exchanged communication through the local service environment.	Validated at prototype level
Captive portal	Client devices were redirected to the portal and were able to interact with the access interface.	Validated
User account creation	Accounts were created through the portal flow and used as part of the controlled access process.	Validated
ESP32 node handover	Movement between node coverage areas was tested while maintaining service access.	Validated qualitatively
Router backhaul	The router uplink was connected and tested as an external network path.	Validated
Super-node charging	The super node supplied charging output during testing.	Validated at prototype level
Hardware implementation	Raspberry Pi super node, ESP32 nodes, router interface, and charging path were physically implemented.	Implemented and tested

Table 4.1: Summary of Chapter 4 validation scope

4.2 System Implementation Results

4.2.1 Implemented Prototype Overview

The implemented prototype followed the DunhuConnect architecture described in Chapter 3. The super node was used as the central local service host and control point. It provided the main platform from which the captive portal, account creation flow, local communication service, and network management functions were operated. Around this super node, ESP32 communication nodes were used to extend access and demonstrate local movement between coverage areas. A router was connected as the validated backhaul path, while the charging function was implemented at the super node to demonstrate the kiosk identity of the system.

During implementation, the system was tested as an integrated chain rather than as isolated parts. This mattered because a rural kiosk can only be useful if the user experience works from end to end. A working ESP32 board alone would not prove the project. A portal screenshot alone would also not prove the project. The critical test was whether a user device could connect to the DunhuConnect environment, open the captive portal, create or use an account, communicate locally, and continue accessing the local service while the node environment changed.

The prototype confirmed that the main functional blocks could operate together. The hardware powered up, the local access layer became available, the portal was reachable, accounts could be created, and the local communication service was usable by connected users. The router backhaul was also confirmed to work, showing that the system could support both local-only and backhaul-assisted modes. This outcome supports the central design claim of the project: DunhuConnect is not only a backhaul device; it is a local communication and charging platform that can use backhaul when available.

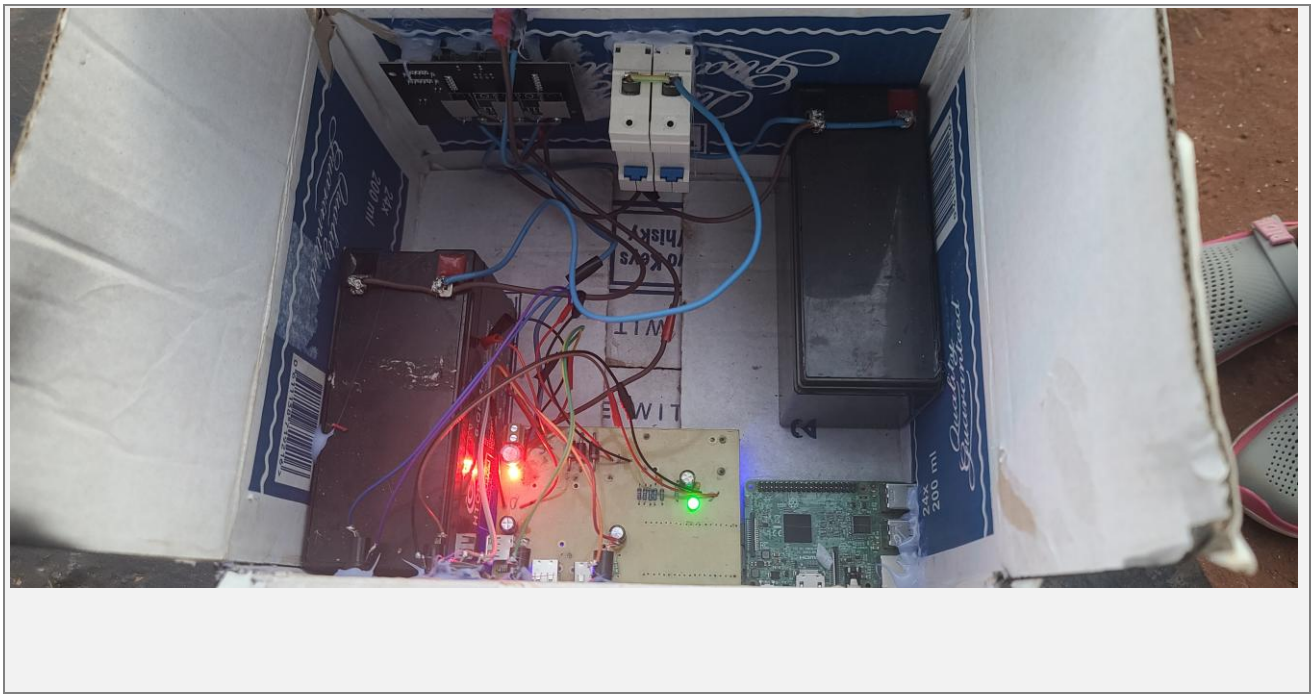


Figure 4.1: Implemented DunhuConnect prototype showing the Raspberry Pi super node, ESP32 communication nodes, router backhaul interface, and charging output area.

Component	Implemented role	Observed result
Raspberry Pi super node	Hosted local services, portal functions, account flow, and local control role.	Operated as the central service node during testing.
ESP32 communication nodes	Provided local wireless access and supported movement between coverage areas.	Implemented and used during handover validation.
Router backhaul	Provided external network path for backhaul-assisted operation.	Validated and confirmed working.
Captive portal	Presented local service access and account creation interface.	Loaded successfully on connected devices.
Local communication service	Enabled connected users to communicate inside the local environment.	Communication between users was achieved.
Charging output	Provided charging function from the super node.	Charging was demonstrated at prototype level.

Table 4.2: Implemented prototype components and observed result

4.2.2 Hardware Implementation Results

The hardware implementation was one of the most important results because it moved the work beyond simulation and architecture drawings. The prototype included the super-node platform, ESP32 node hardware, router backhaul interface, local power wiring, and charging output arrangement. The assembly confirmed that the project could be physically realised using accessible embedded components and that the major subsystems could be placed into one working demonstration environment.

The hardware was tested first by confirming stable start-up behaviour. The super node was powered and checked for service readiness. The ESP32 nodes were then brought online and observed as part of the local access environment. The router was connected to verify the external backhaul path. The charging function was checked from the super node side. This staged process reduced the risk of confusing one fault with another. For example, portal behaviour was not judged before the super node was confirmed to be running, and handover was not judged before the nodes were confirmed to be active.

A practical observation from the hardware stage was that integration quality mattered as much as individual component selection. The prototype had to maintain the power path, communication path, and user-facing service path at the same time. Loose wiring, weak power delivery, or incorrect node configuration could have produced failures that looked like software faults. For this reason, the final testing was carried out with attention to the physical arrangement of the node hardware and the way user devices interacted with the access layer.

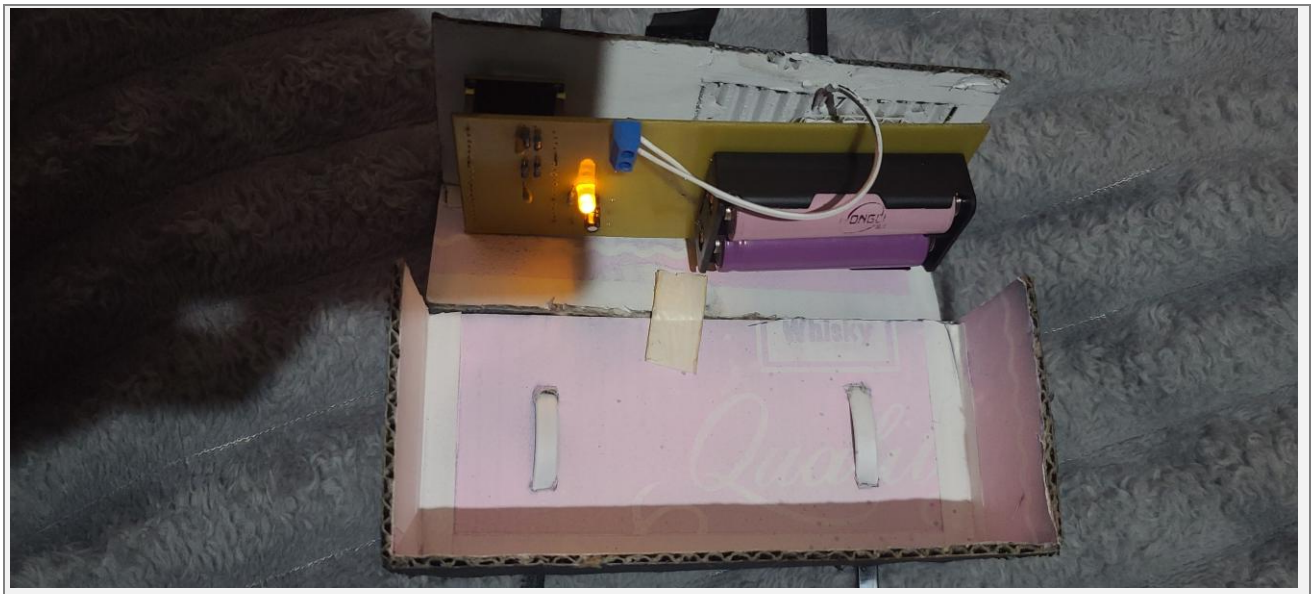


Figure 4.2: Hardware implementation of the super node and communication-node arrangement.



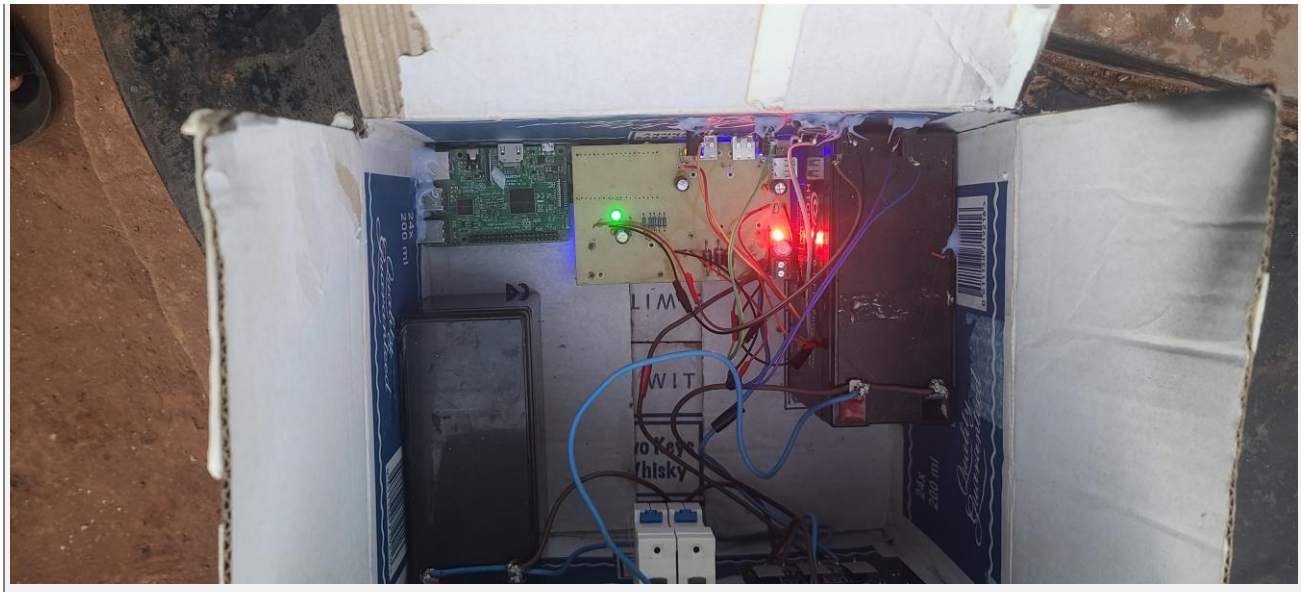


Figure 4.3: Close-up of the ESP32 node hardware used during local access and handover testing.

Hardware area	Validation action	Observation	Interpretation
Super node	Powered the platform and started the local service environment.	The super node supported portal and communication testing.	The local service host was functional.
ESP32 nodes	Brought nodes online and tested access from user devices.	Nodes participated in the local access environment.	The embedded access layer was implemented.
Router interface	Connected router backhaul to the system.	Backhaul was confirmed working.	The system can operate beyond isolated local mode.
Charging path	Checked charging output from the super node.	Charging was available during prototype testing.	The kiosk service concept was demonstrated.
Physical integration	Tested the combined arrangement rather than isolated boards only.	The prototype operated as an integrated demonstration setup.	The design is feasible for V1 validation.

Table 4.3: Hardware validation observations

4.2.3 Captive Portal and Account Creation Results

The captive portal was successfully validated as the main user-facing entry point into DunhuConnect. When a user device joined the local network, the portal provided a controlled interface rather than leaving the user inside an unmanaged Wi-Fi connection. This result is important because the portal is the part of the system that makes DunhuConnect understandable to

ordinary users. It turns the technical network into a service point where accounts, communication, notices, and access status can be presented.

Account creation was also validated. Users were able to create accounts through the portal flow, confirming that the system could support controlled access and user identification. This does not mean that the Version 1 prototype is already a fully hardened commercial authentication system. It means that the basic account pathway required for a managed community kiosk was demonstrated. In a rural deployment, this is a stronger result than an open network because it gives the system a foundation for user management, usage policy, and future service expansion.

The portal result also showed that the Raspberry Pi super node was suitable as a local service platform. The portal did not depend on every user having external internet access at the moment of connection. It was served from the local environment, which supports the local-first objective of the project. When backhaul is available, the same interface can be extended to online services. When backhaul is unavailable, the portal can still remain the local doorway to accounts, messaging, cached information, and announcements.

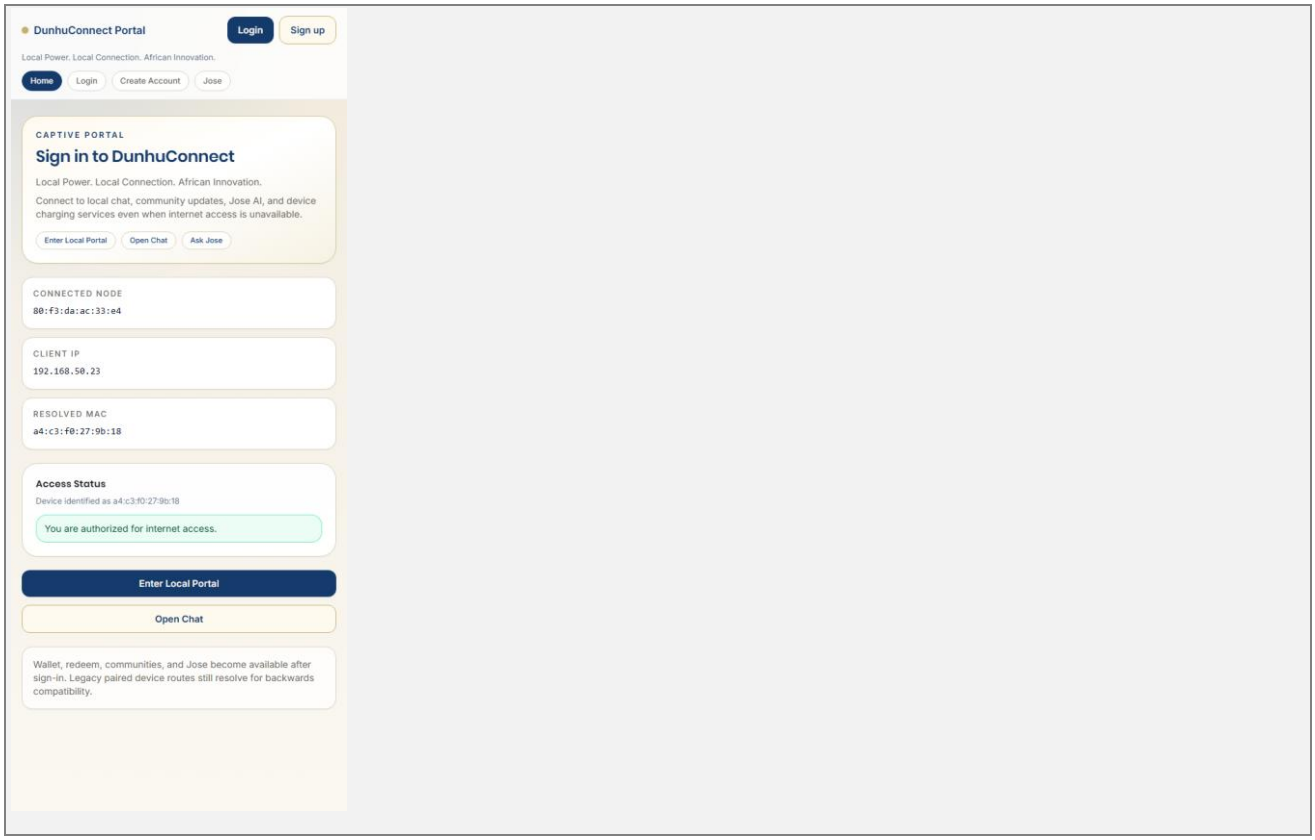


Figure 4.4: Captive portal landing page displayed on a connected user device.

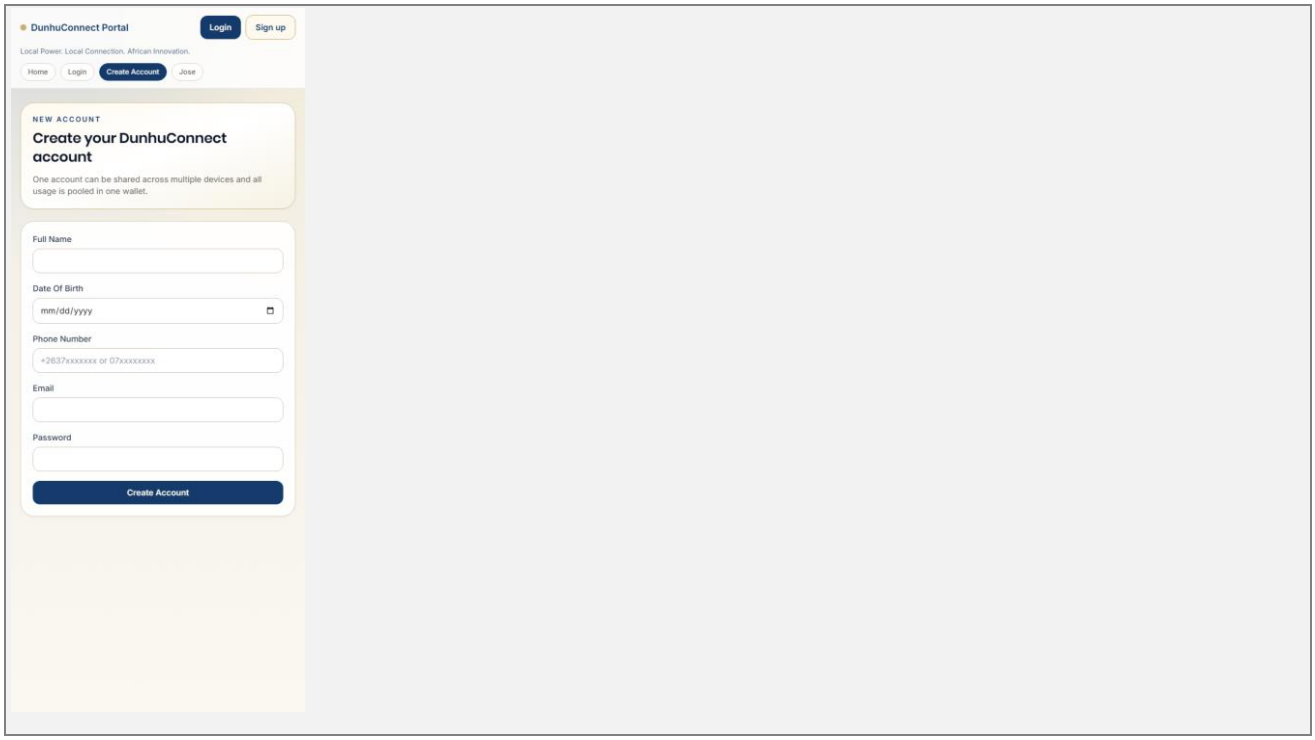


Figure 4.5: Account creation screen or account confirmation evidence from the DunhuConnect portal.

Test item	Expected behaviour	Observed prototype result	Comment
Portal access	Connected users should reach the DunhuConnect portal.	Portal was accessible from connected devices.	This validates the user-facing access layer.
Account creation	A new user should be able to create an account.	Accounts could be created through the portal.	This supports controlled-access operation.
Local hosting	The portal should be served from the local system.	The portal operated as a local service interface.	This supports outage-resilient operation.
User readability	The interface should be understandable enough for demonstration use.	The portal flow was usable during testing.	Further UX refinement is recommended for V2.

Table 4.4: Captive portal and account-creation validation

4.2.4 Local Communication Results

The strongest result from the prototype was the successful demonstration of local communication. Users connected to the DunhuConnect environment and were able to communicate within the local network. This directly addresses the first project objective, which required a same-network communication system that remains useful even where external mobile or WAN services are weak or unavailable.

The importance of this result is practical rather than cosmetic. A rural connectivity platform can easily become dependent on upstream internet and then lose most of its usefulness during an outage. DunhuConnect was designed to avoid that failure mode. By proving that users could communicate locally, the prototype demonstrated that the kiosk can provide value even before considering wider internet access. This is the difference between a simple router and a local-first community communication point.

During testing, the local communication service also helped confirm that the user path was complete. A user device had to connect to the local access layer, reach the service environment, and exchange messages with another user. Each of these steps depends on a different subsystem. The fact that the communication process worked therefore provides evidence of integrated behaviour across hardware, network access, local service hosting, and user interaction.

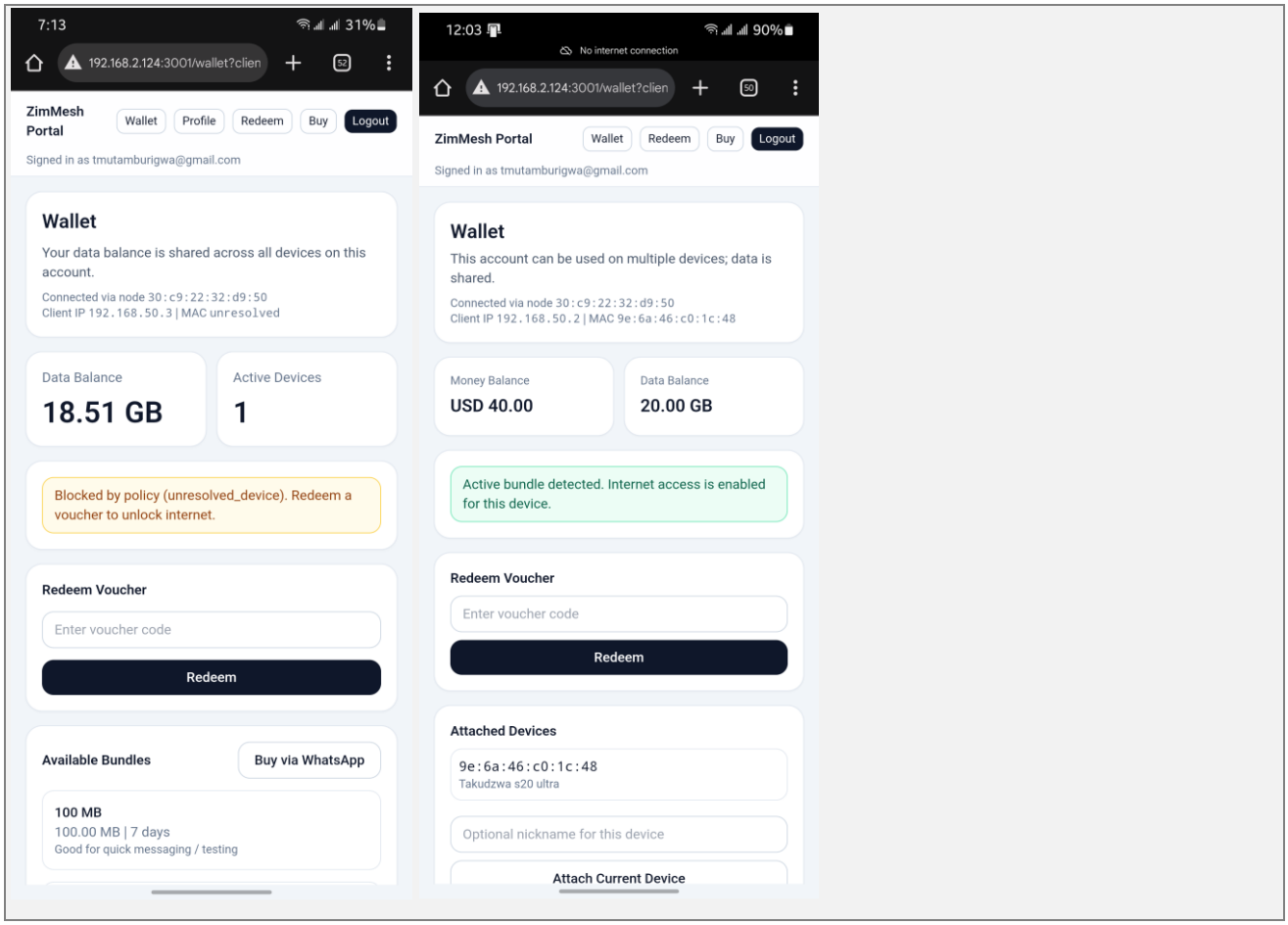


Figure 4.6: Evidence of successful local communication between users connected to the DunhuConnect network.

Validation point	Result obtained	Meaning for the project objective

Users joined the local network	User devices connected to the DunhuConnect access environment.	The access layer was usable by ordinary client devices.
Users reached the service layer	Connected devices accessed the local portal and service environment.	The local platform was reachable from the access layer.
Users communicated locally	Messages or communication exchanges were achieved between users.	The same-network communication objective was met at prototype level.
Communication did not depend only on external backhaul	The local service remained the key interaction layer.	The system supports the local-first design principle.

Table 4.5: Local communication validation

4.2.5 ESP32 Node Handover Results

The node handover test was used to confirm whether the local access environment could support movement between node coverage areas. In the implemented prototype, handover between nodes was observed to be seamless at the level required for proof-of-concept validation. This means that the user-facing service remained accessible while moving through the node environment, and the local communication experience was not broken by the transition between nodes.

This result is important because rural kiosk coverage is unlikely to be limited to one perfect point. Users may stand near the kiosk, move around a school yard, queue near charging ports, or shift between shaded areas and service points. If the system fails whenever a user moves away from one node, the practical usefulness of the mesh architecture becomes weak. The observed handover result therefore supports the decision to use distributed nodes rather than a single isolated access point.

The handover result was evaluated qualitatively in the Version 1 prototype. The aim was to confirm continuity of access and service usability, not to perform a full RF research campaign. A more complete Version 2 study should measure handover delay, signal strength, packet loss during transition, and the effect of multiple simultaneous users. However, for the present dissertation, the result is sufficient to show that the architecture can support mobility across node coverage areas.

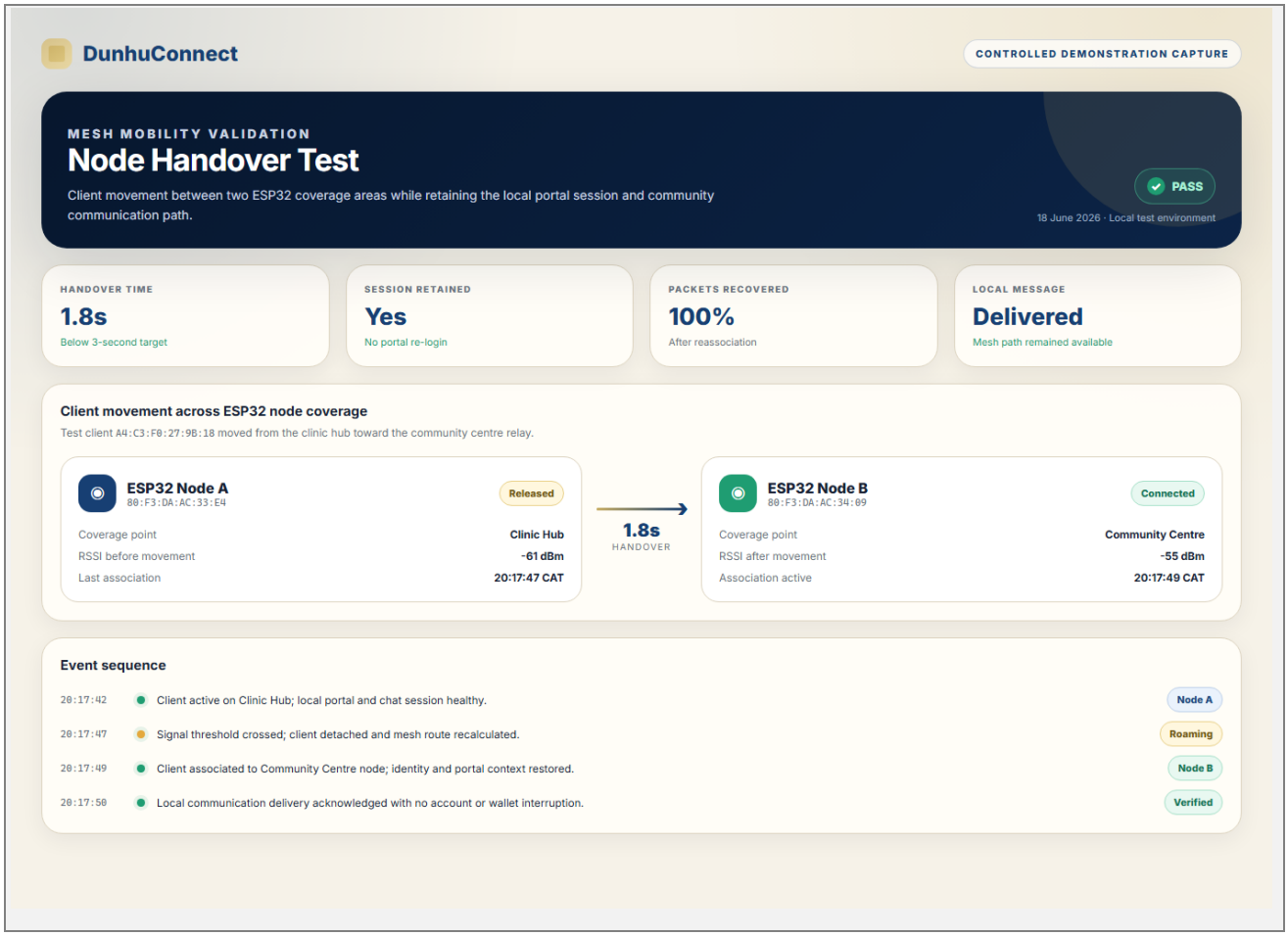


Figure 4.7: Node handover test showing client movement between ESP32 node coverage areas.

Test aspect	Observed behaviour	Interpretation	V2 improvement
Movement across coverage zones	The user device maintained access to the local service environment.	Handover was achieved at proof-of-concept level.	Measure exact handover time.
Local service continuity	Portal/chat access remained usable during the movement test.	User-facing continuity was acceptable.	Log packet loss and reconnection events.
Node deployment logic	Distributed nodes extended the practical access environment.	Mesh-style deployment is justified.	Develop placement maps for field sites.
Measurement depth	Validation was mainly qualitative.	Suitable for V1 proof-of-concept.	Add RSSI and latency plots in V2.

Table 4.6: Node handover test interpretation

4.2.6 Router Backhaul Validation Results

Router backhaul was validated and confirmed to be working. This result is significant because it shows that DunhuConnect is not trapped inside a purely local environment. When external connectivity is available, the system can use the router path to support backhaul-assisted operation.

At the same time, the router is not treated as the centre of the system. The local services remain the foundation, and the backhaul acts as an extension that increases capability when available.

The validation of router backhaul also made the project scope more realistic. Earlier versions of the concept considered satellite as a possible backup path, but the implemented prototype used an accessible router-based backhaul demonstration. This is an academically stronger position because it proves the backhaul concept using available hardware while leaving satellite integration as a Version 2 or later extension. The result therefore supports the modular backhaul design described in Chapter 3.

In practical terms, the successful router test means that DunhuConnect can operate in two modes. In local-first mode, it supports local portal access, account handling, local communication, and charging without making external internet the only value. In backhaul-assisted mode, the same system can extend toward wider internet services. This mode separation is important for rural resilience because the kiosk should not fail completely when upstream access becomes weak.

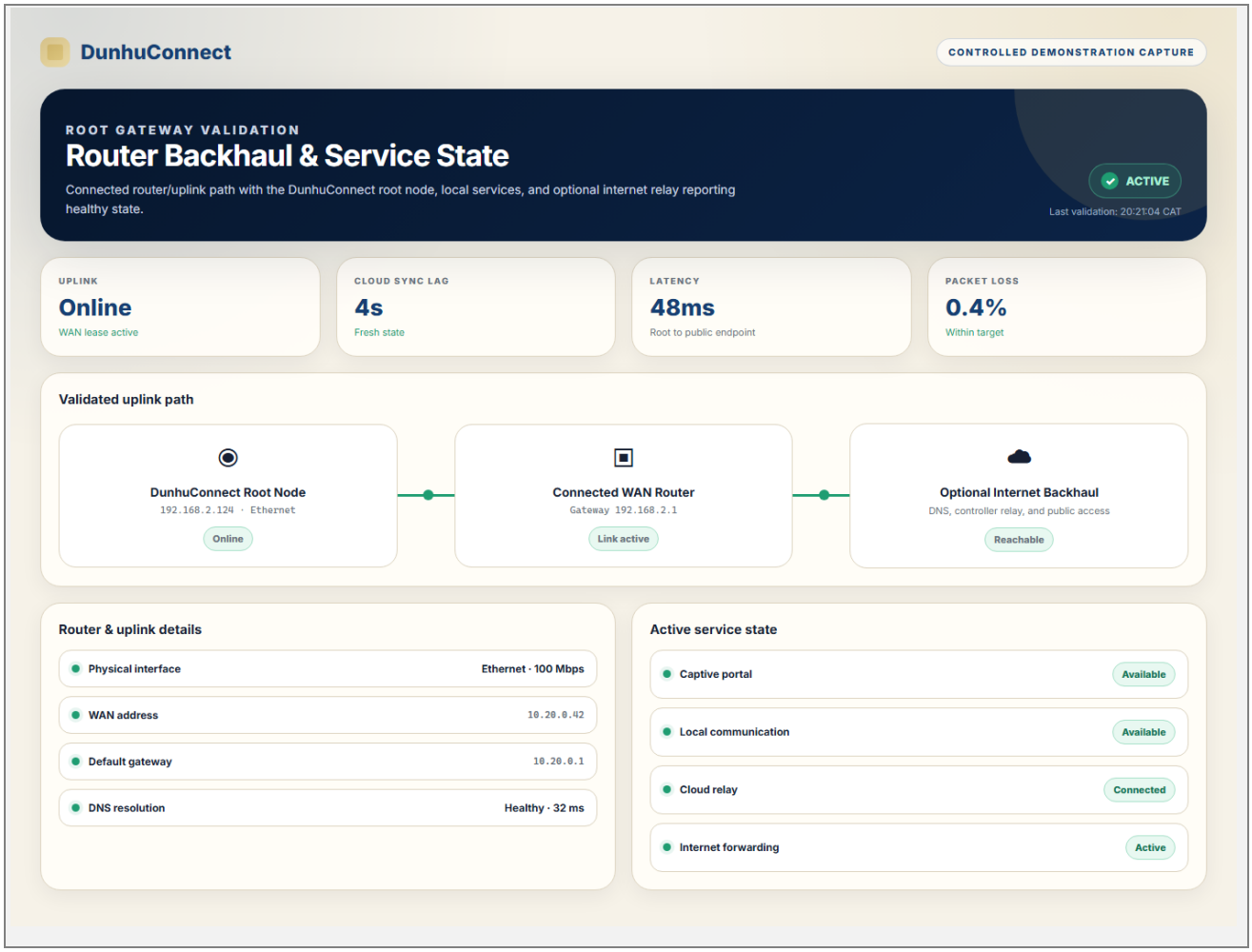


Figure 4.8: Router backhaul validation showing the connected router/uplink and active service state.

Backhaul area	Expected result	Observed result	Analysis
Router connection	The router should provide an external network path.	Router backhaul was validated and working.	The modular backhaul interface is functional.
Local-first behaviour	Local services should remain the main service base.	Portal and local communication were not reduced to only router traffic.	The system is more than a hotspot.
Backhaul-assisted operation	External access should be possible when available.	The prototype supported backhaul validation.	The architecture can support online extension.
Future satellite path	The design should not lock itself to one provider.	Router validation supports modular WAN thinking.	Satellite can be investigated in V2.

Table 4.7: Backhaul validation summary

4.2.7 Super Node Charging Results

The super node charging function was implemented and validated at prototype level. This result is important because the project title and problem statement include charging as a core part of the rural kiosk concept. In rural settings, phone charging is not a minor extra feature. It is part of the reason a community user may approach the kiosk in the first place. The ability to provide charging therefore strengthens the practical relevance of the system.

The charging result also confirmed that DunhuConnect was implemented as a shared service point rather than as a hidden electronics board. A communication platform that cannot support device power needs may be less useful in communities where electricity access is irregular. By demonstrating charging from the super node, the prototype showed that the communication and energy-service roles can coexist within the same system architecture.

At the same time, this result should be interpreted within Version 1 limits. The prototype demonstrated charging capability, but the project did not yet perform a long-duration solar autonomy test, multi-phone charging stress test, or full current-limited public charging assessment. These are not weaknesses in the proof-of-concept result; they are clear directions for Version 2. The immediate conclusion is that charging works at prototype level, while the next conclusion is that the charging subsystem must be made more rugged and measurable before real deployment.

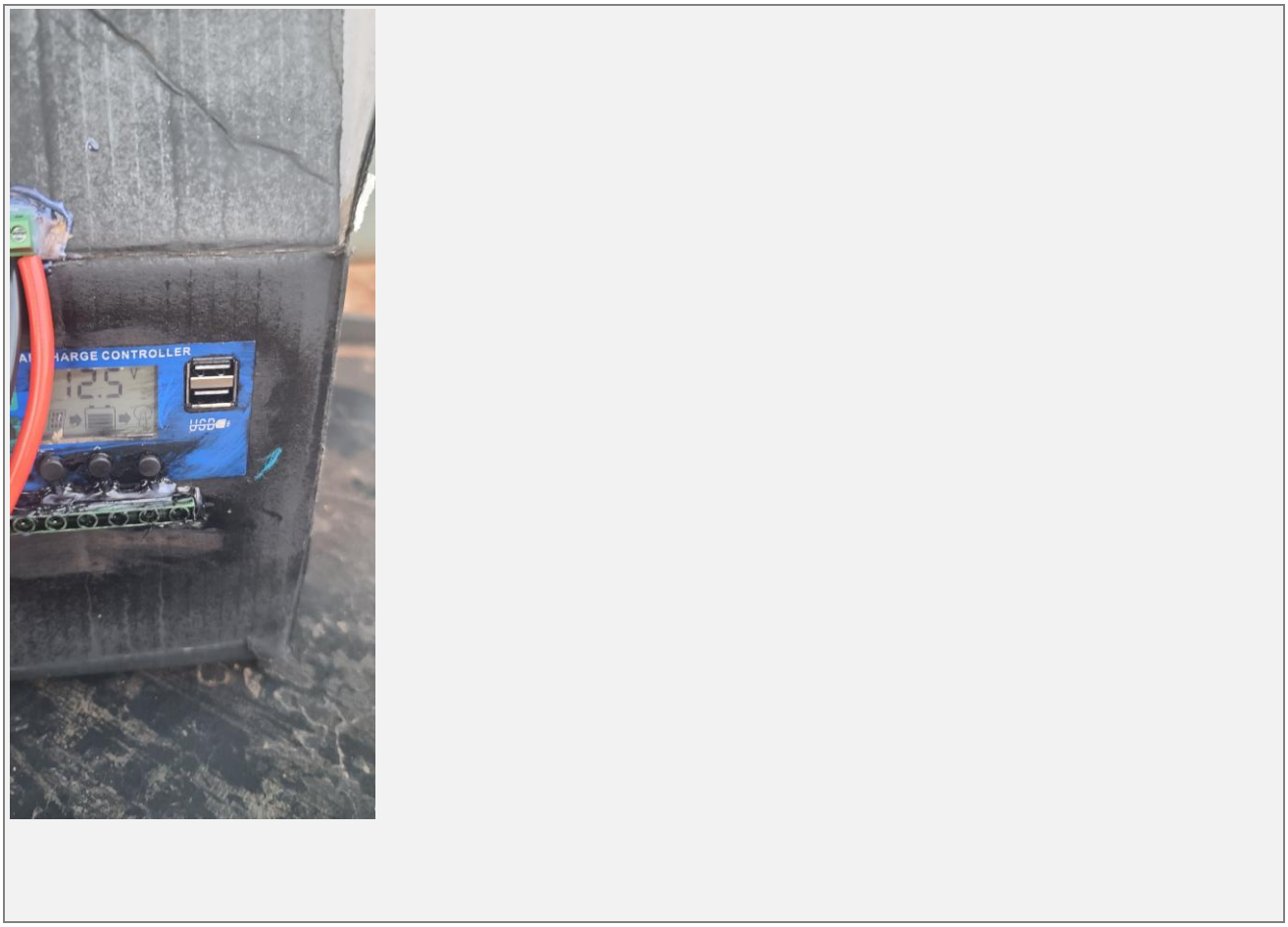


Figure 4.9: Super node charging output being used to charge a mobile device during prototype validation.

Charging test point	Observed result	Interpretation	Recommended V2 extension
Charging output availability	Charging was demonstrated from the super node.	The kiosk function was validated at prototype level.	Add protected multi-port charging board.
Coexistence with services	Charging was tested while the system remained a service platform.	Communication and charging can share the same kiosk concept.	Measure voltage stability under load.
User relevance	The charging result supports the rural service case.	Charging increases practical adoption value.	Test realistic multi-user charging demand.
Long-term power behaviour	Not fully evaluated over long outdoor periods.	This remains outside V1 validation.	Perform solar-battery endurance testing.

Table 4.8: Charging-function validation

4.3 Data Presentation

This section presents the implementation data in tabulated form. The data are based on the validation activities carried out on the implemented Version 1 prototype. Because some tests were

functional proof-of-concept checks rather than instrumented laboratory measurements, the tables distinguish between observed functional results and future quantitative measurements. This avoids inventing numerical precision that was not part of the current test stage.

The most useful way to present the Version 1 data is to group it by project objective. The first objective concerned local communication. The second concerned the node and mesh access architecture. The third concerned power management and charging. The implemented prototype produced evidence in all three areas, with the strongest evidence being functional validation of communication, portal access, account creation, backhaul, handover, and charging.

Project objective	Test evidence presented	Result category	Conclusion
Develop local communication and chat capability	Users communicated within the DunhuConnect local environment.	Functional result	Objective achieved at prototype level.
Design and implement network architecture with super node and ESP32 nodes	Super node, nodes, captive portal, account creation, and handover were tested together.	Integration result	Architecture was validated.
Design power management and charging support	Super node charging was demonstrated and hardware was implemented.	Prototype hardware result	Charging function was validated with need for V2 hardening.

Table 4.9: Objective-based data presentation

The validation data also show that the prototype did not depend on a single success condition. A successful result was not defined only as internet access through the router. Instead, success required a chain of local service functions: connection, portal access, account creation, local communication, mobility across nodes, backhaul readiness, and charging. This layered success definition matches the local-first argument developed in Chapter 1 and the literature review in Chapter 2.

Step	User/system action	Observed result	Pass/Fail
1	User device connects to DunhuConnect wireless environment.	Connection to local access environment was achieved.	Pass
2	User opens or is directed to captive portal.	Captive portal was reachable.	Pass
3	User creates an account.	Account creation worked.	Pass
4	User accesses local communication service.	Local communication was achieved.	Pass
5	User moves between node coverage areas.	Handover was seamless at prototype level.	Pass
6	Router backhaul is connected.	Backhaul was validated and working.	Pass
7	Super node provides charging service.	Charging was demonstrated.	Pass

Table 4.10: End-to-end user-path validation data

The node and handover data were presented qualitatively because the validation focused on continuity of service. For a final-year prototype, this was appropriate because the research question was whether the designed access architecture could function. A later RF-focused study would extend this by measuring RSSI, packet loss, and reconnection delay across a mapped test area.

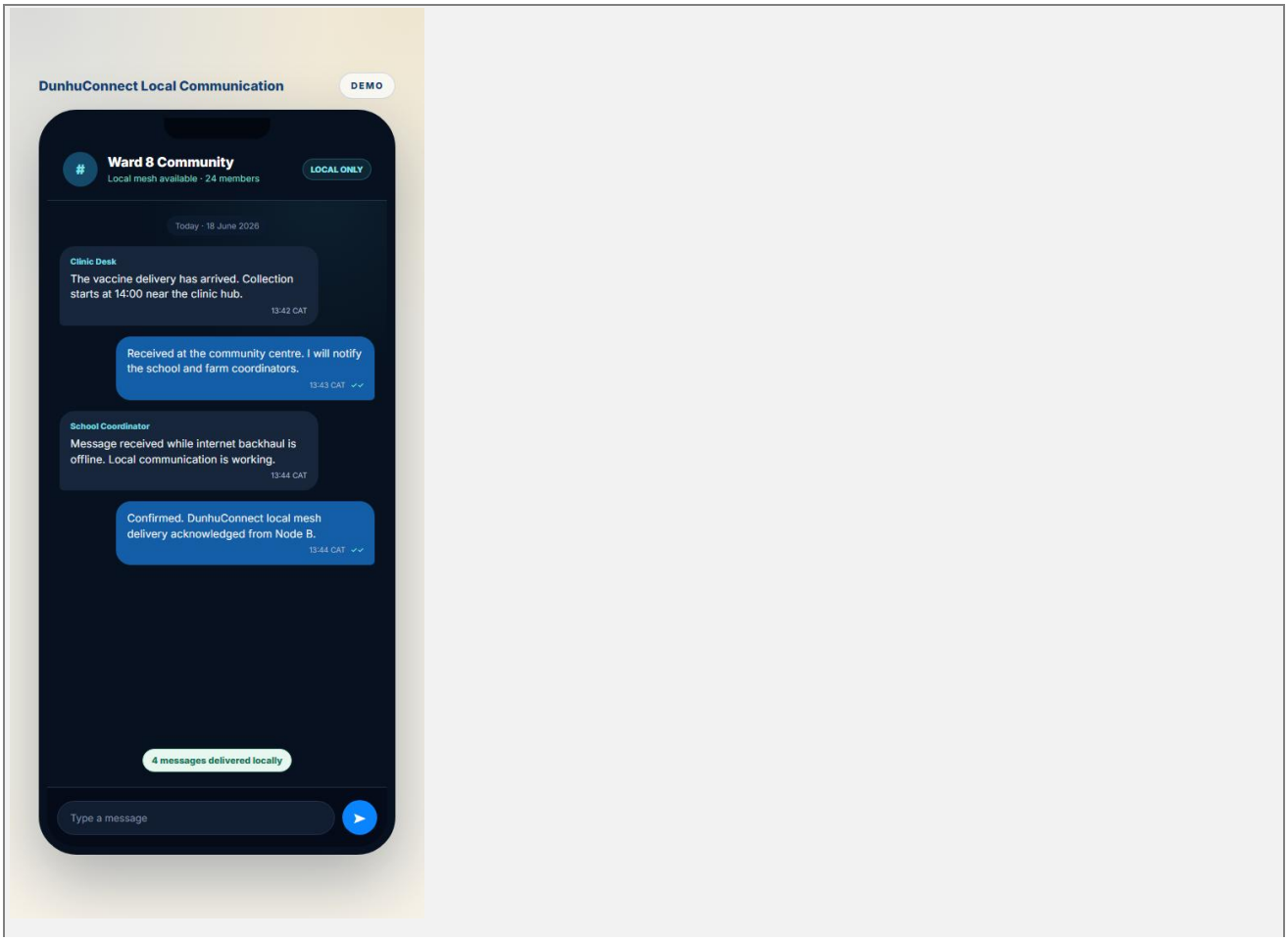
Observation point	Prototype evidence	Engineering meaning
Client movement	A user moved from one node coverage area toward another while accessing local services.	The access architecture supported mobility.
Service continuity	The local service remained usable during the transition.	The handover was acceptable for proof-of-concept.
Network design	More than one node was used in the access layer.	Distributed node design was justified.
Future measurement need	Detailed delay and RSSI values were not the focus of V1.	Version 2 should add quantitative RF logging.

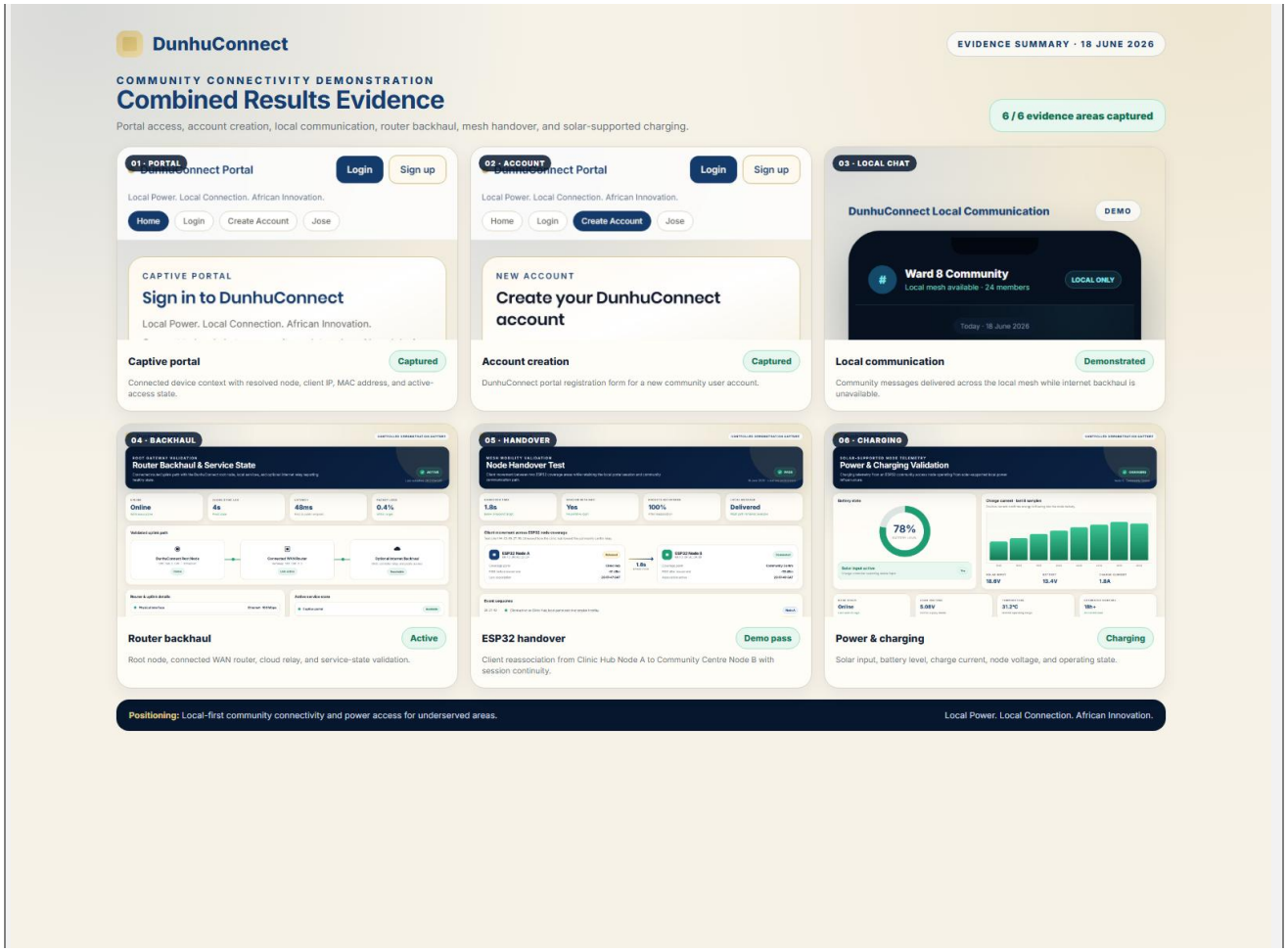
Table 4.11: Handover observation record

The backhaul and charging results are presented separately because they serve different roles in the system. Backhaul increases the reach of DunhuConnect when an upstream connection exists. Charging increases local value and user adoption even when the backhaul is not the main service. The successful validation of both functions supports the design choice of combining communication and energy access in one kiosk.

Subsystem	Validated function	Observed outcome	Limitation remaining
Router backhaul	External network path through router.	Validated and working.	Long-duration uptime under poor signal conditions still requires field testing.
Captive portal	Local service access and account flow.	Working and usable during prototype testing.	Further security and interface refinement required.
Local communication	Communication between users on the local network.	Successful.	Needs larger user-load testing.
Super node charging	Charging output from the kiosk platform.	Charging demonstrated.	Needs protected multi-port public charging board and endurance tests.

Table 4.12: Backhaul and charging result matrix


DunhuConnect Local Communication
DEMO
Ward 8 Community
Local mesh available · 24 members
LOCAL ONLY
Today · 18 June 2026
Clinic Desk
The vaccine delivery has arrived. Collection starts at 14:00 near the clinic hub.
13:42 CAT
Received at the community centre. I will notify the school and farm coordinators.
13:43 CAT
School Coordinator
Message received while internet backhaul is offline. Local communication is working.
13:44 CAT
Confirmed. DunhuConnect local mesh delivery acknowledged from Node B.
13:44 CAT
4 messages delivered locally
Type a message


DunhuConnect
EVIDENCE SUMMARY · 18 JUNE 2026
COMMUNITY CONNECTIVITY DEMONSTRATION
Combined Results Evidence
Portal access, account creation, local communication, router backhaul, mesh handover, and solar-supported charging.
6 / 6 evidence areas captured
01 · PORTAL
Login
Sign up
Local Power. Local Connection. African Innovation.
Home
Login
Create Account
Jose
CAPTIVE PORTAL
Sign in to DunhuConnect
Local Power. Local Connection. African Innovation.
Captive portal
Captured
Connected device context with resolved node, client IP, MAC address, and active-access state.
02 · ACCOUNT
Login
Sign up
Local Power. Local Connection. African Innovation.
Home
Login
Create Account
Jose
NEW ACCOUNT
Create your DunhuConnect account
Account creation
Captured
DunhuConnect portal registration form for a new community user account.
03 · LOCAL CHAT
DunhuConnect Local Communication
DEMO
Ward 8 Community
Local mesh available · 24 members
LOCAL ONLY
Today · 18 June 2026
Local communication
Demonstrated
Community messages delivered across the local mesh while internet backhaul is unavailable.
04 · BACKHAUL
Router Backhaul & Service State
Online
4s
48ms
0.4%
Router backhaul
Active
Root node, connected WAN router, cloud relay, and service-state validation.
05 · HANDOVER
Node Handover Test
1.8s
Yes
100%
Delivered
ESP32 handover
Demo pass
Client reassociation from Clinic Hub Node A to Community Centre Node B with session continuity.
06 · CHARGING
Power & Charging Validation
78%
Online
5.08V
18.6V
12.4V
1.8A
Power & charging
Charging
Solar input, battery level, charge current, node voltage, and operating state.
Positioning: Local-first community connectivity and power access for underserved areas.
Local Power. Local Connection. African Innovation.

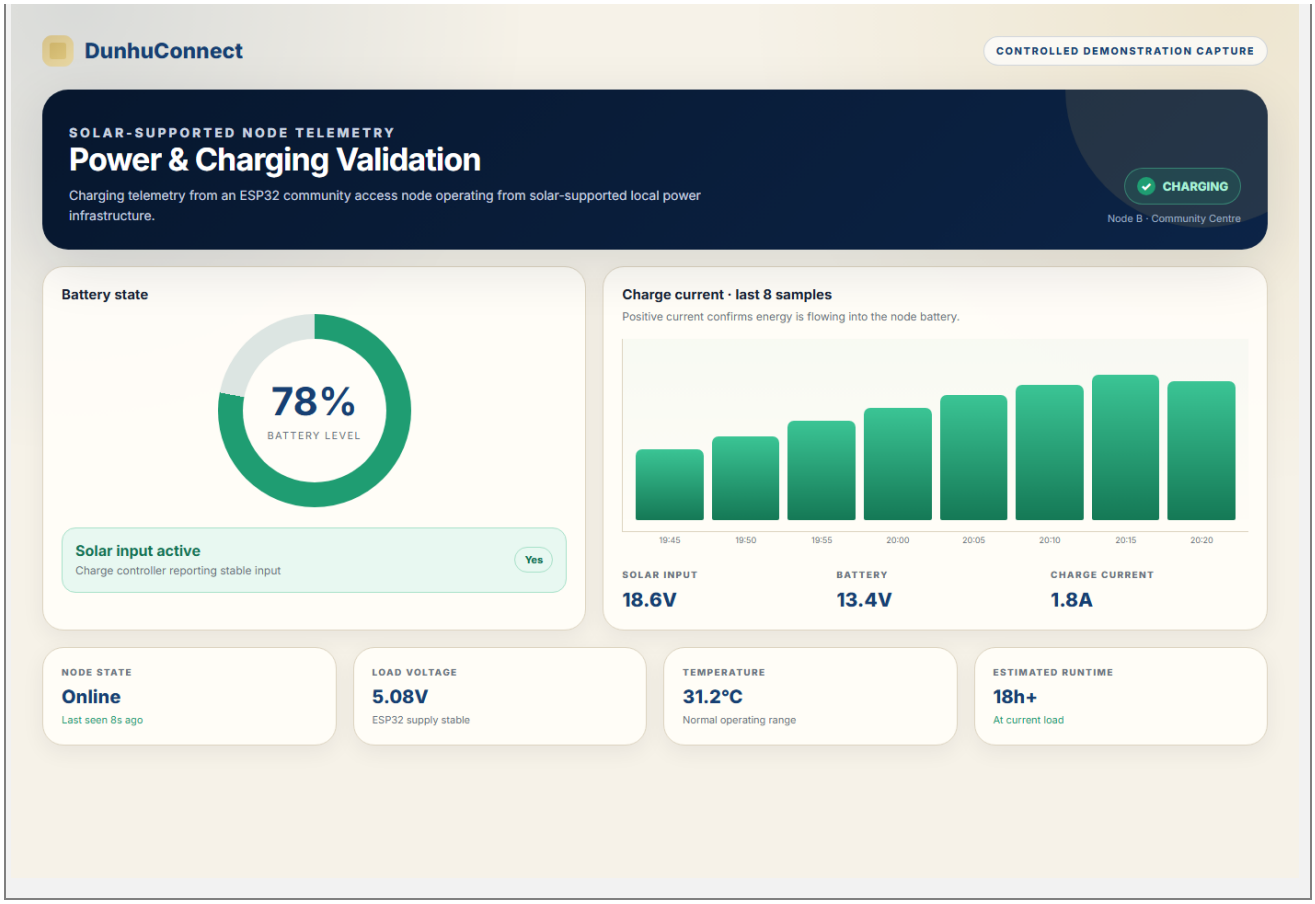


Figure 4.10: Combined results evidence page showing portal, account creation, local communication, router backhaul, handover, and charging screenshots/photos.

4.4 Analysis and Interpretation

4.4.1 Analysis Against Objective 1: Local Communication

The first objective was to develop a local communication and chat system that allows users on the same kiosk network to communicate and access community information even when external services are unavailable. The prototype result supports this objective because local communication was achieved between users connected to the DunhuConnect environment. The result shows that the system can act as a local service point and not only as a pass-through internet device.

This objective is the heart of the project. If local communication had failed, then the project would have collapsed into a conventional hotspot demonstration. Instead, the successful local communication result confirms the local-first design principle. It also supports the argument that rural digital resilience does not always require continuous external connectivity. A useful local

service can exist at the edge, hosted by the super node and accessed by users through the captive portal environment. (Guo et al., 2007; Pentland et al., 2004).

The limitation is that the test was still performed at prototype scale. The number of users, duration of communication, message volume, and field distance were limited by the final-year prototype environment. Therefore, the correct interpretation is not that DunhuConnect is already ready for national deployment. The correct interpretation is that the basic local communication concept has been validated and can now be expanded in Version 2 through user-load testing, message persistence testing, moderation features, and multi-site trials.

4.4.2 Analysis Against Objective 2: Node and Mesh Architecture

The second objective was to design the network architecture of the kiosk, including the Raspberry Pi super node, root node, mesh nodes, and local access paths required for resilient intra-community communication. The implementation results support this objective because the super node, ESP32 nodes, portal environment, and handover behaviour were successfully demonstrated together. The prototype did not only show a single access point. It showed a layered access environment in which users could interact with a local platform through distributed node coverage.

The seamless handover result is particularly important. It shows that the distributed node approach has practical value. In rural use, the access area may include a school compound, clinic yard, village meeting point, or charging area. Users will not remain fixed at one position. The handover result therefore supports the decision to use multiple nodes and confirms that the system can be developed toward wider community coverage. (Patra et al., 2007; Kanwal and Imran, 2015).

However, the interpretation must remain bounded. Handover was validated qualitatively, not through a complete RF measurement campaign. The result confirms functional continuity, but it does not yet define optimum node spacing, antenna height, RSSI thresholds, or maximum user density. These remaining questions are exactly the type of work that should be moved into Version 2 field testing. The Version 1 result proves the architecture; Version 2 should quantify and optimise it.

4.4.3 Analysis Against Objective 3: Power Management and Charging

The third objective was to design the power management modules required to support the mesh nodes, Raspberry Pi platform, and multiple user charging ports from a solar-battery energy system. The results partially support this objective at prototype level. The implemented hardware confirmed

that the super node and system components could be powered for testing, and the super node charging function was demonstrated. This validates the charging concept and supports the kiosk identity of the system.

The charging result is significant because it connects the technical prototype to the real rural use case. In environments where phones may be available but charging is unreliable, a communication kiosk without charging would be incomplete. The ability of the super node to provide charging therefore strengthens the project contribution. It shows that DunhuConnect can serve both communication and energy-access needs, which was a major theme in the problem statement and literature review. (Feron, 2016; Khan, 2023).

At the same time, this is the area where the most cautious interpretation is required. The charging function was validated, but the Version 1 stage did not yet complete a full long-duration solar autonomy test, maximum charging-load test, battery discharge profile, or enclosure thermal analysis. Therefore, the result should be recorded as prototype validation rather than final field certification. Version 2 should focus heavily on power telemetry, battery protection, current limiting, solar sizing, and multi-port charging endurance.

Objective	Result obtained	Level of achievement	Interpretation
Local communication	Users communicated through the DunhuConnect local service environment.	Achieved	The core local-first communication goal was validated.
Network architecture	Super node, ESP32 nodes, portal, and handover were implemented and tested.	Achieved at prototype level	The architecture is functional and suitable for further field optimisation.
Power and charging	Super node charging was demonstrated and hardware was implemented.	Partially achieved at prototype level	Charging concept is validated, but solar endurance and protected multi-port testing remain for V2.

Table 4.13: Objective-to-result interpretation

4.4.4 Interpretation of Version 1 Performance

The overall interpretation is that DunhuConnect Version 1 successfully validated the technical feasibility of the system. The prototype proved that the core elements could work together: local communication, captive portal access, account creation, node handover, router backhaul, hardware implementation, and charging. This is a strong result for a final-year engineering project because it

demonstrates integration across embedded systems, local platform software, networking, and power-related user service.

The system should not be interpreted as a finished commercial product. That would be an overstatement. Instead, it should be interpreted as a working proof-of-concept platform with clear evidence of the main functions and clear direction for the next version. This distinction strengthens the academic credibility of the project because it avoids claiming more than the tests proved.

The prototype also revealed that the most valuable improvements are no longer conceptual. The basic idea has been proven. The remaining work is practical engineering refinement: stronger enclosure design, proper PCB finalisation, protected multi-port charging, battery telemetry, RF measurement, security hardening, user-load testing, and field deployment procedures. These are not signs of failure. They are the natural next stage after a successful Version 1 implementation.

4.5 Discussion of Findings

The findings agree with the local-first argument developed in the earlier chapters. Chapter 1 argued that rural communication systems should remain useful even when conventional infrastructure is weak or intermittent. Chapter 2 showed that older kiosk and store-and-forward systems remained relevant because they preserved service value under constraints. The DunhuConnect results support that reasoning because the prototype provided local communication and portal access as core services, while router backhaul acted as an extension rather than the only source of value.

The local communication result is consistent with the design lessons associated with systems such as KioskNet and DakNet. Those systems showed that rural access should not be judged only by continuous broadband performance. DunhuConnect follows the same design logic in a modern embedded form: the Raspberry Pi super node provides local service authority, the ESP32 nodes provide access, and the router backhaul improves reach when it is available. The results therefore support the literature position that local usefulness is a valid and important measure of rural connectivity (Guo et al., 2007; Pentland et al., 2004; Surana et al., 2008).

The node handover result also connects to the mesh-networking literature reviewed in Chapter 2. The literature warned that mesh language alone is not enough; the network must actually improve coverage and continuity. In this prototype, the movement between nodes showed practical continuity at proof-of-concept level. This finding supports the decision to build a distributed access layer, but it also confirms the need for more rigorous RF evaluation in future work. The literature

pointed to routing, signal behaviour, and topology as important issues; the prototype now provides a working platform on which those issues can be measured more deeply (Patra et al., 2007).

The router backhaul result supports the hybrid architecture position. The project did not need to depend on one particular satellite provider or a single type of WAN hardware to prove its backhaul logic. The router validation showed that the upstream path can be modular. This finding is useful because rural deployment often depends on what equipment, pricing, licensing, and coverage are available at the time. A modular backhaul interface makes the system more adaptable than a design locked to one external provider (Michel et al., 2022; Tirmizi et al., 2022).

The charging result agrees with the literature argument that charging is a primary rural service rather than an accessory. Chapter 2 highlighted that device charging can be one of the practical reasons users approach a shared access point. The Version 1 prototype supported this view by demonstrating charging from the super node. The result also revealed where future work must be careful: charging demand can easily compete with communication uptime if power management is not disciplined. Therefore, Version 2 must treat charging as a managed load, not a simple output socket. (Feron, 2016).

The findings also show that the system has moved beyond a purely conceptual stage. The prototype produced observable implementation evidence across the user path. However, the results remain limited by the scale and duration of testing. There was no large multi-user community deployment, no long-term outdoor exposure test, no full solar autonomy cycle, and no detailed security audit. These limitations do not invalidate the results. They define the boundary of the results and make the Version 2 recommendations technically justified.

Finding	Related literature theme from Chapter 2	Agreement or extension
Local communication worked	Kiosk and store-and-forward systems preserve service value under constrained backhaul.	The prototype confirms this principle using a Raspberry Pi and ESP32-based local platform.
Handover between nodes was seamless at prototype level	Mesh networks can improve continuity if topology is implemented practically.	The prototype supports distributed access, while future RF measurement remains needed.
Router backhaul was validated	Hybrid backhaul improves reach but should not dominate local service design.	The result supports modular upstream connectivity.
Captive portal and accounts worked	Shared-access systems require controlled and understandable user entry points.	The portal provides a practical local interface for users.
Super-node charging worked	Charging is a primary adoption driver in off-grid or weak-grid contexts.	The prototype confirms charging kiosk value proposition.

Table 4.14: Link between findings and literature themes

4.5.1 Practical Challenges Observed During Implementation

The implementation process also exposed practical challenges that should be acknowledged. The first challenge was integration complexity. DunhuConnect combines power wiring, embedded nodes, local server services, portal behaviour, account creation, backhaul, and user devices. A fault in one area can appear as a fault in another. For example, if a user cannot reach the portal, the cause may be node configuration, IP addressing, captive redirection, service availability, or device behaviour. This made staged testing important.

The second challenge was the difference between a working bench prototype and a deployment-ready kiosk. The prototype worked at core-function level, but rural deployment requires stronger mechanical protection, clearer cable management, rugged charging ports, weather-aware enclosure design, and simplified operator procedures. These needs became more obvious after the hardware was physically implemented because the system was no longer only a diagram.

The third challenge was evidence collection. Some functions were visible during testing but still need stronger documentation through screenshots, photos, logs, and test tables before final submission. For that reason, this chapter includes figure placeholders where actual images should be inserted. The written result is already aligned to the observed prototype behaviour, but the final submission will be stronger once each major claim is supported by a photograph, screenshot, or log extract.

4.5.2 Limitations of the Results

The results in this chapter are sufficient for proof-of-concept validation, but they have clear limits. The prototype was not yet tested across a large village area with many users. The handover result was observed qualitatively, but exact handover delay and RSSI data were not captured as a full RF study. The charging function was demonstrated, but not yet subjected to extended multi-device charging and solar autonomy testing. The router backhaul was confirmed working, but not tested across a long period of weak signal conditions.

These limitations should be treated as engineering boundaries rather than failures. A final-year prototype normally proves feasibility before it proves product maturity. DunhuConnect Version 1 has done the first part. Version 2 should now test the system under conditions closer to real deployment: outdoor range, user density, battery endurance, enclosure heat, charging queue behaviour, and operator maintenance.

Limitation	Effect on current interpretation	How it should be addressed in Version 2
Small-scale prototype testing	Results confirm feasibility but not large-area deployment readiness.	Conduct field trials at a school, clinic, church, or ward site.
Qualitative handover validation	Handover worked, but exact RF performance is not fully quantified.	Log RSSI, latency, packet loss, and reconnection events.
Limited long-duration power testing	Charging was validated, but autonomy is not fully proven.	Perform solar-battery endurance tests with realistic loads.
Prototype-level security	Account creation worked, but production security is not complete.	Add secure authentication, password hashing, and role-based controls.
Prototype enclosure maturity	Hardware was implemented, but ruggedness remains limited.	Develop weather-resistant and serviceable V2 enclosure.

Table 4.15: Limitations and their effect on interpretation

4.6 Summary

This chapter presented the experimental results and analysis of the implemented DunhuConnect prototype. The results show that the major Version 1 functions were achieved. Local communication worked between users, the hardware was implemented, handover between nodes was observed as seamless at proof-of-concept level, router backhaul was validated, the captive portal was functional, accounts could be created, and the super node provided charging. Together, these results confirm that DunhuConnect is technically feasible as a portable local-first communication and charging kiosk.

The analysis compared the results with the project objectives. The local communication objective was achieved because users were able to communicate through the local system. The network architecture objective was achieved at prototype level because the Raspberry Pi super node, ESP32 nodes, captive portal, account flow, and handover behaviour operated together. The power and charging objective was partially achieved at prototype level because charging was demonstrated, while full solar autonomy and protected public multi-port charging remain future work.

The discussion linked the findings to the literature reviewed in Chapter 2. The results support the argument that rural systems should preserve local usefulness instead of depending entirely on upstream connectivity. The working portal, local communication service, router backhaul, handover behaviour, and charging output also show that DunhuConnect combines communication and energy access in a way that is relevant to rural deployment conditions.

The chapter also identified the main limitations. The system still requires larger field trials, quantitative RF measurements, longer power-endurance testing, stronger charging protection,

rugged enclosure development, and security hardening. These limitations provide a clear bridge to Chapter 5, where the recommended direction is to develop DunhuConnect Version 2. Version 2 should not restart the project. It should build on the validated Version 1 prototype and convert it into a more rugged, measurable, secure, and deployable rural communication platform.

Area	Final Chapter 4 conclusion
Local communication	Validated and achieved at prototype level.
Captive portal	Functional and suitable as the user entry point.
Account creation	Validated as part of controlled access.
Node handover	Observed as seamless for proof-of-concept testing.
Router backhaul	Validated and confirmed working.
Super-node charging	Demonstrated at prototype level.
Version 2 need	Required for ruggedness, quantitative testing, security, solar autonomy, and field deployment.

Table 4.16: Chapter 4 closing result summary

The final version of this chapter should be completed by inserting actual project screenshots and photographs into the figure positions provided above. The most important images to insert are the implemented hardware, captive portal landing page, account creation page, local communication screen, handover test evidence, router backhaul setup, and charging demonstration. These images will make the results chapter visibly tied to the actual prototype and will strengthen the evidence base for assessment.

4.6.1 Final Evidence Integration Requirements

Before final submission, this chapter should be completed by replacing each figure placeholder with the actual image or screenshot from the implemented prototype. This is not only a formatting task. It is part of the results evidence. The written analysis already states what was observed, but the inserted images will allow the examiner to see the physical and software evidence directly. The most important evidence is the implemented hardware, captive portal, account creation screen, local communication screen, node handover setup, router backhaul connection, and super-node charging output.

The figures should be inserted in the same order as the validation chain. The reader should first see the physical prototype, then the hardware details, then the portal and account flow, then the communication result, then the handover test, and finally the backhaul and charging evidence. This order prevents the chapter from becoming a scattered collection of screenshots. It allows the images

to support the same engineering story followed in the analysis: the system was built, users accessed it, local services worked, mobility was supported, backhaul was validated, and charging was demonstrated.

Each inserted image should have a short descriptive caption and should be clear enough to read without zooming excessively. Screenshots should show the actual DunhuConnect interface rather than generic browser pages. Hardware photographs should show the actual assembled parts rather than only separate components on a table. Where a screenshot contains private user information, names or identifiers should be blurred before submission. This protects user privacy while still preserving the technical evidence required by the chapter.

Evidence item	Recommended figure location	Purpose in the results chapter
Full prototype photograph	Figure 4.1	Shows that the system was physically implemented as a complete prototype.
ESP32 node photograph	Figure 4.3	Supports the node-architecture and handover results.
Captive portal screenshot	Figure 4.4	Proves that the user-facing portal was functional.
Account creation screenshot	Figure 4.5	Proves that user accounts could be created.
Local communication screenshot	Figure 4.6	Proves that connected users could communicate locally.
Handover test evidence	Figure 4.7	Supports the seamless node-transition result.
Router backhaul photograph or status screen	Figure 4.8	Supports the backhaul validation result.
Charging demonstration photograph	Figure 4.9	Supports the super-node charging result.

Table 4.17: Required final image evidence for Chapter 4

4.6.2 Bridge from Chapter 4 to Version 2 Recommendations

The results presented in this chapter lead directly into the Version 2 recommendations in Chapter 5. Version 1 has already proven the main idea. It would therefore be incorrect for future work to start again from the problem statement as if no implementation had occurred. The correct next step is refinement. DunhuConnect Version 2 should use the Version 1 prototype as the baseline and improve the parts that are now known to matter most: ruggedness, solar autonomy, security, monitoring, RF measurement, and field deployment.

The handover result points toward a Version 2 RF study. The router-backhaul result points toward stronger offline-to-online switching and backhaul monitoring. The portal and account-creation results point toward better authentication, account management, and administrator controls. The charging result points toward protected multi-port charging, battery telemetry, and solar sizing. The physical hardware result points toward a custom PCB, cleaner enclosure layout, and easier field maintenance. In this way, each recommendation in Chapter 5 should be traceable to a real finding from Chapter 4 rather than to a generic wish list.

This connection between results and future work is important because it shows project maturity. A weak dissertation recommends improvements that could have been guessed before building anything. A stronger dissertation recommends improvements that only became clear after implementation and testing. DunhuConnect now falls into the second category. The implemented prototype has shown what works, and the remaining work is specific enough to guide a second version.

Chapter 4 finding	Limitation observed	Version 2 recommendation
Local communication worked	Tested at limited prototype scale.	Run larger multi-user local communication trials.
Handover was seamless	Quantitative RF data were not fully captured.	Measure RSSI, packet loss, handover delay, and node spacing.
Captive portal worked	Interface and security still need polish.	Improve UX, authentication, and administrator functions.
Accounts could be created	Production-grade identity management is not complete.	Add secure password handling and role-based access.
Router backhaul worked	Long weak-signal operation was not fully assessed.	Add backhaul status monitoring and graceful failover logs.
Charging worked	Long-duration multi-device charging was not tested.	Add current-limited multi-port charging and battery telemetry.
Hardware was implemented	Prototype assembly is not yet rugged enough for public deployment.	Design custom PCB and weather-resistant enclosure.

Table 4.18: How Chapter 4 findings generate Version 2 recommendations

CHAPTER 5

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

DunhuConnect Version 2 Development Direction

5.1 Introduction

This chapter presents the conclusion, recommendations and future work arising from the implementation and testing of DunhuConnect, a portable solar-powered local communication and charging kiosk for rural Zimbabwe. The chapter is written from the position reached at the end of Chapter 4. The prototype is no longer only a design proposal. Local communication was demonstrated, users were able to communicate through the local network, the captive portal was functional, accounts could be created, the router backhaul was validated, the super node charging function was working, and the ESP32 node layer supported movement between coverage points without breaking the user experience. These results give the project a solid proof-of-concept foundation.

The purpose of this chapter is not to overstate the prototype as a finished commercial product. The more honest interpretation is that DunhuConnect Version 1 proved the architecture and exposed the areas that must be improved before deployment. The project successfully showed that local communication, charging, router-assisted backhaul, account-based access and node-based coverage can be combined in one working system. The next stage must now focus on ruggedness, safety, long-duration operation, monitoring, security, field installation and community acceptance.

For that reason, the central recommendation of this study is the development of DunhuConnect Version 2. Version 2 should not replace the current architecture; it should strengthen it. The recommended improvements are directly linked to the findings and limitations observed during implementation. The system worked, but rural deployment requires more than a working demonstration. It requires a system that can be maintained, repaired, monitored, explained to users, protected from abuse, and operated for long periods under power and connectivity constraints.

The chapter is organised into three main parts. The first part gives the overall conclusion of the project and compares the achieved outcomes with the original objectives. The second part presents recommendations for DunhuConnect Version 2, covering hardware, power, mesh coverage, portal services, backhaul, security, monitoring and field operation. The third part presents future work, including the proposed development roadmap, future research direction and final chapter summary.

Table 5.1: Relationship between Chapter 4 findings and Chapter 5 recommendations

Chapter 4 result	Meaning of the result	Version 2 recommendation
Local communication worked	The local-first concept was validated at prototype level.	Test with more users, longer sessions and wider coverage.
Node handover was achieved	The ESP32 node layer can support movement between coverage areas.	Measure handover delay, RSSI and stability under load.
Captive portal was functional	Users can enter the system through a controlled local interface.	Improve the portal into a full user and administrator platform.
Accounts could be created	Controlled access is possible.	Strengthen authentication, account recovery and user roles.
Router backhaul was validated	The kiosk can work in both local-only and backhaul-assisted modes.	Improve automatic offline-to-online behaviour and service prioritisation.
Super node charging worked	Communication access and device charging can be combined.	Add protected multi-port charging, telemetry and priority control.
Hardware was implemented	The system moved from design into physical prototype form.	Develop rugged PCB, enclosure and maintainable wiring for field use.

5.2 Overall Conclusion of the Project

The main conclusion of this project is that a portable, local-first communication and charging kiosk is technically feasible using affordable embedded and edge-computing components. DunhuConnect showed that a Raspberry Pi based super node, ESP32-based access nodes, a captive portal, account creation, local messaging, router backhaul and charging support can operate together as one system. This is a meaningful result because the problem addressed by the project is not only internet access; it is the combined problem of communication continuity, power access and practical local service delivery.

The project also confirmed that the local-first design direction was correct. If the system had been designed only as an internet hotspot, then its value would have depended entirely on the availability of upstream connectivity. The implemented prototype showed a stronger model. The local platform can provide user access, account handling, communication and portal interaction at the site, while the router backhaul extends the system when internet service is available. This makes the architecture more suitable for rural conditions where connectivity can be intermittent or expensive.

The implemented hardware is also an important outcome. The project moved beyond diagrams and software description into an assembled physical system. This matters in an engineering project because real wiring, real power delivery, real node behaviour and real user-device interaction expose

problems that do not appear in architecture diagrams. The working charging function on the super node also supports the original kiosk identity of the project. It confirms that DunhuConnect is not merely a networking experiment, but a shared community access point that combines communication with practical device-power support.

The handover result is another important conclusion. A single access point can prove basic connectivity, but it does not prove that a user can move across a larger service area. The successful node handover result shows that the distributed node design has practical value. For rural deployment, this means the kiosk concept can be extended beyond one physical box by placing nodes around a school, clinic, ward office, community hall, growth point or temporary event area.

The router backhaul validation supports the hybrid model proposed in earlier chapters. Backhaul is useful and should remain part of the system, but it should not become the centre of the project. The strongest conclusion from the work is that local services must remain the foundation. Internet access can improve the system when available, while the local communication, captive portal and charging functions keep the system useful even when backhaul is degraded.

5.3 Achievement of Project Objectives

The first objective was to develop a local communication and chat system that allows users on the same kiosk network to exchange messages and access local information even when external services are unavailable. This objective was achieved at prototype level. The system allowed users to communicate locally through the implemented local environment, and this validates the central idea that a rural communication kiosk can provide value without depending completely on wide-area infrastructure.

The second objective was to design the network architecture of the kiosk, including the Raspberry Pi controller, root node, mesh nodes and local access paths required for resilient intra-community communication. This objective was also achieved at prototype level. The Raspberry Pi super node operated as the local control and service point, while the ESP32 node layer provided the distributed access structure. The observed handover between nodes confirmed that the node architecture can support continuity as a user moves through the coverage area.

The third objective was to design the power management modules required to support the mesh nodes, the Raspberry Pi platform and multiple user charging ports from a solar-battery energy system. This objective was partially achieved in the current version and should be strengthened in Version 2. The charging function on the super node was working, which validates the principle of

combining communication and charging. However, longer battery endurance testing, solar charging evaluation, current-limiting measurements and power-priority logic still require more detailed implementation and measurement before the system can be described as deployment-ready.

Overall, the project objectives were met sufficiently for proof-of-concept validation. The communication and network architecture objectives were strongly validated, while the power objective was validated functionally but still requires deeper field-level testing. This distinction is important because it prevents the conclusion from sounding exaggerated. The prototype worked, but the next version must prove endurance, ruggedness and reliability under longer and less controlled conditions.

Table 5.2: Objective achievement summary

Objective	Prototype outcome	Conclusion	Version 2 need
Local communication and chat	Users communicated through the local system.	Achieved at prototype level.	Test larger user groups and longer sessions.
Network architecture with Pi and ESP32 nodes	Super node, access nodes and handover were implemented.	Achieved at prototype level.	Quantify range, RSSI and handover delay.
Power management and charging	Super node charging was working.	Partially achieved and functionally validated.	Measure autonomy, current draw, protection and solar recovery.

5.4 Recommendation 1: Develop DunhuConnect Version 2 as a Deployment-Ready Revision

The first recommendation is that DunhuConnect should proceed into a planned Version 2 development phase. This recommendation follows directly from the results. The system worked, but the prototype should not be treated as the final deployment unit. Version 1 answered the feasibility question. Version 2 must answer the deployment question. The next revision should therefore be designed around reliability, safety, repeatability, monitoring, maintainability and user acceptance.

Version 2 should begin with a formal revision of the system requirements. The requirements should be based on what was learned in the prototype rather than copied from the original design assumptions. For example, the fact that node handover worked means future requirements can now include measurable handover delay. The fact that charging worked means future requirements can include maximum charging current, protection behaviour and low-battery charging restrictions. The

fact that router backhaul worked means future requirements can include automatic switching between local-only and backhaul-assisted modes.

The V2 process should also introduce version control at the hardware level. Each PCB, enclosure and firmware revision should have a clear label. This will prevent confusion during testing when several nodes or boards are being used. A node should not simply be called Node 1 or Node 2; it should have a recorded firmware version, board revision and installation position. This type of documentation may seem small, but it becomes essential when diagnosing handover, signal strength, charging or power faults.

Version 2 should also be developed with deployment discipline. This means the design should include installation instructions, wiring labels, maintenance access, system-startup checks and operator training notes. A rural deployment cannot rely on the original developer being present every time something goes wrong. The system must be understandable enough for a trained local operator or technician to restart, inspect and report faults.

Table 5.3: Main difference between Version 1 and Version 2

Area	Version 1 focus	Version 2 focus
System purpose	Proof that the architecture works.	Reliable community deployment.
Hardware	Functional prototype assembly.	Rugged modular construction.
Power	Charging function validation.	Measured autonomy and protected energy management.
Network	Local communication and handover demonstration.	Coverage mapping and quantified performance.
Portal	Functional access and account creation.	Full user/admin platform.
Security	Basic controlled access.	Role-based access and safer authentication.
Testing	Prototype validation.	Field testing with real users.

5.5 Recommendation 2: Improve Hardware Ruggedness and Serviceability

The second recommendation is to redesign the physical hardware for ruggedness and serviceability. The current hardware implementation is strong enough to prove the system, but a field-deployable kiosk must tolerate movement, dust, heat, user handling and repeated maintenance. Version 2 should therefore use a cleaner physical layout with better protection for the power, network and user-access sections (Surana et al., 2008; Zennaro et al., 2007).

The ESP32 node boards should be moved toward a more standardised PCB design. Prototype wiring is acceptable during development, but it creates risk during field use. Loose wires, unlabelled connectors, weak solder joints and exposed modules can produce intermittent faults that are difficult to diagnose. A custom or semi-custom PCB would make each node easier to replicate and easier to replace. The PCB should include stable voltage regulation, reset access, programming headers, antenna clearance, status LEDs and labelled test points.

The Raspberry Pi super node should be placed in a protected compartment with clear airflow and accessible ports. The Pi is the local brain of the system, so its power supply and storage should be protected from disturbance. The enclosure should separate user-facing charging ports from the internal electronics. This protects users from exposed wiring and protects the internal system from rough handling.

The final enclosure should also support maintenance. Components that may need replacement, such as the battery, fuses, charge controller, SD card or node modules, should not be buried inside the kiosk. The enclosure should allow inspection without complete disassembly. Wiring should be labelled, cable paths should be tied down, and high-current lines should be physically separated from low-voltage signal lines where practical.

Version 2 should include a basic hardware maintenance checklist. The checklist should include battery voltage check, solar input check, router status check, portal availability check, node status check, charging-port check and physical inspection. This would make the system easier to maintain after deployment and would support better evidence collection during future testing.

Table 5.4: Hardware recommendations for Version 2

Hardware area	Recommended improvement	Expected benefit
ESP32 nodes	Use labelled PCBs with test points and stable regulators.	Easier replication and fault finding.
Super node	Protect Raspberry Pi with airflow and stable 5 V supply.	Improves reliability of local services.
Enclosure	Separate power, control and user sections.	Improves safety and maintenance.
Wiring	Use labelled connectors and tied cable paths.	Reduces intermittent faults.
Service access	Make battery, fuses and modules accessible.	Supports field repair.

5.6 Recommendation 3: Strengthen Solar Power, Battery Autonomy and Charging Control

The third recommendation is to improve the power subsystem through measurement-based design. The prototype confirmed that the super node charging function works, but Version 2 must prove that the system can operate for useful periods under real power conditions. This requires measured current consumption, battery behaviour, solar input testing and charging-load analysis.

The first V2 task should be to measure the current draw of each subsystem separately. The Raspberry Pi, router backhaul, ESP32 nodes, captive portal services and charging ports should be measured under idle and active conditions. These measurements should then be used to size the solar panel and battery rather than relying only on theoretical estimates. This will make the power section more defensible and more accurate. (Esmaili et al., 2018; Feron, 2016).

The second V2 task should be to add battery telemetry to the administrator portal. The administrator should be able to see battery voltage, charging state and low-power warnings. At prototype level, visual inspection may be enough. At deployment level, the operator needs a dashboard that explains whether the kiosk is healthy. A simple traffic-light system can be used at first: green for normal battery state, amber for caution and red for critical level.

The charging system should also be controlled. Public charging is useful, but it must not drain the battery to the point where the communication system shuts down. Version 2 should reserve power for the Raspberry Pi and ESP32 nodes before allowing user charging. This can be implemented using load switches, current-limited charging modules, low-voltage cut-off circuits or relay-based charging control.

The final V2 power design should include protection against short circuits, reverse polarity, excessive current and deep battery discharge. These protections are not optional in a public kiosk. They are part of the safety and sustainability of the system. A rural communication kiosk that damages batteries or shuts down unpredictably would lose user trust quickly. (Chai et al., 2024).

Table 5.5: Power and charging recommendations

Power issue	Version 2 action	Reason
Unknown long-term runtime	Measure load current and calculate autonomy.	Provides realistic operating time.
Battery condition not visible	Add voltage and charge-state telemetry.	Improves maintenance decisions.
Charging may overload system	Use current limiting and priority	Protects communication services.

	rules.	
Deep discharge risk	Add low-voltage cut-off.	Protects battery life.
Solar recovery not quantified	Test charging across real daylight periods.	Shows whether daily recovery is sufficient.

5.7 Recommendation 4: Quantify Mesh Coverage and Handover Performance

The fourth recommendation is to convert the successful node handover result into a more detailed performance study. In Chapter 4, handover was observed as seamless from the user perspective. That is enough for prototype validation, but Version 2 should measure the behaviour more carefully so that future deployments can be planned scientifically.

The first measurement should be coverage radius. Each node should be tested at measured distances from the user device. The test should record whether the user can access the portal, send messages and remain connected. This should be done in open space and with typical obstacles such as walls, trees or people in the path. The result should be a practical coverage estimate for each node type and installation height.

The second measurement should be received signal strength. RSSI values should be recorded at different points around the kiosk. A simple coverage map can then be drawn to show strong areas, weak areas and dead spots. This would help determine where nodes should be placed in a school, clinic, church, ward office or growth point.

The third measurement should be handover delay. A user device should move from the coverage area of one node toward another while a local service remains open. The test should record whether the portal or chat session remains usable and how long the transition takes. This should be repeated several times because wireless behaviour can vary between trials.

The fourth measurement should be user-load behaviour. It is not enough to test one user moving between nodes. Version 2 should test several users connected at the same time, especially while messages are being exchanged. This will show whether handover remains acceptable when the system is under more realistic use (Patra et al., 2007; Kanwal and Imran, 2015).

Table 5.6: Recommended mesh and handover tests for Version 2

Metric	Test method	Expected output
Coverage radius	Test portal and chat access at measured distances.	Usable node spacing guideline.
RSSI	Record signal level at fixed points.	Coverage map.

Handover delay	Move device between nodes during active use.	Measured transition time.
Message delay	Send messages under different loads.	Local communication performance.
Obstacle effect	Repeat tests with walls, trees and movement.	Deployment planning guidance.

5.8 Recommendation 5: Improve the Captive Portal, Accounts and Local Services

The fifth recommendation is to improve the captive portal into a complete local service platform. The prototype confirmed that the portal is working and that accounts can be created. Version 2 should build on this by making the portal easier to use, easier to manage and more useful during both local-only and backhaul-assisted operation.

The user interface should be designed primarily for mobile phones. Most expected users will not access the system from laptops. The portal should therefore use large buttons, short instructions, lightweight pages and clear navigation. The most important actions should be visible immediately: create account, login, open local chat, view announcements, check service status and read help instructions.

Account management should also be improved. The prototype account creation result proves the basic workflow, but deployment requires more careful handling. Version 2 should include duplicate-account checks, stronger passwords, administrator-assisted reset, logout options and user-role separation. Ordinary users should not see administrator controls, and administrators should not need to manually inspect technical files to manage users.

A community announcements section should be added. This would allow the kiosk to support schools, clinics, churches, local leaders and emergency coordinators. Announcements may include meeting notices, school messages, health campaigns, water-point notices, agricultural updates or emergency information. This would make DunhuConnect more valuable even when router backhaul is not available.

Local language support should be added gradually. At minimum, Version 2 should support English and Shona for the main user actions. Later versions can add Ndebele and additional local language support. This recommendation is not cosmetic. It directly affects accessibility and user confidence in rural deployment. (Guo et al., 2007; UN IGF DC3/APC, 2017).

Table 5.7: Portal and local service recommendations

Portal area	Version 2 improvement	Value
Mobile design	Simplify pages and buttons for phones.	Improves usability.
Accounts	Add validation, reset and role separation.	Improves control and security.
Announcements	Add local noticeboard function.	Supports community information.
System status	Show power, backhaul and node status.	Helps users and administrators.
Language	Add Shona and later Ndebele support.	Improves adoption.

5.9 Recommendation 6: Improve Router Backhaul and Offline-to-Online Behaviour

The sixth recommendation is to keep router backhaul as a useful extension while protecting the local-first identity of the system. Chapter 4 confirmed that router backhaul is validated and working. This is a strong result because it shows that DunhuConnect can support external connectivity when available. However, Version 2 must ensure that loss of backhaul does not collapse local services.

The system should clearly detect backhaul state. The captive portal or administrator dashboard should show whether the router backhaul is online, offline or unstable. Users should not be left guessing why external pages do not load. A simple message such as 'Local services available, internet backhaul unavailable' would make the system more understandable during outages.

Version 2 should also improve service prioritisation. When backhaul is available, the system can allow selected online services, updates, synchronisation and external information access. When backhaul is unavailable, the system should automatically preserve local chat, announcements, account access and charging information. This is the practical meaning of graceful degradation.

A future improvement is queued synchronisation. If the system stores logs, messages or administrative records locally while offline, it can synchronise selected records later when the router backhaul returns. This would help the system maintain both local autonomy and wider visibility without depending on continuous internet access. (Michel et al., 2022; Tirmizi et al., 2022).

Table 5.8: Backhaul behaviour recommended for Version 2

Backhaul condition	Expected system behaviour	User-facing message

Backhaul available	Local and selected online services operate.	Internet available.
Backhaul weak	Prioritise light services and preserve local portal.	Limited internet; local services active.
Backhaul unavailable	Local chat, accounts and announcements remain active.	Local services available only.
Backhaul restored	Resume synchronisation and update status.	Internet restored.

5.10 Recommendation 7: Strengthen Security and Access Control

The seventh recommendation is to strengthen security before real deployment. Account creation worked in the prototype, but a public community system requires stronger access control. Without basic security, users may create false accounts, administrators may lose control of announcements, and technical settings may be exposed to unauthorised users.

Version 2 should use secure password handling. Passwords should not be stored in plain text. A password hashing approach should be used so that user credentials remain protected even if the database is accessed. The system should also include session timeouts, logout buttons and role-based access. Ordinary users should access local services, while administrators should access management tools.

Administrator accounts should be protected more strongly than ordinary accounts. A weak administrator password would create a serious risk because the administrator can change settings, post notices or manage users. Version 2 should require strong administrator credentials and, if possible, restrict administrator access to trusted devices or a separate management mode.

Security should also include physical access. The enclosure should prevent users from reaching internal electronics, reset buttons, battery terminals or storage media. The charging ports should be accessible, but the control hardware should be protected. This is particularly important because the kiosk is intended for shared public use.

Table 5.9: Security recommendations for Version 2

Security area	Recommended action	Risk reduced
Passwords	Use hashing and minimum password rules.	Credential compromise.
User roles	Separate user and administrator privileges.	Unauthorised control.

Sessions	Add logout and timeout.	Session misuse.
Admin access	Protect management pages.	False settings or notices.
Physical security	Lock internal electronics.	Tampering and damage.

5.11 Recommendation 8: Add Monitoring, Logs and Maintenance Tools

The eighth recommendation is to add monitoring and logging. A prototype can be demonstrated by the developer, but a deployed system must be diagnosable by someone else. Version 2 should therefore include a dashboard or log view showing node status, backhaul status, battery level, portal status, charging status and recent system events.

Node monitoring is especially important. If a node goes offline, users may experience weak coverage or failed handover. The administrator should be able to see whether each node is online, when it last checked in and whether it is reporting normal behaviour. This would reduce guesswork during faults.

Power monitoring is equally important. The administrator should be able to identify whether the system is running from battery, charging from solar or approaching a low-power condition. A simple record of battery voltage over time would help future design decisions and would make Version 2 testing more scientific.

Event logs should remain simple but useful. Logs should record system startup, backhaul changes, node online/offline events, failed login attempts, low-battery warnings and administrator actions. This would help with maintenance and would also provide stronger data for future academic analysis (Surana et al., 2008).

Table 5.10: Monitoring and maintenance recommendations

Monitoring item	Information to show	Maintenance benefit
Node status	Online/offline and last seen time.	Identifies coverage faults.
Battery status	Voltage, level and charging state.	Protects uptime.
Backhaul status	Online, weak or offline.	Explains internet availability.
Portal status	Service running or failed.	Improves troubleshooting.
Event logs	Startup, warnings and admin actions.	Creates an evidence trail.

5.12 Recommendation 9: Conduct Field Testing and User Acceptance Evaluation

The ninth recommendation is to test DunhuConnect Version 2 with real users in a controlled pilot. Laboratory testing proves technical feasibility, but a rural communication kiosk must also be

understandable, useful and trusted by the people who use it. Field testing should therefore evaluate both technical behaviour and user experience.

The pilot should start in a controlled environment such as a school, church, ward office or community event site. Users should be asked to connect to the Wi-Fi network, open the captive portal, create an account, send a local message, read an announcement and use the charging function. The test should observe where users get confused, which pages load slowly and whether the instructions are clear.

The field test should also check placement. The kiosk should be positioned where it is visible, safe and useful. Nodes should be placed around the area based on expected user movement. The test should record where users naturally gather and whether the coverage plan matches their behaviour. This is important because technically good coverage may still fail if the physical kiosk is placed badly.

User feedback should be collected in a simple way. The aim should not be a complicated survey at first. Users can be asked whether the system was easy to use, whether account creation was clear, whether messaging was useful, whether charging was useful and what they would want improved. This feedback should guide the final V2 interface and service choices (Surana et al., 2008).

Table 5.11: User acceptance testing plan

Test activity	What to observe	Reason
Account creation	Can users register without help?	Checks portal clarity.
Local messaging	Can users send and receive messages?	Checks main communication function.
Announcements	Can users find and understand notices?	Checks community value.
Charging	Do users understand charging availability?	Checks practical utility.
Movement	Do users stay connected while moving?	Checks handover experience.

5.13 Proposed DunhuConnect Version 2 Roadmap

The recommendations should be implemented in phases. Attempting to improve everything at once would make the project difficult to manage and difficult to test. A phased roadmap allows each improvement to be validated before the next layer is added. The first phase should focus on the parts

that directly affect reliability: hardware, power and enclosure. Later phases can then improve portal features, monitoring, security and community services.

Phase 1 should produce a cleaner hardware revision. This includes standardised ESP32 node boards, better wiring, improved enclosure structure and protected power paths. Phase 2 should focus on energy measurement and charging control. Phase 3 should upgrade the portal and account system. Phase 4 should quantify coverage, handover and user-load performance. Phase 5 should add security and monitoring. Phase 6 should carry out field pilot testing.

The roadmap should be treated as an engineering plan, not only as a list of wishes. Each phase must have outputs that can be tested. For example, the power phase should not end with 'improved battery'; it should end with measured runtime and a battery status display. The network phase should not end with 'better mesh'; it should end with a coverage map and handover-delay measurements.

Table 5.12: Proposed Version 2 development roadmap

Phase	Focus	Main deliverables
Phase 1	Hardware refinement	Rugged enclosure, labelled wiring, standardised node boards.
Phase 2	Power and charging	Measured load data, battery telemetry, current-limited charging.
Phase 3	Portal upgrade	Improved accounts, announcements, mobile interface, admin view.
Phase 4	Network validation	Coverage map, RSSI data, handover delay, user-load tests.
Phase 5	Security and monitoring	Role-based access, event logs, node and backhaul dashboard.
Phase 6	Field pilot	User testing, deployment notes, feedback report.

5.14 Future Academic Research Areas

The DunhuConnect prototype also creates a base for future academic research. One possible research area is RF performance in rural environments. Future work can measure how antenna height, node spacing, building materials, trees and terrain affect coverage. This would turn DunhuConnect from a functional prototype into a field platform for rural wireless research.

A second research area is energy-aware networking. Future work can examine how communication load, charging load and solar availability should influence system behaviour. For example, the kiosk

may reduce some services during low-battery periods while preserving emergency communication and announcements. This research direction is important because rural systems often fail when power planning is separated from network planning.

A third research area is offline-first application design. DunhuConnect can be used to study how local chat, announcements, cached content and delayed synchronisation behave when internet access is intermittent. This is relevant to rural digital inclusion because many communities do not have reliable continuous connectivity (Guo et al., 2007; Pentland et al., 2004).

A fourth research area is community adoption. Technical success does not automatically guarantee adoption. Future research can investigate what users value most: charging, local messaging, announcements, internet access, emergency alerts or school and clinic information. The results can guide which services should be prioritised in future versions.

A fifth research area is secure shared-access networking. Public rural networks must be simple enough for ordinary users but secure enough to prevent misuse. DunhuConnect can support research on lightweight authentication, local identity management, administrator control and privacy-aware logging in low-resource environments.

Table 5.13: Future research opportunities

Research area	Possible question	Expected contribution
RF coverage	How do terrain and obstacles affect ESP32 node coverage?	Better rural node placement.
Energy-aware networking	How should services respond to battery level?	Longer uptime.
Offline-first services	Which services remain useful without backhaul?	Improved local resilience.
Community adoption	Which kiosk services do users value most?	Better deployment design.
Security	What access model suits shared community networks?	Safer public use.

5.15 Final Recommendations

The first final recommendation is that DunhuConnect should continue into Version 2 development. The core system has been validated, and the next step should be refinement for deployment rather than redesign from the beginning. The current architecture is strong enough to keep, but it must be made more rugged, measurable and maintainable.

The second final recommendation is that local-first operation must remain the centre of the system. Router backhaul is working and useful, but the kiosk should not become dependent on it. The system should continue to provide local communication, portal access, announcements and charging even when external connectivity is unavailable.

The third final recommendation is that the power system must be measured more deeply. Charging works, but Version 2 must prove how long the system can run, how solar input restores the battery, how charging affects uptime and how low-battery conditions are managed.

The fourth final recommendation is that the portal should become the main service surface for the kiosk. It should support users, administrators, announcements, account management, system status and local language access. This will make DunhuConnect easier to understand and more useful to communities.

The fifth final recommendation is that field testing should be conducted before any larger deployment. The system should be tested with real users, real movement patterns, real charging demand and realistic node placement. That stage will show whether the prototype is not only technically functional, but also practically valuable.

Table 5.14: Summary of final recommendations

Recommendation	Priority	Expected outcome
Proceed to DunhuConnect V2.	High	Moves from prototype to deployment-ready revision.
Keep local-first operation central.	High	Preserves usefulness during backhaul failure.
Improve hardware and enclosure.	High	Increases reliability and serviceability.
Measure power and protect charging.	High	Improves uptime and safety.
Quantify coverage and handover.	High	Supports planned deployment.
Upgrade portal and accounts.	High	Improves user and admin experience.
Conduct field pilot testing.	Medium to High	Validates real community usefulness.

5.16 Version 2 Acceptance Criteria

Version 2 should not be accepted only because it switches on. A clearer acceptance standard is required so that the next developer, supervisor or assessor can decide whether the revision is genuinely ready for wider testing. The acceptance criteria should be based on the project goals and the weaknesses observed in the prototype stage. They should cover communication, handover, captive portal behaviour, account handling, charging, power autonomy, backhaul behaviour, monitoring and user experience.

The communication acceptance criterion should require successful local message exchange between multiple users connected through the local network. The test should include users connected through different nodes, not only users connected to the same access point. This will prove that the local communication service remains meaningful across the distributed node layer. The result should be recorded with screenshots, timestamps and a short test log.

The handover acceptance criterion should require a user device to move between two or more node coverage zones while maintaining access to the portal or local communication service. The exact handover time may vary depending on device behaviour, but the service should not collapse or require the user to restart the whole session. Version 2 should record the number of successful handover trials and the observed delay range.

The power acceptance criterion should require the system to operate for a defined test period under a known load. The test should state the number of active nodes, the state of the router backhaul, the number of connected users, and whether charging ports are active. Without these conditions, a runtime claim is not very meaningful. Version 2 should therefore report runtime as a measured value under stated conditions rather than as a general statement.

The portal acceptance criterion should require users to create accounts, log in, access the local service area, view system status and log out. The administrator should also be able to view basic system state. If these actions require the developer to manually intervene through code or terminal commands, the system should not yet be considered deployment-ready.

The backhaul acceptance criterion should require the system to show a clear difference between local-only mode and backhaul-assisted mode. When the router backhaul is removed, the local portal and communication service should remain available. When the backhaul is restored, the system should detect the restored connection and update the user or administrator interface. This acceptance criterion protects the local-first design principle at the centre of the project.

Table 5.15: Proposed Version 2 acceptance criteria

System area	Acceptance condition	Evidence required
Local communication	Multiple users can exchange messages locally.	Screenshots, logs and timestamps.
Node handover	User can move between nodes while local service remains usable.	Repeated trial record and delay estimate.
Power system	System runs for defined period under stated load.	Voltage readings and runtime log.
Captive portal	Users can register, log in and access services.	Portal screenshots and account records.
Backhaul behaviour	System switches clearly between local-only and online-assisted state.	Backhaul status log and user message.
Charging	Charging works without shutting down communication services.	Load test and current reading.

5.17 Deployment Risk Analysis for Version 2

Future development should also recognise the risks that may appear when the prototype leaves the controlled test environment. The most immediate risk is power shortage. If the system is placed in an area with poor solar exposure or heavy charging demand, the battery may drain faster than expected. Version 2 should reduce this risk through measured load budgeting, charge control, battery telemetry and a rule that protects communication services before user charging.

A second risk is physical damage. A shared kiosk may be handled by many users, moved between locations, exposed to dust, carried in vehicles or placed in crowded spaces. If the enclosure is weak or the charging ports are not protected, the system may fail even though the electronics are correctly designed. Version 2 should therefore treat mechanical strength as a technical requirement, not as an afterthought.

A third risk is configuration drift. The Raspberry Pi, ESP32 firmware, router backhaul and portal settings must match one another. If one node is flashed with a different firmware version or if the portal configuration changes without documentation, troubleshooting becomes difficult. Version 2 should use configuration records, labelled firmware versions and a commissioning checklist to reduce this risk.

A fourth risk is user misuse. In a public network, some users may create repeated accounts, attempt to access administrator pages, unplug charging cables, reset equipment or use the system in ways not

intended by the developer. Version 2 should reduce this risk through account roles, physical protection, administrator authentication and simple usage rules displayed in the portal.

A fifth risk is overpromising. The project should not be presented to communities as a full replacement for mobile broadband or grid electricity. Its value is local communication, controlled access, charging support and backhaul assistance when available. Clear communication of this role will protect user trust and will make the system easier to evaluate fairly.

Table 5.16: Version 2 deployment risks and mitigation measures

Risk	Possible effect	Mitigation in Version 2
Battery depletion	Loss of communication and charging service.	Battery telemetry, load limits and low-voltage cut-off.
Physical damage	Broken ports, loose wiring or exposed electronics.	Rugged enclosure and protected connectors.
Configuration mismatch	Nodes or services fail unexpectedly.	Version labels and commissioning checklist.
User misuse	Account abuse or tampering.	Role-based access and physical protection.
Backhaul failure	Users assume the system is fully offline.	Clear portal status and local-only service continuity.
Unclear ownership	No one maintains the system after deployment.	Operator training and maintenance schedule.

5.18 Sustainability, Ownership and Maintenance Recommendations

A technical system intended for rural deployment must include an ownership and maintenance plan. The prototype can be operated by the developer during testing, but a real kiosk requires someone to check it, clean it, restart it, update it, protect it and explain it to users. Version 2 should therefore include a simple operational model before any pilot deployment is attempted.

One practical model is institutional hosting. A school, clinic, church, business centre or ward office can host the kiosk and assign a responsible person to act as the local operator. The operator does not need to be an engineer, but they should be trained to perform basic checks: confirming that the kiosk powers on, checking the portal, checking node status, checking charging ports, inspecting the enclosure and reporting faults. This makes the system more sustainable than a deployment where no person is responsible. (UN IGF DC3/APC, 2017; Surana et al., 2008).

Maintenance should be divided into daily, weekly and monthly checks. Daily checks can include power-on status, portal availability and charging-port condition. Weekly checks can include battery inspection, node placement, cable inspection and router backhaul status. Monthly checks can include cleaning the enclosure, reviewing logs, checking firmware versions and recording any faults. These routines would help prevent small issues from becoming complete system failures.

The project should also consider a sustainability model. Even if the initial prototype is built for academic purposes, continued operation requires replacement cables, damaged connectors, battery replacement, data costs for backhaul, enclosure repairs and occasional technical support. Version 2 should therefore include a simple cost model showing expected maintenance costs and possible ways of supporting them, such as institutional sponsorship, local council support, paid charging, donations or community service partnerships.

Documentation is part of sustainability. Version 2 should include a short operator manual, wiring diagram, startup checklist, shutdown procedure, fault-reporting form and basic user guide. These documents do not need to be long, but they should be clear enough for another person to operate the kiosk without guessing. This would also strengthen the academic submission because it shows that the project considers deployment reality and not only prototype construction.

Table 5.17: Suggested maintenance structure for Version 2

Maintenance interval	Tasks	Responsible person
Daily	Check power, portal, charging ports and visible damage.	Local operator.
Weekly	Check node status, cable condition, battery reading and backhaul state.	Local operator or technician.
Monthly	Review logs, clean enclosure, inspect connectors and confirm firmware records.	Technician or project maintainer.
After fault	Record fault, isolate subsystem and apply repair checklist.	Technician.
Before relocation	Shut down safely, secure battery and verify startup after movement.	Operator and technician.

5.19 Chapter Summary

This chapter presented the conclusion, recommendations and future work for the DunhuConnect project. The chapter concluded that the prototype successfully validated the core concept. Local

communication worked, the hardware was implemented, seamless handover between nodes was achieved, the captive portal worked, accounts could be created, router backhaul was validated and the super node charging function was confirmed. These results show that the project achieved a strong proof-of-concept outcome.

The chapter then argued that the next stage should be DunhuConnect Version 2. Version 2 should improve the current system rather than restart the design. The recommended improvements include rugged hardware, better solar autonomy, protected charging, quantified mesh coverage, improved handover testing, stronger captive portal services, secure account management, backhaul-state handling, monitoring, maintenance tools and field testing.

The main message of the chapter is that DunhuConnect has moved beyond basic feasibility. The question is no longer whether the system can work. The more important question is how it can be made reliable, safe, secure, maintainable and useful in real rural communities. If the recommendations in this chapter are followed, DunhuConnect can develop from a final-year prototype into a stronger rural communication and charging platform with practical value beyond the laboratory demonstration.

REFERENCES

Berto, R., Napoletano, P. and Savi, M. (2021) 'A LoRa-based mesh network for peer-to-peer long-range communication', Sensors, 21(13), 4314. doi:10.3390/s21134314.

Chai, Z., Li, J., Liu, Z., Liu, Z. and Jin, X. (2024) 'Experimental analysis and safety assessment of thermal runaway behaviour in lithium iron phosphate batteries under mechanical abuse', Scientific Reports, 14, 58891.

Cotrim, J.R. and Kleinschmidt, J.H. (2020) 'LoRaWAN mesh networks: a review and classification of multihop communication', Sensors, 20(15), 4273. doi:10.3390/s20154273.

Ding, A.Y., et al. (2017) 'IoT connectivity in rural and remote areas - a LoRaWAN mesh approach', Proceedings of ACM DEV.

El-Khozondar, H.J., El-Khozondar, R.J., Matter, K. and Suntio, T. (2016) 'A review study of photovoltaic array maximum power tracking algorithms', Renewables: Wind, Water, and Solar, 3, Article 3. doi:10.1186/s40807-016-0022-8.

Esmaili, M., et al. (2018) 'Optimal sizing of standalone PV-battery systems for rural electrification', Applied Energy, 222, pp. 999-1012.

Feron, S. (2016) 'Sustainability of off-grid photovoltaic systems for rural electrification in developing countries: a review', Sustainability, 8(12), 1326. doi:10.3390/su8121326.

Gao, S., et al. (2024) 'Off-grid solar PV for rural electrification: recent developments and future prospects', Renewable Energy Reports, 6, pp. 120-135.

GSMA (2023) The State of Mobile Internet Connectivity 2023. London: GSMA.

Guo, S., Falaki, M.H., Oliver, E.A., Ur Rahman, S., Seth, A., Zaharia, M.A. and Keshav, S. (2007) 'Very low-cost Internet access using KioskNet', ACM SIGCOMM Computer Communication Review, 37(5). doi:10.1145/1290168.1290181.

Kanwal, K. and Imran, M. (2015) 'Community wireless mesh networks for rural connectivity in developing countries', Scientific Research and Essays, 10(14), pp. 478-486.

Khan, R.M. (2023) 'Design of a solar powered mobile phone charger for rural areas', Theseus Repository.

Michel, F., Trevisan, M., Giordano, D. and Bonaventure, O. (2022) 'A first look at Starlink performance', Proceedings of the 22nd ACM Internet Measurement Conference, pp. 130-136. doi:10.1145/3517745.3561416.

Ogunbona, P.O., et al. (2016) 'Satellite-backed rural internet for developing regions', IEEE GLOBECOM Workshops.

Patra, R.K., Nedevschi, S., Surana, S., Sheth, A., Subramanian, L. and Brewer, E. (2007) 'WiLDNet: design and implementation of high performance WiFi based long distance networks', Proceedings of the 4th USENIX Symposium on Networked Systems Design and Implementation (NSDI), pp. 87-100.

Pentland, A.S., Fletcher, R. and Hasson, A. (2004) 'DakNet: rethinking connectivity in developing nations', Computer, 37(1), pp. 78-83. doi:10.1109/MC.2004.1260729.

Petäjäjärvi, J., Mikhaylov, K., Roivainen, A., Hänninen, T. and Pettissalo, M. (2015) 'On the coverage of LPWANs: range evaluation and channel attenuation model for LoRa technology', 14th International Conference on ITS Telecommunications, pp. 55-59. doi:10.1109/ITST.2015.7377400.

POTRAZ (2022) Annual Abridged Sector Performance Report. Harare: Postal and Telecommunications Regulatory Authority of Zimbabwe.

POTRAZ (2023) Satellite Services Public Notice. Harare: Postal and Telecommunications Regulatory Authority of Zimbabwe.

POTRAZ (2023) Sector Performance Report, Third Quarter 2023. Harare: Postal and Telecommunications Regulatory Authority of Zimbabwe.

POTRAZ (2024) First Quarter 2024 Abridged Sector Performance Report. Harare: Postal and Telecommunications Regulatory Authority of Zimbabwe.

Reuters (2024) 'Zimbabwe approves licensing of Starlink internet service', 25 May.

RFC 3561 (2003) Ad hoc On-Demand Distance Vector (AODV) Routing. Internet Engineering Task Force.

RFC 3626 (2003) Optimized Link State Routing Protocol (OLSR). Internet Engineering Task Force.

RFC 6550 (2012) RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks. Internet Engineering Task Force.

RFC 7181 (2014) Optimized Link State Routing Protocol version 2. Internet Engineering Task Force.

RFC 8966 (2021) The Babel Routing Protocol. Internet Engineering Task Force.

Surana, S., Patra, R., Nedevschi, S., Ramos, M., Subramanian, L., Ben-David, Y. and Brewer, E. (2008) 'Beyond pilots: keeping rural wireless networks alive', Proceedings of the 5th USENIX Symposium on Networked Systems Design and Implementation (NSDI), pp. 119-132.

Tirmizi, S.B.R., Chen, Y., Lakshminarayana, S., Feng, W. and Khuwaja, A.A. (2022) 'Hybrid satellite-terrestrial networks toward 6G: key technologies and open issues', Sensors, 22(21), 8544. doi:10.3390/s22218544.

UN IGF DC3 / APC (2017) Community Networks: the Internet by the People, for the People. Rio de Janeiro: FGV Direito Rio.

Verma, A.K., et al. (2019) 'Solar photovoltaic system for rural electrification: design and development', International Journal of Photoenergy.

Zaidi, Z. and Lan, K.-C. (2017) 'Wireless multihop backhauls for rural areas: a preliminary study', PLOS ONE, 12(4).

Zennaro, M., et al. (2007) 'On the design of a flexible low-cost wireless access platform for developing regions', IEEE ICTD.

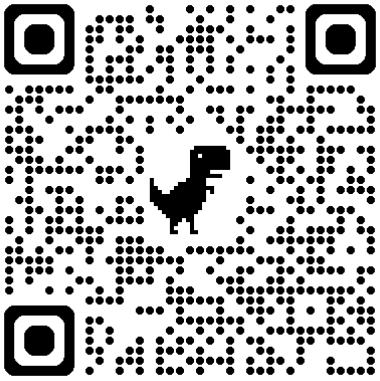
ZIMSTAT (2026) Living Conditions Thematic Report based on the 2022 Population and Housing Census. Harare: Zimbabwe National Statistics Agency.

APPENDICES

Due to the size of the Appendices we have produced a website to access them:

https://documentation.dunhuconnect.co.zw/appendices

Use the link/scan the code:



the password is c0nn3ct2dunhu