Optimizing Data Consistency in Intermittent Network Environments: A Hybrid Synchronization Protocol for Rural Micro-Finance Applications

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Abstract — Rural Self-Help Groups (SHGs) in India form the backbone of grassroots financial inclusion; however, their record-keeping remains largely paper-based and error-prone. Digitizing these ledgers introduces a critical challenge: maintaining data consistency when network connectivity is unreliable or absent. This study presents a hybrid synchronization protocol implemented in the Bharat Bachat Android application, which is specifically designed to guarantee data consistency for SHG ledger operations under intermittent network conditions. The protocol combines a local-first SQLite edge database with a conflict-aware, timestamp-driven synchronization engine that asynchronously replicates records to a centralized Laravel/MySQL backend. This study examines the consistency guarantees of this design, the mechanisms that prevent data loss or corruption during prolonged offline periods, and the conflict resolution strategies employed when multiple offline sessions converge. The results demonstrate that the proposed protocol achieves strong eventual consistency with zero data loss across disconnection periods, making it a viable and cost-effective solution for rural microfinance digitization.

Keywords: Self-Help Group (SHG) Digitization; Offline-First Synchronization; Data Consistency Protocol; SQLite Edge Database; Conflict Resolution Mechanism; Rural Microfinance Systems;

I. Introduction

India's SHG ecosystem, comprising over 12 million active groups, collectively manages billions of rupees in savings and microloans at the village level. The Gat Pramukh (group administrator) typically records attendance, contributions, penalties, and loan transactions by hand in a paper ledger during weekly or monthly meetings. This method is vulnerable to physical damage, transcription errors, and the complete absence of audit trails.

Transitioning to a digital platform is an obvious improvement in this regard. However, conventional cloud-first mobile applications assume persistent Internet access. In rural Maharashtra and comparable regions, cellular connectivity is frequently intermittent, dropping mid-session or entirely absent in low-signal villages. A cloud-dependent application that freezes or crashes when connectivity is lost is not merely inconvenient; it is functionally undeployable in these environments.

The Bharat Bachat application addresses this by inverting the conventional architecture: the mobile device is treated as an authoritative data source during active use, and the cloud server functions as an asynchronous consistency target. This paper focuses specifically on how data consistency — the guarantee that all copies of the ledger eventually reflect the same correct state — is maintained throughout this process and the precise mechanisms that achieve it.

II. Literature Review and Research Gap

The CAP theorem (Brewer, 2000) states that distributed systems cannot simultaneously guarantee consistency, availability, and partition tolerance. In mobile environments where network partitions are routine, prior research has widely adopted eventual consistency models that sacrifice immediate consistency for continued availability. Kleppmann et al. (2019) introduced the local-first software paradigm, in which the user's device holds the primary copy of the data and cloud servers serve as synchronization facilitators rather than primary sources of truth. This model closely aligns with the requirements of SHG applications. Similarly, the architecture of Amazon Dynamo (DeCandia et al., 2007) demonstrated that optimistic replication with vector-clock-based conflict detection could maintain high availability under unreliable network conditions.

Why Do We Need a New Protocol? Despite these advancements, existing commercial offline-first solutions (such as Firebase Firestore) impose per-read/write billing models that are economically prohibitive for rural NGOs operating on thin margins. Furthermore, conventional cloud-dependent applications frequently freeze or crash in low-signal villages in rural Maharashtra, rendering them functionally undeployable. Therefore, there is a critical need for a low-cost, offline-capable architecture that guarantees ledger integrity without relying on expensive commercial cloud syncing services.

How Are We Addressing the Gap? Most local-first research addresses collaborative tools (document editors, project management) where simultaneous multi-user edits on the same record are common and drive complex Conflict-free Replicated Data Type (CRDT) implementations. SHG ledger operations present a structurally different problem: a single administrator writes all records for a group, meaning that write conflicts are rare, but data ordering and integrity across synchronization gaps are critical. This study addresses this gap by proposing a lightweight, deterministic, timestamp-based consistency protocol tuned for single-writer, multi-reader SHG ledger contexts.

III. Proposed Architecture

The core infrastructure of the Bharat Bachat system relies on a dual-tier database strategy designed to decouple user interaction from network latency.

– Edge Storage Layer (SQLite): An embedded relational database that sits directly within the Android mobile application. It handles all immediate read and write queries, granting users instantaneous feedback without waiting for server validation.

- Offline Operation Queue: Whenever a user alters data while offline (e.g., adding a penalty), the application logs the transaction and tags it with a sync_pending status. This queue safely stores the actions locally until the conditions improve.
- Centralized Backend (Laravel/MySQL): A remote RESTful API built on the Laravel PHP framework manages the central repository hosted on the cloud server. It acts as the ultimate authority, consolidating decentralized data from multiple SHG groups.
- Timestamp Resolution Protocol: To handle discrepancies when data are uploaded, the server evaluates the precise Unix timestamps of incoming requests, ensuring that the most recent and legitimate ledger entry is preserved.

IV. Overview of Synchronization Methods

To justify the architecture of the *Bharat Bachat* application, it is important to look at how mobile applications typically handle data synchronization and evaluate why a hybrid approach is the most effective solution for intermittent network zones.

A. Traditional Synchronization Paradigms

When a mobile application needs to share data with a central server, it generally follows one of two traditional approaches. Each approach presents a specific trade-off between keeping data identical across devices (Consistency) and keeping the app running when the internet drops (Availability).

1) Synchronous (Real-Time) Synchronization Engine

- How it Works: In a synchronous model, the application depends entirely on a continuous internet connection. When a user creates a transaction, the app sends a request directly to the server and waits for a response. The transaction is not finalized locally, and the user interface remains locked or loading, until the server sends back a success confirmation (such as an HTTP 200 OK message).
- Limitations in Rural Areas: If the mobile signal is weak or drops entirely—which is a daily reality in rural villages—the connection times out. This causes the application to freeze, lag, or crash. While this method guarantees that data on the server and the phone match perfectly, it makes the app completely unusable without strong internet access.

2) Asynchronous (Deferred/Batch) Synchronization Engine

- How it Works: This model detaches the app's daily operations from the state of the network using a "store-and-forward" workflow. When a user saves data, it is written immediately to a local database on the phone. The application continues to function normally even if there is no internet. A separate background process is responsible for collecting these saved changes and sending them to the cloud later when a network connection is found.
- Limitations: Although this ensures the app stays open and responsive offline, it introduces the risk of delayed data updates. If two users edit the exact same record while offline, their data will conflict when both devices try to sync with the server at the same time. The backend requires a dedicated system to handle these overlaps cleanly.

B. Synchronization Paths and Conflict …….Resolution

Developers typically choose from three main paths to move data, alongside specific methods to handle conflicting updates.

1) Primary Synchronization Paths:

- Real-Time Sync: Data goes straight to the server. It fails instantly if the user goes offline, making it impractical for rural microfinance.
- Continuous Background Sync: The app keeps an open, persistent connection (like WebSockets) to stream updates instantly. This rapidly drains the phone's battery and consumes a large amount of mobile data, which rural users cannot afford.
- Batch Sync: Data is saved locally and sent to the server in groups later on. This handles network drops perfectly but requires clear rules for merging data.
- Common Conflict Resolution Methods:
- Operational Transformation (OT) & CRDTs: These are highly complex algorithms used in multi-user live editing tools (like Google Docs) to merge changes text-by-text. They require massive computing power and are overly complicated for simple accounting ledgers.
- Last-Write-Wins (LWW) via Timestamps: A straightforward, definitive approach. The server checks the exact timestamp of when the action happened on the phone and saves the newest version.

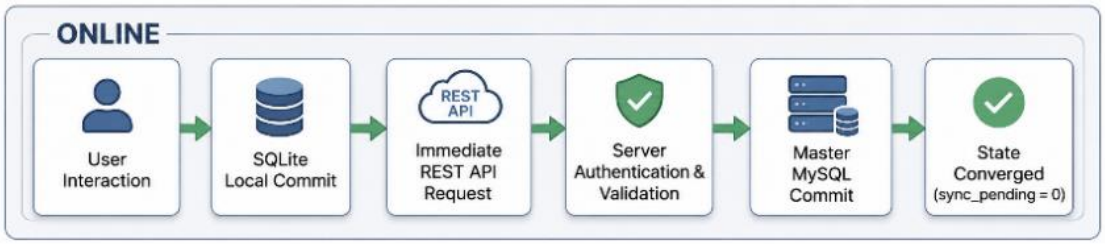
C. Why a Hybrid Approach was Chosen for ……Bharat Bachat

Our proposed system uses a Hybrid Synchronization Protocol to combine the best parts of both methods. To the user, the app feels *Synchronous* because it records reads and writes instantly into a local SQLite database with zero loading screens. Behind the scenes, it acts *Asynchronously* by queueing those transactions and sending them to our Laravel server in efficient compressed batches only when internet is available. By using a clean Last-Write-Wins timestamp check on the server, we achieve reliable data consistency without heavy code or expensive cloud bills.

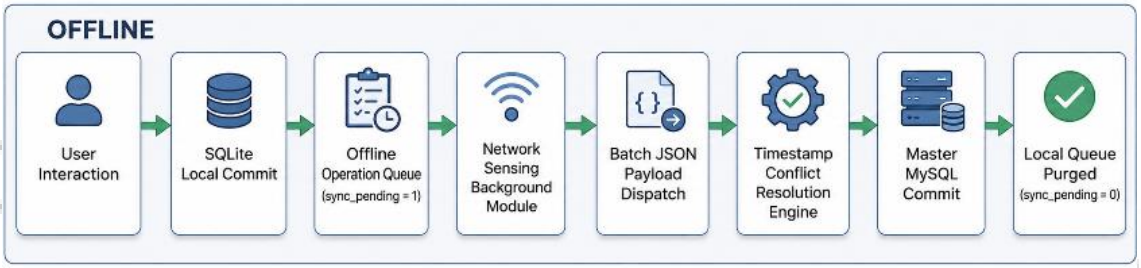
V. System Workflow and Synchronization

The data flow ensures high availability through the following lifecycle:

- Action Initiation: The Gat Pramukh inputs data, such as marking a member as present or noting a monthly financial contribution.
- Local Commit: The app instantly saves this information to the local SQLite tables and immediately refreshes the user interface.



- Network Sensing: The transaction is flagged in the background. The application actively monitors the mobile operating system for internet reachability.
- Payload Delivery: Upon detecting a stable network, the app compiles all pending actions into a lightweight JSON payload and dispatches it via a POST request to the Laravel API.
- Server Validation: : The backend processes the payload, verifies role permissions, resolves any chronological conflicts, updates the master MySQL database, and sends a success confirmation back to the device to clear the local queue.



VI. KEY MODULES

- Instant Dashboard: A fully functional interface that loads SHG metrics, member lists, and previous meeting topics instantly from device memory, bypassing network loading screens.
- Ledger Management: Interfaces dedicated to logging financial contributions, applying non-repayment penalties, and tracking loans, all engineered to function offline.
- Automated Report Generation: A local module that compiles validated savings and loan data into formatted PDF documents, allowing the Pramukh to easily distribute records via WhatsApp.

VII. SYSTEM BENEFITS

1) Uninterrupted Operations: SHG meetings can be conducted in the most remote locations without fear of software downtime or data loss.
2) Reduced Bandwidth Consumption: By syncing data in compressed JSON batches rather than constant API polling, the app conserves cellular data, which is a critical factor for rural users.
3) Cost Predictability: Utilizing standard relational databases (SQLite and MySQL) with a PHP backend avoids the unpredictable scaling billing cycles of commercial NoSQL cloud database services.

VIII. LIMITATIONS

1) Data Latency: Because the system relies on eventual consistency, there might be a slight delay before an individual member sees their updated loan status on their own device, depending on when the Pramukh's device regains connectivity.
2) Storage Requirements: Maintaining a comprehensive local replica of the group's history requires sufficient persistent storage space on the administrator's smartphone.

IX. CONCLUSION

Transitioning rural microfinance operations from paper to digital mediums requires architectural empathy for the infrastructural realities of the target environment. The Bharat Bachat application proves that a hybrid synchronization approach—anchoring operations on local SQLite storage while asynchronously communicating with a central Laravel server—offers a highly resilient solution. By prioritizing local-first data availability and implementing lightweight background synchronization, this protocol successfully overcomes the limitations of intermittent rural connectivity, providing SHGs with a reliable, efficient, and transparent tool for community financial management.

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