Peer-to-Peer (P2P) Communication as a Solution for Remote Areas Without Internet: A Case Study in Yangalia

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Abstract

This paper presents a low-cost, peer-to-peer (P2P) communication solution tailored for remote areas with limited access to traditional communication networks. The proposed system is decentralised, requiring no servers or specialised hardware, relying solely on mobile devices that can connect to the same subnet. This makes the solution highly mobile, easy to implement, and scalable without significant infrastructure investment[1] (Pacitti et al., 2012). Our tests, using different mobile hotspot devices such as the *SM-N986B* and *iPhone 15 Pro Max*, demonstrated that while communication was stable within an 80-metre range under optimal conditions, device performance varied significantly. Although interference from external signals and environmental factors were not fully addressed, the solution shows promise for deployment in rural regions. Further research is needed to refine device compatibility and explore more robust alternatives, such as Wi-Fi access points or base stations, to improve both range and reliability in real-world rural settings.

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1. Introduction

1.1 **Problem Statement**

Access to reliable communication infrastructure is a persistent challenge in rural areas, where internet connectivity is often unavailable or prohibitively expensive[2] (Pacitti et al., 2012). For many villages, like Yangalia, Central African Republic, traditional communication systems are insufficient, leaving residents isolated from essential information and services. This project explores the potential of P2P networks as a viable, low-cost alternative for local communication, focusing on environments with no internet access.

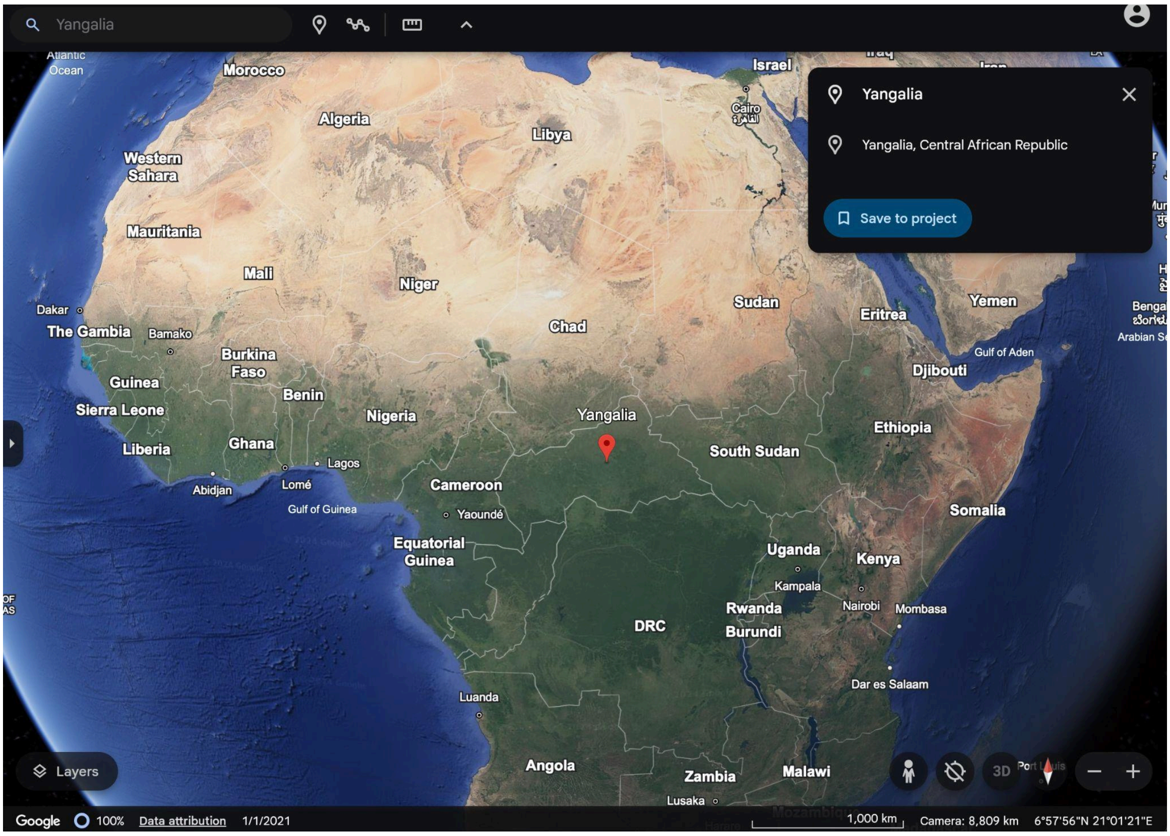

Fig 1.1.1: Geographical Location of Yangalia, as captured from Google Earth

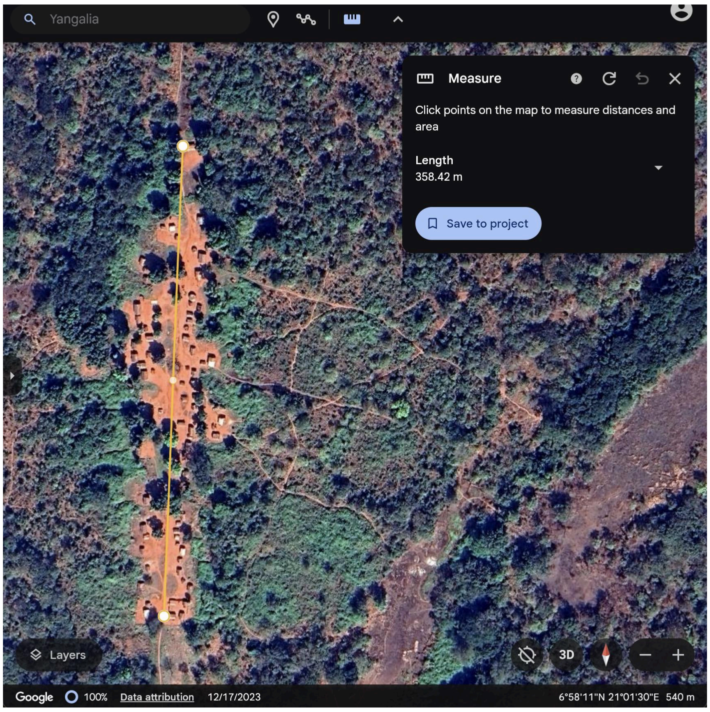

Fig 1.1.2: A Detailed View of Yangalia and its Geographical Size from Google Earth

1.2 **Motivation**

In a world where connectivity is a fundamental pillar of societal growth[3] (Manyika & Roxburgh, n.d.), we were inspired by the harsh reality that many remote communities remain isolated due to the lack of reliable telecommunications and basic infrastructure. From the fire signals of ancient China to the satellites orbiting the Earth today, we witnessed the huge role played by communication in improving education, country development, community cohesion and safety, which compelled us to create a solution that bridges this gap for remote areas.

1.3 **Research Objectives**

This research aims to develop and test a P2P-based communication system that can operate without an internet connection. By leveraging locally connected devices, the project will evaluate how P2P can bridge the communication gap in rural regions like Yangalia. The objective is to implement a working prototype that allows devices within the same local network (subnet) to exchange messages.

1.4 **Structure of the Paper**

The rest of this paper is organised as follows: Section 2 discusses the background and related work on communication in rural areas and P2P networks. Section 3 introduces the proposed solution, including technical details and design choices. Section 4 outlines the system design and architecture. Section 5 presents the evaluation results of the prototype, and Section 6 concludes with the key findings and potential future work.

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2. Background and Related Work

2.1 Existing Solutions and Limitations

In rural areas without reliable internet access, several existing solutions attempt to bridge the communication gap. However, each comes with its limitations.

2.1.1 Mobile Data

Mobile data networks offer a degree of connectivity, but their effectiveness is often limited in rural regions. Coverage gaps, especially in remote areas, hinder access, while data speeds can be inconsistent[4] (Zhang et al., 2021). Additionally, the cost of mobile data plans may be prohibitive for some users, further restricting access.

2.1.2 Wireless Fidelity (Wi-Fi)

Utilising Wi-Fi to access the internet for communication in remote areas poses significant challenges and costs. Implementing Wi-Fi infrastructure requires substantial investment from telecom companies to extend internet services into low-population regions such as Yangalia. The limited user base in these rural communities often leads to a situation where the revenue generated from Wi-Fi subscriptions is insufficient to cover the costs of establishing and maintaining the necessary infrastructure[5] (El, 2020).

2.1.3 Radio Communication

Radio communication provides a reliable alternative for basic communication, particularly in emergency services. However, it often lacks the bandwidth necessary for data-intensive applications, such as video conferencing and large file transfers[5] (El, 2020), which can hinder the adoption of modern technologies that require higher data transfer rates.

Additionally, utilising radio communication often requires designated equipment, such as transceivers or repeaters, which can come at a significant extra cost. These expenses can create barriers for users in rural areas who may already face financial constraints. While radio systems can effectively transmit voice communication over long distances, their limitations in bandwidth and high equipment costs make them less viable for broader communication needs.

2.1.4 Satellite Communication

Satellite communication offers extensive coverage[6] (Su et al., 2019), even in remote locations. However, it comes with significant latency issues and high costs[7] (Sanctis et al., 2015). The technology can also be affected by weather conditions[8] (Hogg & Chu, 1975), which may disrupt service. Furthermore, data caps are often imposed, limiting the amount of information that can be transmitted[9] (Botta & Pescape, 2014), which can be a significant drawback for users requiring consistent connectivity.

2.2 **Overview of P2P Networks**

P2P networks distribute the communication workload across a decentralised system of peers, where each device (node) serves as both a client and a server. This makes P2P networks suitable for environments where centralised infrastructure is absent, such as rural areas. Previous studies have shown that P2P networks can enhance communication resilience and reduce dependency on costly infrastructure.

2.3 **Related Research**

P2P communication has been explored in various studies, particularly as a solution for enhancing connectivity in areas with limited or no internet access. Below is a review of past research highlighting key findings and implementations:

2.3.1 Community Networks and Mesh Networking

A significant body of research has focused on community networks, which often utilise P2P communication to provide internet access in underserved areas. Studies illustrate how mesh networks allow users to share resources, such as internet connectivity, among themselves, effectively bypassing the need for traditional ISPs[11] (Cilfone, 2019). These networks have shown promise in rural communities where installation of conventional infrastructure is economically unfeasible.

2.3.2 Disaster Recovery Communication

Research discusses the application of P2P communication in disaster recovery scenarios[12] (Yatbaz et al., 2018). The authors highlight how P2P systems can facilitate communication among survivors when conventional networks are down. By using mobile devices and creating ad hoc networks, communities can share vital information, coordinate responses, and enhance resilience.

2.3.3 Village-Level Communication Solutions

Studies have explored P2P technology as a means of communication in rural villages, where traditional internet access is sparse[5][10] (El, 2020) (Baig et al., 2022). Findings indicate that P2P systems enable villagers to communicate effectively, share agricultural information, and engage in local governance without relying on centralised internet infrastructure. This was achieved using basic mobile devices and local mesh networking.

2.3.4 Social Connectivity and Information Dissemination

Another aspect of P2P research involves its role in enhancing social connectivity and information dissemination in rural communities. Studies examine how P2P systems can be leveraged to facilitate communication among community members, thus improving local information flow and engagement in community events and initiatives[5] (El, 2020).

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3. Proposed Solution

3.1 **P2P Architecture Overview**

The proposed system is designed to enable communication between devices connected to the same local network (subnet) without the need for an external internet connection[1] (Pacitti et al., 2012). Using Python, the system broadcasts and listens for messages within the same subnet, allowing users to exchange information locally.

3.2 **Key Features of the Solution**

3.2.1 Decentralised Communication

In a decentralised architecture, all devices within the same subnet can communicate directly with one another, eliminating the need for central servers[1] (Pacitti et al., 2012). This approach not only reduces costs associated with server infrastructure but also minimises power consumption, making it a more energy-efficient solution.

3.2.2 Low-Cost and Mobile Infrastructure

The absence of dedicated servers significantly lowers both implementation and maintenance costs. Additionally, the P2P model allows users to utilise their existing mobile devices equipped with wireless capabilities, negating the need for specialised hardware. This flexibility is particularly beneficial in rural settings, where access to expensive technology can be limited.

3.2.3 Scalability and Sustainability

The scalability of the P2P network is directly linked to the coverage area of the Wi-Fi signal, which can extend beyond 400 metres under optimal conditions[10] (Baig et al., 2022). This range is sufficient to connect users in small, remote villages like Yangalia. Furthermore, the decentralised nature of this network reduces environmental impact by eliminating the need for energy-intensive servers, promoting sustainable use of resources.

3.2.4 Ability to Function Offline

The P2P communication model enables users to interact without requiring an internet connection. This is especially valuable in rural areas, where internet access may be unreliable or unavailable. Users can seamlessly connect and communicate with one another, enhancing social interaction and information exchange within their community.

3.3 **Implementation Details**

The prototype of the solution leverages Python's networking capabilities, specifically using socket programming to handle the sending and receiving of data packets across devices. Each node in the network acts as both a sender and a receiver, ensuring messages can be shared across all connected devices.

GitHub Repository: https://github.com/Jason-Liu-123/REMOTE

3.4 **Challenges and Assumptions**

Given the team's limited experience with implementing P2P networks, there are several challenges to overcome, including learning message delivery across varying distances and ensuring the system functions effectively in a real-world environment. Additionally, the limited timeframe poses a challenge when building and optimising our solution.

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4. System Design and Architecture

4.1 **System Overview**

The proposed system consists of a hotspot device (such as a mobile phone, Wi-Fi access point, or base station) and multiple peer devices that connect to the network. The hotspot device acts as the central node, enabling communication among all connected peers within the same subnet. Each peer device, such as a laptop, mobile phone, or any device equipped with a wireless card, can broadcast and listen to messages across the network. This setup allows for decentralised communication, where messages can be exchanged directly between devices without the need for an internet connection or external server infrastructure.

The system relies on the Wi-Fi protocol to establish a local area network (LAN), allowing for efficient communication over distances. The devices within the network communicate using P2P principles, where each device can both transmit and receive information, ensuring resilience even if one device leaves the network. This design reduces the cost of infrastructure and enhances the flexibility of the system in remote areas with limited connectivity options, like Yangalia.

4.2 **Component Breakdown**

Explain each component in the system:

4.2.1 Nodes (Devices)

The system comprises two main types of nodes: the hotspot device and multiple peer devices. The hotspot device, which can be a mobile phone, Wi-Fi router, or a base station, functions as the central hub that creates the local network. This device generates a wireless LAN (WLAN) to which peer devices can connect. The peer devices are any devices equipped with wireless capabilities, such as laptops, smartphones, or tablets. Each peer device can broadcast and listen to messages across the network, facilitating direct communication without the need for an external server or internet access.

4.2.2 Data Flow

Once connected to the network created by the hotspot device, peer devices communicate by broadcasting messages across the subnet. The data flow is decentralised, meaning each peer device can both send and receive messages, acting as both a transmitter and a receiver. This P2P communication model ensures that devices can directly exchange information within the range of the hotspot, eliminating the need for centralised control or routing through external servers.

The system is based on the broadcast and listen model:

- *Broadcasting*: When a device transmits data, it sends the information to all devices within the subnet. This could include messages, alerts, or any relevant data packets that need to be shared.
- *Listening*: Peer devices are continuously listening for broadcasts from other peers within the network. Upon receiving a broadcast, the devices process the data and take appropriate action (e.g., display a message, store information).

This decentralised flow of data allows the system to remain functional even in offline environments, making it particularly useful for rural areas like Yangalia, where internet access may be unavailable.

4.3 **Deployment in Rural Areas**

Deploying a P2P communication network in rural areas like Yangalia requires careful consideration of local conditions, infrastructure limitations, and communication needs. Given the limited or absent internet connectivity in such regions, this solution offers significant potential to improve local communication without the need for extensive infrastructure investments.

4.3.1 Infrastructure Requirements

Deployment begins with minimal infrastructure—a mobile device (such as a smartphone) or Wi-Fi router acting as a hotspot and multiple peer devices connected within the same subnet. These devices could be existing mobile phones, laptops, or other wireless-enabled devices commonly found in households or local communities. The lightweight nature of this setup reduces costs and simplifies installation, as no additional infrastructure like telecom towers or dedicated communication hardware is needed.

4.3.2 Scalability in Rural Contexts

The system's scalability is ideal for small villages like Yangalia. The coverage of a Wi-Fi hotspot, especially in the 2.4 GHz range, can extend over 400 meters in ideal conditions, enabling a local area network that can cover a large portion of a rural community without needing multiple access points. This is particularly advantageous in open, rural environments where interference is minimal, allowing the network to operate efficiently over longer distances.

4.3.3 Adaptability to Remote Conditions

The P2P network is well-suited for areas with power limitations. Since the system does not require external servers or high-power equipment, it consumes less energy, making it more sustainable in regions where electricity may be unreliable. The ability to function offline is a critical feature, ensuring that local communication continues even during power outages or in remote areas where mobile towers are unavailable.

4.3.4 Cost Efficiency

One of the key benefits of P2P deployment in rural areas is the low cost. With minimal infrastructure required, communities can use their existing devices to participate in the network. This contrasts with the high costs associated with other communication methods, such as satellite or fibre-optic installations, which often require substantial investment and maintenance fees.

4.3.5 Challenges and Considerations

Despite its advantages, deploying P2P in rural areas does face challenges. Environmental factors like terrain, dense vegetation, and weather conditions can affect Wi-Fi signal strength and coverage. Additionally, ensuring that the local population has the necessary technical knowledge to use the network effectively may require initial training or educational programs.

5. Evaluation and Results

5.1 **Test Setup**

To evaluate the system, we will connect two laptops to a mobile hotspot and run a series of tests to assess how well the P2P communication system performs under different conditions. Specifically, we will measure the time it takes for messages to travel between devices and how varying the distance between devices impacts communication reliability.

The test was carried out at The University of Sydney Quadrangle using the following devices:

	Alienware M16 R1	MacBook Pro A2918
Processor	i9-13900HX	M3
RAM	32GB	24GB
Wireless Connectivity	Wi-Fi 6E (Wi-Fi 802.11ax)	Wi-Fi 6E (0x14E4, 0x4388)
OS	Windows 11 Home	MacOS 14.6.1

Table 5.1.1: Specifications of Peer Devices

	Samsung SM-N986B	iPhone 15 Pro Max
Processor	Exynos 990	A17 Pro
RAM	12GB	8GB
Hotspot Frequency Used	5GHz	5GHz
OS	Android 13	iOS 18.0 (22A3354)

Table 5.1.2: Specifications of Hotspotting Devices

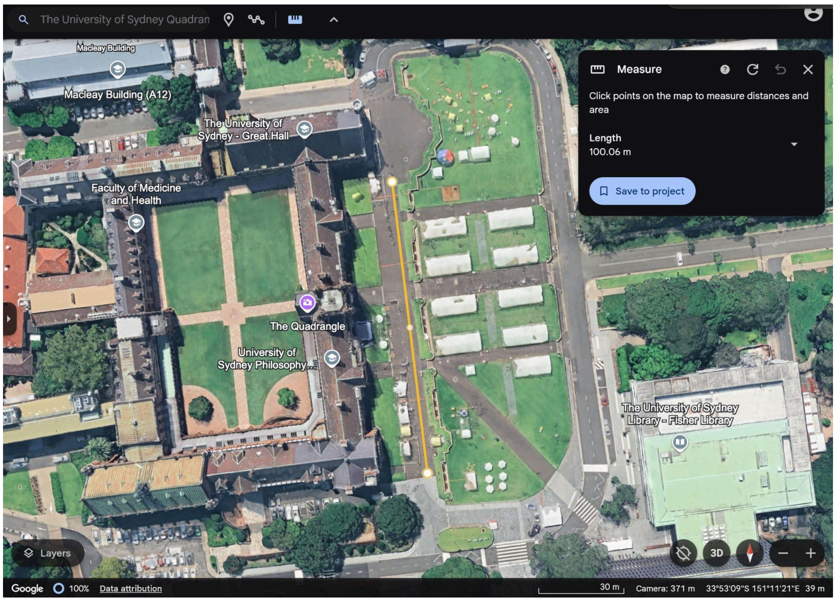

Fig 5.1.1: A Detailed View of the Quadrangle and its Geographical Size from Google Earth

5.2 **Metrics for Evaluation**

For our evaluation, we will test the performance of the P2P communication system by assessing latency at varying distances from the hotspotting device. In this setup, the *Alienware M16 R1* will be positioned close to the hotspot device, while the *MacBook Pro A2918* will be situated at an increasing distance away from the hotspot.

To measure latency, we will implement the ping command on the *MacBook*, which sends packets of data from one device to another and measures the time it takes for each packet to travel to the destination and back. This will allow us to gauge the effectiveness of the P2P solution at different distances from the hotspot. The primary objective is to identify the practical maximum distance at which the system remains operational, ensuring that connections are not lost.

The metrics we will focus on during testing include:

- **Round-Trip Time (RTT)**: The average time taken for packets to travel from the MacBook Pro to the hotspot and back, measured in milliseconds (ms).
- **Packet Loss**: The percentage of packets that do not successfully return to the originating device, indicating reliability at various distances.

By systematically increasing the distance between the devices and recording the results of the ping tests, we aim to establish a clear understanding of the operational limits of our solution in rural environments. This data will help inform future implementations and optimisations of the P2P communication system in similar contexts.

5.3 **Results**

Distance (m)	Latency (ms) Packet 1	Packet 2	Packet 3	Packet 4	Packet 5	Average	Packet Loss (%)
10	62.273	83.974	106.206	100.433	146.814	99.940	0
20	218.257	134.076	269.117	149.992	72.610	168.810	0
30	276.104	107.079	-	45.719	65.193	123.524	20
40	163.198	134.777	154.324	71.470	-	130.942	20
50	437.924	-	722.542	-	15.814	392.127	40
60	-	404.809	-	80.258	116.785	200.617	40
70	72.924	-	-	-	-	72.924	80
80	-	-	-	-	-	-	100

Table 5.3.1 Result Table When Using SM-N986B as Hotspotting Device

Distance (m)	Latency (ms) Packet 1	Packet 2	Packet 3	Packet 4	Packet 5	Average	Packet Loss (%)
10	26.378	266.824	168.889	85.432	309.642	171.433	0
20	167.184	57.622	545.865	158.310	76.892	201.175	0
30	703.532	319.245	545.211	152.677	72.211	357.775	0
40	553.627	163.713	116.813	590.263	212.819	327.447	0
50	156.191	370.172	395.592	209.375	128.546	251.965	0
60	1008.802	142.057	62.155	353.684	223.878	358.115	0
70	164.057	336.396	153.602	101.133	17.969	154.631	0
80	557.147	180.95	176.376	408.764	257.029	316.062	0
90	1011.231	134.034	168.628	397.109	231.324	388.465	0
100	305.854	498.767	312.881	169.153	91.945	275.720	0

Table 5.3.2 Result Table When Using iPhone 15 Pro Max as Hotspotting Device

5.4 **Discussion**

The results from the latency and packet loss tests indicate significant variations in performance depending on both the distance from the hotspot and the device used as the hotspotting source.

- Performance with *SM-N986B* as Hotspotting Device

  From the results in Table 5.3.1, the average latency exhibited limited correlation with increasing distance from the hotspot. However, as the distance increased, especially beyond 50 metres, there was a significant rise in packet loss, with 40% loss at 50 metres and a complete loss of communication at 80 metres. This suggests that while latency alone may not be the primary issue at longer distances, the stability of the connection becomes a challenge. The complete packet loss at 80 metres indicates the practical communication limit for this hotspot-peer pairing in the tested environment, emphasising the impact of distance on signal reliability.

- Performance with *iPhone 15 Pro Max* as Hotspotting Device

  When the *iPhone 15 Pro Max* was used as the hotspot (Table 5.3.2), a similar pattern emerged with latency being less strongly associated with distance. However, unlike the *SM-N986B* setup, no packets were lost within 100 metres, demonstrating better performance and stability at extended distances. This is a notable distinction, as it indicates that the *iPhone 15 Pro Max* was able to maintain consistent communication across longer distances without significant degradation in packet transmission. Unfortunately, due to space limitations at the testing site, the actual maximum communication range could not be tested beyond 100 metres. However, the absence of packet loss within this range suggests that the *iPhone 15 Pro Max* may support even greater coverage in similar rural environments.

5.4.1 Comparison and Insights

The stark difference in performance between the two hotspotting devices suggests that device-specific factors, such as the quality of the wireless radio and hotspot capabilities, play a significant role in determining the effective range and reliability of P2P communication. The superior performance of the *iPhone 15 Pro Max* in this context may be attributed to better hardware optimization, especially when paired with another Apple device (the *MacBook Pro*). This highlights the potential for certain hotspot-peer combinations to provide an extended communication range compared to others, a key consideration for deploying P2P networks in rural areas.

5.4.2 Limitations

Despite efforts to minimise interference, the testing was conducted in an environment where external factors could not be entirely controlled. Although the tests were carried out at midnight to reduce signal interference from other devices, there was still potential interference from sources such as the university's Wi-Fi network, active Bluetooth devices, and other nearby electronics. This interference may have impacted the accuracy of the results, particularly in terms of signal stability and packet loss at varying distances.

Furthermore, the test environment did not fully replicate the actual conditions in rural areas. The hotspot and peer devices were high-end models that may not reflect the types of devices available in more remote settings, where older or less capable hardware is more common. Additionally, environmental factors such as terrain, vegetation, and local interference in rural areas could significantly affect the performance of the P2P network in ways that were not fully captured in this test. As such, the results from this experiment may not fully generalise to real-world deployment scenarios in remote regions like Yangalia.

The use of 10-metre increments between measurements introduces limitations in determining the precise maximum range of communication. The relatively large step size between distance measurements reduces the accuracy of the point at which the connection becomes unreliable. As a result, the deduced maximum range in this testing environment may not fully capture the nuanced performance characteristics of the system at distances just beyond the last successful communication point. Smaller increments in future testing could provide more precise insights into the practical range limits of the P2P network.

5.4.3 Conclusion

Overall, these findings demonstrate the variability in communication performance depending on the hotspot device used, reinforcing the importance of selecting appropriate hardware for P2P solutions in challenging rural environments. Future testing could explore the impact of other variables such as signal interference, device orientation, and environmental factors, further refining the understanding of optimal deployment strategies.

However, the test conditions, including interference from nearby signals, the use of high-end devices, and limited accuracy, limit the generalizability of these results to rural environments. Further testing in actual field conditions is required to determine the true performance limits.

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6. Conclusion and Future Work

6.1 **Summary of Findings**

This research demonstrated the viability of P2P communication as a low-cost, scalable solution for rural areas without internet access. Through testing different hotspot devices, we found that P2P networks can maintain effective communication over significant distances, with device performance being a key factor. The iPhone 15 Pro Max provided a stable connection up to 100 metres without packet loss, whereas the SM-N986B struggled with connection stability beyond 50 metres. This highlights the potential of P2P to bridge communication gaps in remote areas by using existing mobile devices, eliminating the need for expensive infrastructure like servers or wired internet.

6.2 **Limitations**

The current solution, which relies on mobile phones to create a WLAN via hotspot, has a limited coverage range of approximately 80 metres in optimal conditions. In rural or remote areas where lower-end devices are more common, this effective communication range may be further restricted, potentially impacting the reliability of the P2P network. Additionally, this study did not explore the underlying causes of the significant performance differences between different hotspotting devices, such as the iPhone 15 Pro Max and SM-N986B.

6.3 **Future Work**

Further research could investigate these variations and how hardware capabilities influence range and stability. Moreover, replacing mobile hotspots with more robust infrastructure, such as dedicated Wi-Fi access points or base stations, could significantly enhance both coverage and connection quality, making the P2P solution more practical for larger or more densely distributed rural areas.

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