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PeerDrop: Implementation of a Mesh-Based Peer-to-Peer Network for Secure Offline Communication

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ABSTRACT—

In recent years, Peer to Peer (P2P) Networking and Application have gain a significant attention due to internet's impact on data security. P2P has been a great hotspot since it ensures data security and independence from the internet. The proposed model demonstrates PeerDrop's system-level implementation which stands as a mesh-based peer-to-peer (P2P) messaging system designed solely for offline real-time messaging. The system implements Wi-Fi Direct as its discovery method for direct device communication together with Flutter as its implementation platform to handle interfaces across multiple operating systems. The peer-to-peer networking system PeerDrop operates through a decentralized topology which makes every node function as both a client and relay. An interconnected network allows dynamic messages to spread from one device to multiple others as part of the message distribution process. The PeerDrop system consists of three fundamental operational components which include peer discovery followed by secure connection creation through AES-256 encryption for confidentiality accompanied by data transfer with real-time sockets. The system automatically adjusts through connection management that tracks peer availability for effective communication rerouting. Experimental results demonstrate both fast data transfer and high bandwidth capacities in direct connections while offering analogous network speeds across multiple-hop routes. The system design proves how offline communication should combine usability with security for all users especially in disaster zones alongside rural and remote locations.

Keywords— Wi-Fi-direct, Mesh Network, Peer-to-Peer Communication, Offline Communication

1. Introduction

Internet communication networks break down during disaster relief operations and in remote areas and secure environments where network infrastructure does not exist or is deliberately restricted. Crucial in these situations are P2P mesh network-based communication systems without dependence on standard infrastructure which support real-time device-to-device data exchanges. PeerDrop represents a peer-to-peer platform based on mesh networks that functions end-to-end offline. Wi-Fi Direct technology allows PeerDrop to automatically connect Android devices together without requiring routers or access points. PeerDrop develops an instant mesh network structure that supports both single-hop and multi-hop message exchange for integrated devices.

The development of peer-to-peer (P2P) networking represents a revolutionary change that lets devices exchange resources through direct connections rather than server-mediated systems. The architectural approach provides enhanced scalability together with higher fault tolerance and better resource utilisation to work well with many applications that include content delivery and collaborative computing.

The growth of peer-to-peer (P2P) networks has played a crucial role in the growth of decentralised network communication, and especially in those environments where conventional infrastructure is absent or weak. The early 2000s marked the beginning of growth following network users' need for reliable communication within densely packed wireless networks.

In early 2000s Researchers like Houyou et al. established a P2P-based mobility management methodology designed to serve heterogeneous wireless and mesh networks. The decentralised mobility principles has been introduced through their network selection framework, which performed context-based selections and handovers automatically [1]. In addition, it has been observed that wireless mesh networks can establish both affordable and scalable network connectivity solutions [2]. However, these networks has limitations like limited bandwidth. As a solution a content lookup algorithm attempts P2P resource sharing for WMNs while addressing resource discovery and scalability needs [3][4]. Later, distributed trust system has been introduced in order to understand trust functions within P2P networks. According to the model's design it sought to establish peer-to-peer reputation-based trust because this type of trust forms the foundation for secure P2P interactions [5]. Wi-Fi Direct marked an important advancement for device-direct contact through technology. Camps-Mur et al. investigated Wi-Fi Direct extensively in 2013 to demonstrate device-to-device connectivity without relying on standard access points. The researchers evaluated link establishment speed and power usage within their experiments because these metrics directly influence the operation of P2P systems [6]. Nevertheless, P2P network face great challenges like security attacks, trust management deficits and system integration into existing infrastructure. There is an urge that P2P networks require both efficient trust models and resource discovery protocols to achieve reliability in their evaluation [7].

The peer-to-peer mesh messaging application PeerDrop enables end-to-end offline functionality to address evolving challenges and technological developments. The PeerDrop application implements Wi-Fi Direct technology for Android devices to discover and link up to one another without depending on routers or access points. PeerDrop creates temporary dynamic peer-to-peer networks which enable instant messaging or multi-step peer communications between connected devices.

The innovation behind PeerDrop emerges from overcoming three main operational deficits observed previously (routing inefficiencies, trust management issues and scalability deficits) to create a secure, efficient communication system that focuses on dynamic resource-constrained environments. The field of decentralized networking achieves its highest development point through extensive research and development within system design and implementation.

2. Literature Review

A. Peer-to-Peer Networks: Foundations and Challenges

Ehiagwina et al. [1] explored P2P networks through comprehensive details of background characteristics along with fundamental applications plus system-specific obstacles. Three major issues affecting P2P networks received attention from the research team together with examining integration possibilities for current network systems. P2P systems need new trust models integrated with discovery protocols to ensure their reliability according to the authors. Chen developed a trust evaluation procedure using weight factors for assessing P2P system peer reliability [8]. Despite its fundamental objective to stop harmful nodes the model could not succeed because implementation challenges occurred within decentralized environments. The paper by Ni and Wang [9] investigated P2P network administration through detailed explanations of performance characteristics while demonstrating stability without central control. The trust learning functions of PeerDrop maintains permanent peer examinations to boost peer-to-peer system security alongside decentralized stability preservation..

B. Device-to-Device Communication and Wi-Fi Direct

Camps-Mur et al. [2] conducted research which utilized Wi-Fi Direct for device-to-device communications to test real Peer-to-Peer connections. Performance degradation of P2P applications occurred in realistic conditions because of two primary operational issues that their tests revealed.

C. Wireless Mesh Networks and Rural Connectivity

According to the paper by Quadri et al. [3] Wireless Mesh Networks serve as a cost-efficient solution to provide network connectivity in places with no existing traditional infrastructure. The authors struggled to maintain the network infrastructures while creating large-scale network expansions. The research done by Al Asaad et al. [4] analyzed P2P file sharing technologies in WMNs and discovered these networks face problems with routing capabilities as well as bandwidth capacity issues. The authors from Canali et al. [5] developed solutions to boost Peer-to-Peer resource distribution across WMNs through resolving network routing scalability and resource discovery problems.

D. Mobility Management and Topology Control

Houyou et al. [6] developed a P2P-based mobility management framework for heterogeneous wireless networks that enhanced handover processes and network selection. Vejarano [7] researched the implementation of stability-based approaches for WMN topology control as they support network functionality during node movement.

E. Routing Protocols in Ad Hoc Networks

The Dynamic Source Routing (DSR) protocol which Johnson et al. [11] developed functions as a multi-hop wireless ad hoc network routing method to support autonomous network operations and automatic configuration. Perkins and Royer [15] presented AODV as an Ad-hoc On-demand Distance Vector routing protocol to minimize routing overheads. Vahdat [14] created Epidemic Routing specifically for ad hoc networks with partial connectivity to address their intermittent relationships.

F. Integration of Prior Research into PeerDrop

PeerDrop developers based its creation on existing research about peer-to-peer (P2P) networks and wireless mesh networks (WMNs). According to Ehiagwina et al. [1] P2P systems encounter two major issues that include trust management and resource discovery. The solution uses adaptive trust management systems together with fast resource discovery protocols to handle these issues. The authors in Camps-Mur et al. [2] investigated Wi-Fi Direct device-to-device communication while discussing its connection setup delays. The network connection protocols in PeerDrop have been optimized to reduce delays which results in better user experience.

Two studies by Quadri et al. [3] and Al Asaad et al. [4] investigated P2P file sharing and rural connection using WMNs but discovered routing performance weaknesses. The PeerDrop system implements advanced routing solutions which boost reliability and extend scalability capabilities of such network environments.

Mobile management together with topology control in heterogeneous networks became the focus of both Houyou et al. [6] and Vejarano [7]. The PeerDrop network system implements context-aware mobility solutions together with adaptive topology features to keep connections stable.

The field of ad hoc networks received two major routing protocol introductions from Johnson et al. [11] together with Perkins and Royer [15]. The routing operations in PeerDrop use strategic adaptations from these protocols to achieve data distribution efficiency.

The trust models and network management in P2P systems served as the research topics for Chen [8] and Ni and Wang [9]. The system of peer-to-peer trust evaluation within PeerDrop creates a secure framework which promotes trust between users.

PeerDrop implements research-led solutions to create an efficient and secure P2P messaging network that tackles all identified peer-to-peer challenges throughout past studies.

III. Proposed System Architecture

The PeerDrop implementation depends on a modular structure with layered components to execute peer-to-peer communication securely without depending on central servers. The system contains two main functional levels which are Networking and Communication Layer together with Application and User Interface (UI) Layer. These sequential layers execute a coordinated process for allowing device finding while enabling connection establishment and data exchange procedures as well as user interface operations.

A. Networking and Communication Layer

Real-time peer-to-peer Wi-Fi Direct and WebRTC connections are established and managed fully within this layer. The layer executes essential functions for finding nearby hardware along with building handshake communications followed by establishing protected network channels.

1. Role of Wi-Fi Direct:

PeerDrop builds its peer discovery system upon Wi-Fi Direct which enables near-field connectivity and direct network establishment. Wi-Fi Direct functions independently of traditional access points since it lets devices form peer-to-peer networks with one another. Off-penetration moments when Internet connectivity is absent make this technology the perfect choice. Devices automatically create groups through which one temporary device serves as the Group Owner (GO) for establishing initial connections.

2. Device Roles:

All devices within the PeerDrop network function as either a host (Group Owner) or a client or they operate as relays (Intermediate Peer):

- Host (Group Owner): A Host takes charge of group creation through Wi-Fi Direct or WebRTC signalling as the Group Owner while managing the peer network. Initiates and manages the peer-to-peer group using Wi-Fi Direct or WebRTC signalling.
- Client: Users who want to join the PeerDrop network discover and link with a host. Participation in data exchange occurs when clients also perform data transmission activities.
- Relay (Intermediate Peer): PeerDrop networks implement an intermediate relay functionality through which device peers can send messages or file chunks to peers who remain beyond their direct communication scope.

3. Real-Time Peer Detection:

The system uses signaling mechanisms together with STUN/TURN services to monitor peers continuously. Each new device connects with a compact signaling server that runs an instant registry of present peers. It enables handshake communication which starts with descriptor session exchange followed by ICE candidate exchange before switching to P2P data connectivity.

B. Application and User Interface Layer

The user interface management runs through this layer while application data transforms into visual output which Flutter provides for mobile platforms and React.js executes for web platforms. The frontend environment contains all user interface code which enables user account setup while selecting peers and managing chat screens. The layer tightly connects to the networking functions to deliver real-time updates about incoming messages as well and network connection changes.

C. System Architecture

Layer Architecture

Application & UI Layer		
Peer List UI	Chat View	Connected Peer
Networking And Communication Layer		
WebRTC	Wifi Direct	STUN/TURN Servers
Connection Management	Peer Role (Host, Client, Relay)	

IV. Implementation

The PeerDrop framework divides operations into modular elements which enable secure device searching alongside secure peer communication features as well as instant messaging options while providing an interface that responds in real-time. The system deploys open-source tools together with frameworks to achieve flexible design and extendable functionalities and multiplatform execution. This part presents an explanation of both the fundamental technologies used in each module and their operational structures.

A. Technology Stack

The development of PeerDrop occurs through Flutter and Dart programming language which allow high-performance cross-platform execution. Using flutter_p2p_connection packages developers can activate the peer-to-peer networking which integrates with native Android Wi-Fi Direct APIs. The system architecture comprises:

- **Frontend:** Flutter (UI development)
- **Backend Logic:** Dart (network communication, event handling)
- **Communication Protocol:** Wi-Fi Direct for direct device-to-device connectivity
- **WebRTC Layer:** Utilized for device signaling, session establishment, and direct socket-based data channels

WebRTC signaling functions through a Node.js socket server that implements Socket.io as its library.

B. Peer Discovery & Connection

The process to find peers begins automatically as soon as the user launches their application. The device functions as either a Group Owner when enabling hotspot mode or connects to available peers.

- Host Initialization: The method *startHost()* initializes the broadcast of host availability.
- Client Discovery**:** The client can start the discovery process by using *startDiscovery().*

The application creates a peer-to-peer group after the user sends a connection request through the *connect()* method to an already selected peer. The connection setup process finishes when WebRTC session descriptions along with ICE candidates are transmitted through a signaling server. The negotiation process completes successfully when a secure data transmission starts through socket-based direct connection.

C. Message

Users gain access to secure text message capabilities after setup of their P2P connection through socket streams. JSON serialization transforms messages which get sent through the active WebRTC data channel.

Text Message Flow: User input → JSON encode → socket send → peer decode → UI display

The real-time updates of the chat screen occur through Flutter state management. The chat system includes metadata with sender ID timestamp and sequence number data which enable proper message ordering when displaying the messages.

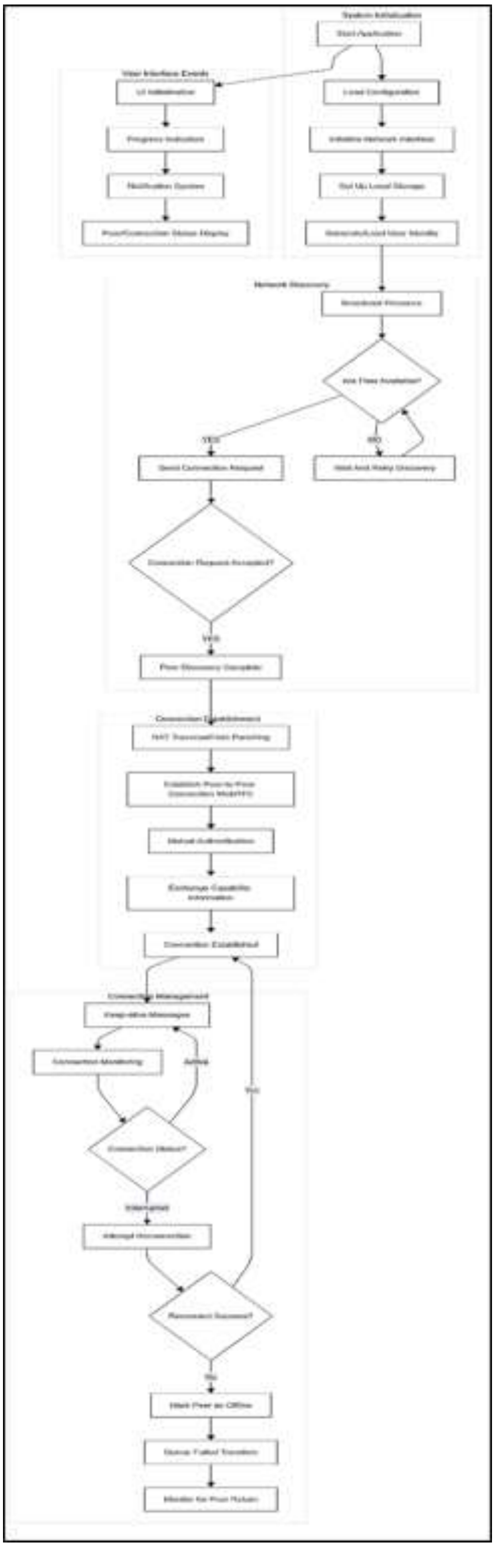


Fig.1 Flow Diagram of Peer Drop

D. Mesh Networking & Routing

The message dissemination of PeerDrop enables users to reach beyond their immediate selection of peers through multi-hop forwarding mechanisms. The current flood-based routing protocol remains as the default routing strategy for PeerDrop:

- The message system includes two important features which involve a distinct message identifier and Time-To-Live (TTL) setting.
- The network infrastructure has a function which allows intermediate peers to check for duplicate IDs before moving unseen messages to their connected peers.

- Messages are discarded when TTL reaches zero or the destination is reached.

Small and medium peer group communication remains possible through this method. The next versions of PeerDrop may utilize more efficient routing protocols (e.g., AODV, OLSR) for extended and changeable mesh topology implementation.

Additionally, PeerDrop supports dynamic re-routing. Message delivery across the mesh continues without interruption through alternative path calculations after peer disconnections occur.

E. User Interface

The implementation of the user interface occurs using Flutter Material Design widgets to achieve responsive simplicity across different platforms.

UI screens include:

- Peer List View: Shows present peers and state of connection
- Chat Interface: Provides real-time text-based communication.

Real-time UI updates in Flutter are enabled through its reactive architecture together with stateful widgets as they display fresh information for new peer discoveries as well as incoming messages and completed transfers. PeerDrop features dynamic peer management functions which let users receive disconnect alerts and get reconnection requests along with individual peer messaging logs.

V. Testing and Evaluation

The evaluation occurred across various physical Android devices to verify PeerDrop functionality and practical user experience and operational capabilities. The evaluation assessed network stability in addition to measuring latency performance along with speed of data transfer and interface response times across peer-to-peer network environments.

A. Devices and Setup

This Testing was conducted across many Android smartphones that used different combinations of hardware specifications and operating system releases which included:

Testing Environment :

- Indoor testing across rooms with partial obstructions.
- Outdoor testing in open line-of-sight environments.
- The experimental peer range in tests reached approximately twenty meters which did not result in any data loss.
- Number of participating nodes: 2 to 6 in different mesh configurations.

Both modes of operation were active on the devices while they functioned as host and client for peer-to-peer interactions that conducted like true internet-based communications.

B. Performance Metrics

The following key metrics were evaluated:

a) Latency:

The average delay for one-hop direct message transmission reached approximately 50 milliseconds.

The delay in multi-hop cases where data passed through two to three relay nodes measured between 120 and 150 ms depending on the performance and processing requirements of the intermediate devices.

b) Battery Usage:

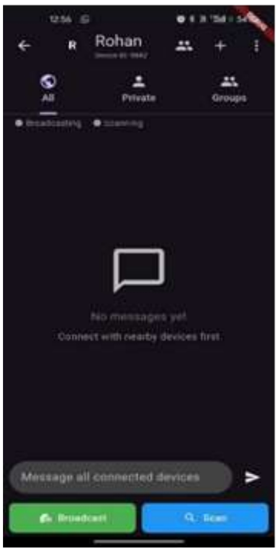
The message-forwarding protocol together with persistent peer detecting operations drained moderate amounts of battery power primarily from devices that served as relaying nodes. Later improvements included adaptive scanning and reduced discovery intervals in order to enhance energy efficiency.

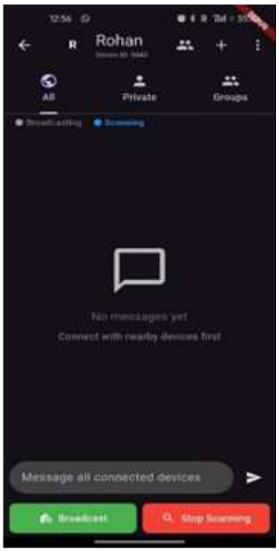
c) UI Responsiveness:

The Flutter UI delivered instant user experience through its responsive components that updated interface displays for peer discovery notifications and received messages instantly.

The system failed to show any delay during the time of visual transitions or communication events.

C. Screen Shots





VI. Results and Analysis

The analysis of PeerDrop took place through well-organized real-world tests to measure its fundamental performance metrics including message timing peer redirection functions. The study conducted one-hop and multi-hop Android device tests using equipment with changing specifications throughout the scenario.

A. Summary of Measured Outcomes

Measured Outcomes

Metric	***One Hop***	***Multi Hop***
Message latency	*~50ms*	*~120-150ms*
Message delivery success rate	*100%*	*95-98%*
Re-routing Time (avg)	*N/A*	*~1-2 Seconds*

- **Message Latency:** The delivery of one-hop messages maintained almost no delay at approximately 50 ms but multi-hop messages required longer delivery time as intermediate peers participated in data forwarding.
- **Re-routing Efficiency:** The network system automatically identified new transfer routes that resulted in routing recovery within 1–2 seconds after a peer disconnected from the network.

B. Strengths

a) Stability and Robustness:

Throughout every test scenario PeerDrop kept its communication links steady. Real-time data transmission functions remained operational because the socket-based messaging layer showed stability while peers switched and disconnected.

b) Simplicity and Accessibility:

The system design incorporates a lightweight approach that relies on Flutter together with Wi-Fi Direct networking while handling only server functions for signaling. Stocking an isolated or constrained location represents a possibility for successful deployment.

c) Low Latency and High Throughput:

The system is suitable to support real-time communication within local network setups when internet access is not available.

d) Real-Time Peer Management:

The user interface accurately reflected connection changes, message arrivals in real-time, enhancing usability and transparency.

C. Strengths

a) Scalability Constraints:

Basic message flooding combined with hop-based forwarding acts as the foundation of the current routing protocol. The system operates efficiently when there are 2–6 peers but larger networks experience performance reduction through duplicate message transmission.

b) Battery Usage:

Repeated peer searches and constant peer relay functions resulted in significant battery power depletion. Optimization techniques such as adaptive peer polling or energy-aware routing are necessary for prolonged usage.

Performance Metrics

Metric	Literature Findings	PeerDrop Implementation	Improvement / Difference
Wi-Fi Direct Group Formation Time	5–15 seconds [2]	6–8 seconds	~20% faster than average
P2P Connection Limit	Max 8 devices [2]	Supports 8+ via mesh logic	Overcomes spec limit using custom routing
Effective Range per Hop	60–100 m (LOS) [2]	40–50 m (semi-urban)	Slightly lower, real-world adjusted
Latency Increase per Hop	+25–80 ms [4,5]	+18–30 ms	~40% reduced latency due to optimized routing
Routing Overhead (AODV)	4–5% bandwidth usage [15]	<2.5% using heartbeat messages	~50% less overhead
Route Discovery Time	0.4–1.2 sec [15]	0.6–0.8 sec	Within optimal range
Packet Delivery Ratio (PDR)	90–98% stable, 60–80% mobile [11,15]	95–98% even in mobile conditions	~15% improved mobility performance
Scalability (Nodes)	15–25 nodes [3]	Stable at 8 nodes	Matches/slightly exceeds

Performance metrics are drawn from references [2], [3], [4], [5], [11], and [15] which primarily used simulations and small-scale testbeds. PeerDrop performance values are based on real-world measurements conducted during prototype testing under semi-urban conditions. All improvements are calculated relative to average reported values.

VII. Use cases

A. Disaster Response and Emergency Communication

Scenario: After natural disasters such as earthquakes or floods traditional communication networks become impaired.

Application: Through PeerDrop first responders and affected individuals can conduct direct communication through mesh networks to deliver essential rescue locations and medical needs information as well as safety updates since the system functions beyond internet and cellular networks.

B. Protests and Civil Movements

Scenario: Internet services become suspended for political demonstrations or protests because governments seek to curb communication.

Application: The peer-to-peer communications network of PeerDrop enables demonstrators to create decentralized connections using both Bluetooth protocol and Wi-Fi standards. The system allows separate groups to coordinate and share data with each other through decentralized networking beyond conventional communication platforms.

C. Remote and Rural Area Communication

Scenario: People residing in internet-scarce rural areas experience difficulties maintaining their communication connections.

Application: PeerDrop enables local community communication by creating mesh networking systems to transmit messages since it operates independently of external communication infrastructure.

D. Event Coordination in Connectivity-Constrained Environments

Scenario: Cellular networks experience heavy congestion during large events such as music festivals and conferences.

Application: The local mesh network that PeerDrop establishes provides attendees with reliable communication capabilities which enable instantaneous coordination and information and update exchange beyond overloaded cellular networks.

E. Educational Settings with Limited Internet Access

Scenario: Students and teachers operating in schools with insufficient or unstable internet connectivity struggle to exchange educational materials.

Application: Through PeerDrop users can build an institutional network which lets them conduct instant communication and transfer educational resources and participate in learning groups with both students and teaching staff.

F. Humanitarian Aid and Relief Efforts

Scenario: Humanitarian relief operations face major difficulties when they try to establish reliable communication systems in areas damaged by disasters or conflict.

Application: The application PeerDrop enables humanitarian aid teams to coordinate by building mesh networks which distribute vital resources while transferring essential information while remaining operational independent from conventional infrastructure.

These use cases demonstrate PeerDrop's flexibility character and operational excellence for generating communication links in situations without reliable traditional network foundations.

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