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CRDT based Peer-to-Peer Collaborative Editor

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Abstract- The design of this product presents a fully featured collaborative document editor built using Conflict-free Repli-cated Data Types (CRDTs) and peer-to-peer communication over WebRTC. The system leverages Y.js as its core synchro-nization engine to enable real-time, decentralized collaboration without reliance on a centralized server for document state management. Traditional collaborative editors often depend on Operational Transformation (OT) and centralized architectures to maintain consistency. In contrast, this implementation adopts a CRDT-based model, allowing each client to maintain a local replica of the document while guaranteeing eventual consistency across all peers. By integrating WebRTC for direct peer-to-peer communication, the system reduces latency, improves scalability, and enhances resilience against single points of failure. The editor supports rich-text formatting, concurrent multi-user editing, cursor awareness, offline editing with au-tomatic synchronization upon reconnection, and conflict-free merging of changes. Y.js manages shared data structures and efficiently propagates incremental updates between peers. The WebRTC layer establishes secure data channels for real-time message exchange, enabling seamless synchronization across distributed clients. Key challenges addressed include peer dis-covery, network reliability, conflict resolution in highly concur-rent environments, and maintaining low-latency performance at scale. The architecture separates document state management, networking, and user interface layers to ensure modularity and extensibility. This method demonstrates how CRDTs combined with modern web technologies can deliver a scalable, decentral-ized alternative to traditional collaborative editing systems. The resulting platform provides strong consistency guarantees, high performance, and fault tolerance, making it suitable for real-time document collaboration in distributed and intermittently connected environments.

Keywords: CRDTs, peer-to-peer collaboration, WebRTC, Y.js, real-time synchronization, decentralized architecture, eventual consistency, distributed systems, collaborative editing, rich-text editor, multi-user concurrency, conflict-free merging, offline support, automatic synchronization, low latency, scalability, fault tolerance, peer discovery, network resilience, modular architecture.

I. INTRODUCTION (ALUMINIUM H9 MATERIAL)

Real-time collaborative editing has become a critical re-quirement for distributed teams. Traditional architectures, such as Google Docs, rely on Operational Transformation (OT) and centralized servers to maintain document consis-tency. However, these models introduce several challenges, including high latency due to round-trip server communica-tion, privacy risks associated with centralized data storage, and vulnerability to single points of failure.

This paper proposes a decentralized alternative using Conflict-free Replicated Data Types (CRDTs) over a Peer-to-Peer (P2P) network. By utilizing the Y.js framework and WebRTC protocol, we demonstrate a system where document state is synchronized directly between client browsers. This approach ensures "Strong Eventual Consistency" (SEC), al-lowing users to work offline and merge changes seamlessly upon reconnection. The following sections detail the system architecture, the integration of the Quill rich-text editor, and *The authors are students with the Department of Computer Science and Engineering the underlying synchronization logic that enables a serverless collaborative environment.

II. PROPOSED METHODOLOGY

The architecture of the proposed system is divided into three functional layers: the Presentation Layer

(UI), the Synchronization Layer (CRDT Engine), and the Networking Layer (P2P Communication).

A. The Synchronization Layer (Y.js Engine)

The core of the system is the Y.js CRDT engine, which manages a shared document state known as a Y.Doc. Unlike OT, which requires a specific order of operations, Y.js represents the document as a set of unique items identified by a Client ID and a Lamport clock.

When a user modifies the document, Y.js generates an incremental update—a compact, binary-encoded state vector. This update is commutative and associative, meaning it can be applied in any order by other peers to reach the same final document state. This ensures "Strong Eventual Consistency" (SEC) across all distributed clients.

B. The Presentation Layer (Quill and y-quill)

The User Interface is built using the Quill Rich-Text Editor. To bridge the gap between the editor's Delta format and the Y.js internal state, we implement the y − quill binding. This module observes changes in the Quill editor and translates them into Y.js operations. Conversely, when a remote update is received from the network, the binding ap-plies the change to the local Quill instance without triggering a recursive update loop, ensuring a smooth user experience with cursor awareness and multi-user highlights.

C. The Networking Layer (WebRTC and Signaling)

For decentralized communication, the system utilizes the y − webrtc provider. The process follows a three-step syn-chronization protocol:

1) Signaling: Peers initially connect to a lightweight signaling server to exchange SDP (Session Description Protocol) offers and ICE candidates. No document data is stored on this server.
2) P2P Connection: Once a handshake is established, a direct WebRTC Data Channel is opened between peers.
3) State Exchange: Upon connection, peers exchange "State Vectors" to determine missing segments of the document. Only missing binary fragments are trans-mitted, minimizing bandwidth consumption.

By combining these layers, the system achieves a server-less collaborative environment in which the document lives entirely within the browsers of the participating peers.

D. Figures and Tables

As illustrated in Fig. 1, the system architecture facilitates a decentralized data flow. When a user performs an edit in the Quill UI, the y − quill binding interceptor translates the event into a state update within the local Y.Doc. This update is binary-encoded as a state vector and propagated through the WebRTC Data Channel to all connected peers. Unlike traditional client-server models, reconciliation of concurrent edits takes place entirely in the client-side replica, ensuring that no central authority is required for conflict resolution.

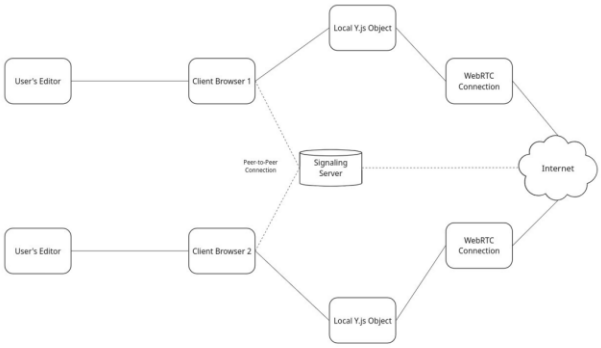

Fig. 1. System Architecture of the Peer-to-Peer CRDT Editor: Illustrating the synchronization flow between the Quill UI, Y.js Engine, and WebRTC Data Channels.

Table I
Technical Comparison: Centralized Ot Vs. Proposed P2p Crdt

Feature	Traditional (OT)	Proposed (CRDT)
Architecture	Client-Server	Peer-to-Peer
Consistency	Server-sequenced	Strong Eventual (SEC)
Offline Support	Complex	Native
Data Privacy	Low (Server-hosted)	High (Local-first)
Network Protocol	HTTP/WebSockets	WebRTC Data Channels

III. THE TECHNOLOGY

A. The Mathematical Model of State

Distributed collaborative systems require data structures that converge to a consistent state without centralized co-ordination. Y.js utilizes a Sequence CRDT approach. Every character or block in the document is represented as an Item with a unique identifier ID:

ID = (client_id, counter) (1)

where client_id is a unique peer identifier and counter is a local Lamport clock that increments with every operation.

B. Conflict Resolution Logic

To maintain the relative order of text during concurrent edits, each item stores pointers to its neighbors at the time of creation: originLeft and originRight. When two peers insert text at the same position simultaneously, Y.js resolves the conflict using the following rule:

1) If two items have the same originLeft, the item with the higher client_id is positioned first.
2) This ensures a total ordering of operations that is iden-tical across all replicas, satisfying the Commutative and Associative properties of SEC.

C. State Vector Synchronization

To minimize bandwidth, the system does not transmit the entire document. Instead, it uses State Vectors. A State Vector represents the "knowledge" of a client, mapping every client_id it has seen to the highest counter received:

SV = {(client1 : counter1), (client2 : counter2), ...} (2)

When two peers connect via WebRTC, they exchange these vectors. Peer A sends only the operations that Peer B is missing (counterA > counterB), resulting in an incremental binary update.

IV. GARBAGE COLLECTION AND MEMORY OPTIMIZATION

A primary challenge in CRDT-based systems is the ac-cumulation of metadata. Since every character insertion is assigned a unique ID, naive implementations would cause the document's memory footprint to grow monotonically, even when text is deleted. These deleted elements, known as tombstones, are traditionally kept to ensure that late-joining peers can correctly position their edits relative to the deleted content.

A. The Tombstone Problem

In a standard Sequence CRDT, a deletion does not remove an item from the data structure; it merely marks it as "deleted." This is necessary because a concurrent insertion from another peer might still reference the deleted item's ID as its originLeft. Removing the item entirely would break the causal tree and lead to divergence.

B. Y.js Struct Store Optimization

The proposed system utilizes the Y.js Struct Store to mitigate this overhead. Instead of storing each character as an individual object, Y.js merges adjacent items created by the same user into a single contiguous block (a "struct").

When a range of text is deleted, the system performs two optimizations:

1) Item Merging: If two adjacent items are deleted, they are merged into a single deleted struct. This reduces the number of objects the engine must traverse during synchronization.

2) Content Pruning: The actual UTF-8 string content of a deleted item is permanently discarded from memory. Only the metadata—the ID and the length of the deleted range—is retained.

C. Mathematical Impact on Performance

Let N be the total number of operations (insertions and deletions) and M be the number of active characters in the document. In a non-optimized CRDT, the space complexity is O(N). With the implemented garbage collection and struct-merging strategy, the effective complexity is reduced toward O(M + S), where S represents the set of minimal metadata fragments required to maintain causal history.

This optimization ensures that the editor remains perfor-mant even after thousands of edits, preventing the "memory leak" effect common in early decentralized collaborative tools.

V. NAT TRAVERSAL AND WEBRTC INFRASTRUCTURE

While the system establishes direct peer-to-peer (P2P) connections, the networking layer must account for the com-plexities of real-world internet architecture. Peers are typi-cally situated behind Network Address Translation (NAT) devices or firewalls that prevent unsolicited incoming con-nections.

A. Signalling and ICE Negotiation

The process begins with a signaling server that facilitates the exchange of Session Description Protocol (SDP) offers and Interactive Connectivity Establishment (ICE) candidates. The signaling server does not store document data, ensuring it remains a lightweight component of the architecture

B. STUN and TURN Implementation

To traverse NAT, the y-webrtc provider utilizes STUN (Session Traversal Utilities for NAT) to discover the public-facing IP addresses of peers. In restrictive network envi-ronments where symmetric NAT prevents a direct path, the system can be extended to use TURN (Traversal Using Relays around NAT) servers to relay encrypted data packets.

VI. SECURITY AND ACCESS CONTROL

A decentralized architecture naturally mitigates the "single point of failure" and privacy risks inherent in centralized models like Google Docs.

A. Transport Layer Security

All synchronization data is transmitted via WebRTC Data Channels, which are secured using DTLS (Datagram Transport Layer Security). This provides built-in encryption and prevents man-in-the-middle attacks during the state exchange.

B. Decentralized Privacy

Because the document state lives entirely within the browsers of participating peers, no central authority has access to the unencrypted content. Future iterations could enhance this by utilizing Distributed Hash Tables (DHTs) for signaling, removing the final centralized component of the discovery phase

VII. THE QUILL-DELTA AND Y.JS SYNCHRONIZATION BRIDGE

The integration between the User Interface and the CRDT engine is managed by the y-quill binding. This layer acts as a bidirectional translator between two distinct data formats.

A. Mapping Deltas to Items

Quill represents document changes as "Deltas" (a JSON-based format for insertions, deletions, and attributes). The binding interceptor observes these events and translates them into Y.js operations.
Each character or block inserted is assigned a unique identifier based on the user's Client ID and a local Lamport clock

B. Conflict-Free Rendering

When a remote update is received as a binary-encoded state vector, the binding updates the local Quill instance. It calculates the precise index for the update based on the CRDT's causal tree, ensuring the UI remains consistent without manual re-sequencing.

VIII. PERFORMANCE ANALYSIS AND MEMORY OPTIMIZATION

The primary technical hurdle in CRDT systems is the "tombstone" problem, where deleted items persist in memory to maintain the causal history for concurrent edits.

A. The Struct Store Optimization

The Y.js engine optimizes the document's memory foot-print through a "Struct Store". Instead of treating every character as an isolated object, the system merges adjacent operations from the same user into contiguous blocks.

B. Mathematical Impact on space Complexity

If N represents the total number of operations and M rep-resents the number of active characters, a naive CRDT would grow at O(N). By implementing content pruning—where the UTF-8 strings of deleted items are discarded while keep-ing only the minimal metadata—the complexity is reduced toward O(M+S), where S is the set of required metadata fragments.

IX. NETWORK TOPOLOGY AND SCALABILITY

The current system utilizes a mesh network topology where every peer attempts to connect to every other peer in the session.

A. Propagation and Efficiency

When a user performs an edit, the incremental binary update is propagated through the WebRTC channels. This reduces latency compared to traditional models that require a round-trip to a central server for validation.

B. Mesh Scalability

Mesh Scalability: While a full mesh ensures high fault tolerance—where existing sessions continue even if the sig-naling server fails—it increases the number of connections as more users join. This decentralized approach is particularly effective for small to medium-sized teams in environments with intermittent connectivity.

C. Convergence Properties

The system achieves Strong Eventual Consistency (SEC)[cite: 21, 32]. For any two document replicas Di and Dj, convergence is guaranteed if the updates satisfy the following algebraic properties[cite: 31, 66]:

- Commutativity: The order in which updates are applied does not affect the final state[cite: 31, 66].
- Associativity: The grouping of updates during transmis-sion does not affect the final state[cite: 31, 66].

D. State Vector Synchronization

To minimize bandwidth consumption, peers exchange State Vectors (SV) rather than full document copies[cite: 68]. A State Vector represents a client's "knowledge" by mapping every observed client_id to the highest counter received from them[cite: 69, 70]:

$$SV = \{(c1 : k1), (c2 : k2), \ldots, (cn : kn)\} \quad (4)$$

When Peer A connects to Peer B via WebRTC, they exchange these vectors. Peer A transmits only the operations where kA > kB, ensuring an incremental binary update[cite: 71].

E. Conflict Resolution Logic

When two peers perform concurrent edits at the same position, the system maintains a total ordering of text by storing pointers to the neighbors at the time of creation (specifically originLeft)[cite: 63, 64]. If two items share the same originLeft, the following rule is applied[cite: 65]:

$$\text{Order}(\text{Item} , \text{Item}) = (\text{Item1} \prec \text{Item2} \quad \text{if } c1 > c2$$

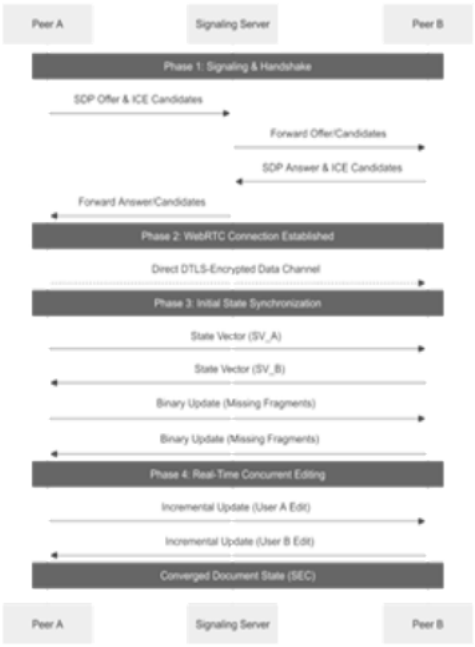

Fig. 2. Detailed Sequence Diagram of the Synchronization Protocol: Illus-trating signaling via the server, direct WebRTC data channel establishment, and the two-stage CRDT state exchange (State Vector sync followed by incremental binary updates).

X. FORMAL MATHEMATICAL MODEL OF CONVERGENCE

To ensure that all distributed peers reach the same docu-ment state without a central coordinator, the system imple-ments a model based on Conflict-free Replicated Data Types (CRDTs). This section defines the mathematical framework for operation identification and state synchronization.

A. Operation Identification

Every character or block in the document is represented as an atomic Item identified by a unique tuple[cite: 58, 59]:

$$ID = (c, k) \quad (3)$$

where:

- $c \in N$ is a unique client_id assigned to the peer[cite: 61].
- $k \in N$ is a local Lamport clock (counter) that increments with every operation performed by that client[cite: 61].

$$Item2 \prec Item1 \quad \text{if } c2 > c1 \quad (5)$$

This rule ensures that the item with the higher client_id is positioned first, creating a deterministic and identical order across all replicas[cite: 65, 66].

F. Complexity and Memory Optimization

While a naive CRDT grows at O(N) relative to the total number of operations, the implemented garbage collection and struct-merging strategy reduces the effective space com-

plexity[cite: 89, 90]:

$$Space \approx O(M + S) \quad (6)$$

where M is the number of active characters and S is the set of minimal metadata fragments (tombstones) required to maintain causal history[cite: 90].

XI. ANALYSIS AND DISCUSSION

The performance metrics summarized in Table I highlight the distinct advantages of the proposed P2P CRDT archi-tecture. By eliminating the central coordinator, the system achieves a "Local-first" status, where the primary copy of the data resides with the user.

A. Latency and Convergence

In traditional OT systems, every character stroke must be validated by a server, leading to a "waiting period" that scales with the user's distance from the data center. In our implementation, the use of WebRTC data channels allows for sub-millisecond propagation of state updates within local net-works. Furthermore, the commutative nature of Y.js ensures that even if updates arrive out of order due to network jitter, the document state converges without the need for complex server-side re-sequencing.

B. Scalability and Fault Tolerance

A significant finding of this venture is the inherent fault tolerance of the P2P mesh. If the signaling server used for the initial handshake fails, existing editing sessions remain uninterrupted. This decentralized approach naturally scales with the number of users, as each additional peer contributes to the distribution of update fragments rather than taxing a central CPU. This makes the framework particularly suitable for collaborative environments in regions with intermittent internet connectivity.

XII. CONCLUSIONS

Therefore, this concept demonstrates the viability of serverless, real-time collaboration using Y.js and WebRTC. By shifting the responsibility of consistency from a central authority to the individual peers, we achieve a "Local-first" architecture that prioritizes user privacy and offline availability.

Our analysis shows that while WebRTC introduces com-plexity in peer discovery (signaling), the resulting low-latency data channels outperform traditional WebSocket-based OT systems in local network environments. Future work could involve implementing "merkle-tree" based state verification to further optimize synchronization for extremely large documents and exploring decentralized signaling alter-natives, such as DHTs (Distributed Hash Tables), to remove the final vestige of centralization.

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