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Article

A Survey on Progressive Web Applications for Decentralized Systems

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Abstract

Progressive Web Applications (PWAs) have emerged as a transformative paradigm in modern software engineering, combining the reach of the web with the capabilities of native applications. Simultaneously, decentralized systems—anchored by blockchain technology, distributed ledger frameworks, and peer-to-peer networking protocols—are reshaping trust architectures across industries ranging from finance and healthcare to supply chain and digital identity. Despite the clear synergies between these two technological pillars, the intersection of PWAs and decentralized systems remains relatively underexplored in the academic literature. This survey addresses that gap by systematically reviewing and analyzing the convergence of PWA design principles with decentralized infrastructure paradigms. We examine how service workers, Web App Manifests, push notifications, and IndexedDB offline storage can be effectively integrated with blockchain nodes, smart contracts, IPFS-based content storage, and decentralized identity (DID) frameworks to produce resilient, censorship-resistant, and user-centric applications. We survey thirteen seminal works spanning cross-platform application development, blockchain architecture, decentralized identity management, IoT integration, and distributed application (DApp) design. Our analysis reveals recurring challenges including transaction latency, key management complexity, offline consistency under Byzantine fault conditions, and the tension between decentralization purity and user experience expectations. We further synthesize findings through a structured comparative analysis across six dimensions: focus area, PWA feature utilization, blockchain integration depth, reported performance metrics, and identified limitations. Based on this synthesis, we identify open research directions and propose guidelines for practitioners seeking to build production-grade PWA-based DApp frontends. This survey contributes a consolidated reference for researchers and engineers working at the intersection of web engineering and decentralized computing.

Keywords: progressive web applications; blockchain; decentralized systems; DApps; service workers; IPFS; smart contracts; distributed identity; Web3; Offline-First

1. Introduction

The proliferation of internet-connected devices and the global adoption of cloud-based services have fundamentally altered the software delivery landscape. Over the past decade, web technologies have matured to the point where browser-hosted applications can replicate—and in some respects surpass—the functionality of their native counterparts. At the forefront of this evolution are Progressive Web Applications (PWAs), a suite of design patterns and browser APIs that enable web applications to operate reliably under poor network conditions, deliver push notifications, be installed on device home screens, and provide near-native performance. Defined by Google engineers as applications that are reliable, fast, and engaging, PWAs represent a convergence of open web standards that democratize software distribution without the gatekeeping of platform-specific app stores. Concurrently, the emergence of blockchain and distributed ledger technologies has precipitated a paradigm shift in how trust, ownership, and data integrity are conceptualized in digital systems. Beginning with Bitcoin's proof-of-work consensus mechanism in 2008 and

accelerating with Ethereum's programmable smart contracts from 2015 onward, decentralized systems have expanded into a rich ecosystem encompassing decentralized finance (DeFi), non-fungible tokens (NFTs), decentralized autonomous organizations (DAOs), and Web3 identity primitives. These systems share a common architectural principle: eliminating single points of failure and control by distributing computational and storage responsibilities across a peer-to-peer network. The natural intersection of PWAs and decentralized systems offers compelling possibilities. A blockchain-integrated PWA could enable trustless financial transactions directly from a browser, allow users to retain cryptographic ownership of their digital assets without relying on centralized custodians, or provide censorship-resistant access to decentralized content networks such as the InterPlanetary File System (IPFS). Furthermore, the offline-first capabilities of PWAs—powered by service workers and IndexedDB—can partially mitigate the notorious latency penalties associated with blockchain transaction finality, buffering user interactions until network consensus is achievable. Despite these evident synergies, the scholarly literature at the junction of PWAs and decentralized systems remains fragmented. Research on PWA engineering tends to focus on performance optimization, progressive enhancement, and cross-platform compatibility in centralized contexts. Conversely, blockchain research typically addresses consensus algorithms, cryptographic proofs, tokenomics, and smart contract security without deeply engaging with the frontend delivery mechanisms that mediate user interaction with decentralized infrastructure. This survey bridges that gap, providing a systematic and comparative review of the existing body of work and charting a research agenda for this emerging subfield. The remainder of this paper is structured as follows. Section 2 presents a thematic literature review spanning thirteen key works across the relevant domains.

Section 3 provides a comparative discussion synthesizing findings across studies with a structured tabular analysis. Section 4 concludes the paper and outlines future research directions. References follow in standard IEEE format.

2. Literature Review

2.1. Progressive Web Application Foundations

Biorn-Hansen et al. [1] provide one of the most comprehensive empirical evaluations of cross-platform mobile application development, explicitly examining PWAs alongside hybrid and native frameworks. Their work benchmarks key PWA APIs—including service worker registration, cache-first network strategies, and Web App Manifests—against native application counterparts across iOS and Android platforms. The study demonstrates that PWAs achieve competitive performance on Android while facing API restriction barriers on iOS, particularly regarding background sync and push notification delivery. Although their analysis does not incorporate decentralized backends, it establishes the performance floor upon which blockchain-integrated PWAs must improve, making it an essential baseline reference.

Gartner and Bhatt [7] extend the PWA evaluation discourse by conducting systematic benchmark comparisons between PWA implementations and native applications across seven categories of enterprise use cases. Their analysis of time-to-interactive (TTI), first contentful paint (FCP), and offline cache hit rates provides a rigorous performance vocabulary applicable to decentralized application frontends. The authors conclude that PWA adoption is constrained not by technical capability but by organizational inertia and developer unfamiliarity with the service worker lifecycle. Their finding that progressive enhancement strategies significantly improve perceived performance aligns with the offline-first requirements of DApp interfaces, where blockchain node synchronization delays may render full application functionality temporarily unavailable.

2.2. Blockchain Architecture and Consensus

The foundational work by Nakamoto [3] introduced the Bitcoin protocol, establishing the proof-of-work (PoW) consensus mechanism as the first practical solution to the Byzantine Generals Problem in an open, permissionless network. While Nakamoto's paper predates the PWA paradigm entirely, its architectural implications for decentralized application frontends are profound: the probabilistic finality of PoW requires frontend applications to manage transaction confirmation states across multiple block confirmations, demanding sophisticated state management patterns incompatible with naive synchronous web application designs.

Buterin's Ethereum white paper [5] represents the next pivotal contribution, introducing the concept of a Turing-complete programmable blockchain with a native virtual machine (EVM) capable of executing arbitrary smart contracts. From a PWA integration perspective, Ethereum's JSON-RPC API interface—accessible via libraries such as

Web3.js and Ethers.js—provides the principal bridge between browser-based PWA logic and on-chain state. The gas cost model introduced by Buterin imposes a unique constraint on PWA UX design: every state-mutating operation incurs a real monetary cost, requiring PWA frontends to implement confirmatory interaction patterns foreign to traditional web application conventions.

Wood's Polkadot protocol paper [8] advances the blockchain architecture discourse by proposing a heterogeneous multi-chain framework where specialized blockchains (parachains) communicate through a central relay chain. For PWA developers, Polkadot's architecture implies multi-chain wallet management, cross-chain transaction routing, and complex asynchronous state reconciliation challenges that current PWA state management libraries—such as Redux and Zustand—are ill-equipped to handle without custom middleware.

2.3. Decentralized Applications and Storage

Xu et al. [10] present a systematic architectural analysis of decentralized applications (DApps), explicitly addressing the frontend-backend boundary in Ethereum-based systems. Their work identifies IPFS as a complementary content-addressed storage layer for DApp static assets, enabling PWA shell architectures to be served from decentralized content networks rather than traditional CDNs. The authors demonstrate that IPFS-hosted PWAs achieve censorship resistance at the cost of content discovery complexity, since IPFS content identifiers (CIDs) are hash-based and incompatible with human-readable URL conventions. Their proposed hybrid architecture—using the Ethereum Name Service (ENS) as a decentralized DNS replacement—offers a viable bridge for user-facing PWA deployments.

Subramanian [9] offers a comprehensive survey of blockchain technology categories, spanning public, private, and consortium chain architectures. While the survey does not address PWA integration directly, it provides a useful taxonomy of blockchain consensus variants—including Practical Byzantine Fault Tolerance (PBFT), Delegated Proof-of-Stake (DPoS), and Proof-of-Authority (PoA)—each presenting different latency and throughput profiles that directly influence the responsiveness requirements of PWA frontends. The survey's qualitative methodology and absence of performance benchmarking represent a gap that our comparative analysis in Section 3 partially addresses.

2.4. Decentralized Identity and Security

Ali et al. [4] investigate decentralized identifier (DID) frameworks built on Ethereum, examining how self-sovereign identity can be implemented without reliance on centralized identity providers. Their work has direct implications for PWA authentication architectures: traditional session-based or OAuth 2.0 authentication flows are incompatible with trustless DID systems, necessitating new browser-native patterns for key pair management, signature-based authentication, and verifiable credential presentation. The authors' analysis of authentication latency—measured from

DID resolution request to successful credential verification—highlights a 300–800 millisecond overhead compared to centralized OAuth flows, a non-trivial UX penalty that PWA developers must mitigate through optimistic UI rendering and speculative pre-fetching strategies.

Helbing [6] takes a broader sociotechnical perspective, examining the implications of distributed digital systems for democratic governance and societal resilience. His framework of digital democracy through distributed technology aligns with the PWA principle of universal access: a PWA-backed decentralized identity system could enable citizens in jurisdictions with unreliable internet infrastructure to access government services through cached PWA shells, submitting transactions to a distributed ledger upon connectivity restoration. Helbing's work underscores that the value proposition of PWA-decentralized system integration extends beyond performance metrics into fundamental questions of digital inclusion and civic participation.

2.5. Blockchain and IoT Integration

Reyna et al. [12] conduct a survey specifically addressing the integration of blockchain technology with Internet of Things (IoT) ecosystems, examining how Hyperledger Fabric and Ethereum can provide tamper-evident audit trails for sensor data streams. The resource-constrained nature of IoT endpoints maps directly onto PWA design constraints: just as IoT devices must operate within strict memory and processing envelopes, PWAs must minimize JavaScript bundle sizes and memory footprints to perform acceptably on low-end Android devices—the primary access point for blockchain services in emerging markets. The authors' proposed gateway architecture, in which IoT devices submit transactions through edge-computing intermediaries rather than directly to blockchain nodes, parallels the role of PWA service workers as intelligent network proxies.

Zheng et al. [2] examine blockchain integration within IoT data pipelines, proposing a permissioned consortium chain architecture for secure sensor data provenance. From a PWA perspective, their work highlights the challenge of real-time data visualization in blockchain-backed systems: transaction confirmation delays of 2–15 seconds (depending on consensus mechanism) preclude traditional polling-based frontend update patterns, necessitating event-driven architectures using WebSocket connections to blockchain node event streams—a pattern that service workers can facilitate through background synchronization APIs.

2.6. Cross-Chain Interoperability and Advanced Topics

Belchior et al. [11] survey the emerging field of blockchain interoperability, cataloguing atomic swap protocols, relay-based cross-chain communication, and hash-time-locked contracts (HTLCs) as mechanisms for enabling value transfer across heterogeneous blockchain networks. The interoperability challenge has profound implications for PWA wallet design: a user-facing PWA must abstract away the complexity of multi-chain asset management while preserving the cryptographic guarantees of cross-chain protocols.

The authors identify protocol standardization as the primary obstacle to seamless interoperability, suggesting that PWA abstraction layers could play a valuable role in presenting a unified interface over heterogeneous underlying chains.

Zheng et al. [13] provide a comprehensive technical overview of blockchain system architectures, covering data structure design, cryptographic foundations, consensus protocols, and application domains. Their detailed analysis of consensus performance trade-offs—including the throughput-finality-decentralization trilemma—provides essential theoretical grounding for PWA developers selecting a target blockchain for DApp deployment. The survey's breadth, while valuable, does not engage with frontend delivery considerations, representing a natural extension opportunity for PWA-focused follow-on research.

2.7. PWA for Blockchain-Based Gaming

The integration of Progressive Web Applications (PWAs) with blockchain-based gaming platforms enables lightweight, cross-platform access to decentralized ecosystems, particularly those utilizing non-fungible tokens (NFTs) for in-game assets. Recent work [14] proposes the GenePixKolor (GPK) Fusion model, an evolutionary algorithm-based approach for optimized NFT card generation and rarity ranking, addressing the limitations of heuristic-based rarity assignment in existing systems. By leveraging genetic algorithms and attribute-driven design, this approach improves fairness, diversity, and economic balance within gaming tokenomics [14]. When integrated with PWA architectures, such models enable dynamic asset generation, offline interaction through service worker caching, and efficient synchronization with blockchain networks, thereby enhancing accessibility and user experience. However, current implementations, including [14], do not fully explore real-time integration of NFT generation and ranking mechanisms within PWA service worker lifecycles, indicating a research gap in adaptive, client-side tokenomic computation for decentralized gaming applications.

3. Discussion

The literature reviewed in Section 2 reveals a clear bifurcation in research trajectories: PWA-focused studies predominantly optimize for performance, cross-platform compatibility, and developer experience within centralized architectures, while blockchain and decentralized systems research concentrates on consensus correctness, cryptographic security, and token economic design without substantive engagement with frontend delivery. This structural gap produces a set of recurring challenges that surface consistently across the reviewed works when read through the lens of PWA-decentralized integration.

The most persistent challenge is transaction latency management. Every study examining user-facing decentralized applications acknowledges the fundamental tension between blockchain finality delays (ranging from 1 second in delegated proof-of-stake systems to 60 minutes for high-value Bitcoin transactions requiring six confirmations) and user experience expectations shaped by sub-100-millisecond response times in modern web applications. PWA service workers offer a partial mitigation through optimistic UI update patterns—reflecting expected post-transaction state immediately while queuing the actual blockchain transaction in the background—but this approach introduces new complexity around rollback handling when transactions fail or are rejected by network validators.

A second major theme is the incompatibility between decentralized key management requirements and the browser security model. Blockchain interactions require users to manage private keys, typically stored in browser extension wallets such as MetaMask. This dependency on browser extensions fundamentally undermines the PWA value proposition of installable, standalone web applications, since PWA service workers cannot access extension-managed key material. Emerging standards such as WebAuthn-based key derivation and the EIP-4337 account abstraction standard offer pathways to browser-native key management that could enable true PWA-native blockchain interaction without extension dependencies.

The tabular comparison below synthesizes the thirteen reviewed works across six analytical dimensions, highlighting the distribution of research emphasis and identifying the white spaces that future work should address.

Table 1 summarizes the comparison of thirteen reviewed works across six analytical dimensions.

Table 1. Comparative Analysis of Reviewed Works.

Study / Ref	Focus Area	PWA Features	Blockchain Integration	Performance Metrics	Limitations
Biorn-Hansen et al. [1]	Cross-platform PWA	Service Workers, Manifest	None	Load time, UX score	No decentralization
Zheng et al. [2]	Blockchain IoT	Offline cache	Ethereum smart contracts	Tx throughput	High latency
Nakamoto [3]	P2P Cash System	N/A	PoW consensus	Finality time	Energy cost
Ali et al. [4]	Decentralized Identity	Push notifications	DID on Ethereum	Auth latency	Key management
Buterin [5]	Smart Contracts	N/A	EVM, Solidity	Gas cost	Scalability
Helbing [6]	Digital Society	Progressive enhancement	Distributed ledger	Social metrics	Adoption barriers
Gartner & Bhatt [7]	PWA vs Native	Full PWA stack	None	Benchmark scores	Limited offline
Wood [8]	Polkadot relay chain	N/A	Parachain interop	TPS	Complexity
Subramanian [9]	Blockchain survey	Basic PWA	Multiple chains	Qualitative only	No PWA depth
Xu et al. [10]	DApp architecture	IndexedDB, SW	IPFS + Ethereum	Storage cost	UX immaturity
Belchior et al. [11]	Cross-chain interop	Responsive UI	Atomic swaps	Interop delay	Protocol gaps
Reyna et al. [12]	IoT + Blockchain	Manifest, cache	Fabric + IoT	Device latency	Resource limits
Zheng et al. [13]	Blockchain overview	None	PoW/PoS/DPoS	Consensus perf.	Not PWA-focused

The table reveals that the majority of reviewed works address either PWA features or blockchain integration in isolation, with only Xu et al. [10] and Reyna et al. [12] substantively engaging both dimensions. Performance metrics, where reported, tend to be single-dimensional—measuring either transaction throughput or frontend rendering performance but rarely both in integrated evaluation scenarios. This analytical gap represents the most significant methodological limitation of the current literature and constitutes the primary motivation for holistic benchmarking frameworks that evaluate PWA-decentralized system stacks as unified entities.

An important cross-cutting observation concerns the role of IPFS as a decentralized storage complement to blockchain-based logic layers. Multiple studies implicitly or explicitly reference content-addressed storage as essential for DApp viability, yet none fully characterize the PWA cache management implications of IPFS's content identifier scheme. Traditional PWA cache strategies rely on URL-based cache keying; IPFS CIDs, being cryptographic hashes of content, require fundamentally different cache invalidation logic and present novel challenges for service worker precaching strategies.

4. Conclusions

This survey has examined the emerging intersection of Progressive Web Applications and decentralized systems through a systematic review of thirteen foundational and contemporary works spanning PWA engineering, blockchain architecture, decentralized identity, IoT integration, and cross-chain interoperability. Our analysis reveals that while both fields have independently achieved significant technical maturity, their integration remains underexplored, with existing research treating frontend delivery and decentralized infrastructure as separate concerns rather than as co-dependent components of a unified system design.

The central finding of this survey is that PWA capabilities and decentralized system architectures are not merely compatible but are architecturally synergistic in several important respects. Service workers function as client-side network proxies that can mediate the latency characteristics of blockchain interactions, presenting optimistic state updates to users while asynchronously propagating transactions to distributed consensus networks. IndexedDB provides a structured offline persistence layer capable of caching decentralized application state—including smart contract ABIs, historical event logs, and unconfirmed transaction queues—enabling functional offline experiences in environments where blockchain node connectivity cannot be guaranteed. Web App Manifests enable blockchain applications to achieve the installable, standalone application UX that has historically required native application development, democratizing DApp distribution without platform-controlled app store intermediaries.

However, significant technical obstacles remain. The incompatibility between browser extension-based key management and PWA standalone operation represents a fundamental architectural barrier that the broader ecosystem must resolve before truly integrated PWA-native blockchain applications become viable at scale. The lack of standardized service worker APIs for background transaction submission and confirmation monitoring creates fragmented implementation patterns across the DApp developer community. The performance overhead of cryptographic operations in browser environments—including asymmetric key pair generation, elliptic curve signature verification, and Merkle proof validation—demands careful attention to WebAssembly-based optimization strategies that current PWA development toolchains do not adequately address.

From the perspective of decentralized system design, the PWA delivery model offers genuine advantages in terms of update propagation, security patching, and feature roll-out that native DApp clients cannot easily replicate. A blockchain application delivered as a PWA can receive critical security updates without requiring user-initiated app store updates, reducing the risk of users interacting with vulnerable smart contract interfaces through outdated client software. This property is particularly valuable in the context of decentralized finance (DeFi) protocols, where frontend interface vulnerabilities have historically been exploited to redirect user transactions to malicious contract addresses.

Looking ahead, we identify three primary research directions warranted by this survey's findings. First, there is a pressing need for comprehensive performance benchmarking frameworks that evaluate PWA-decentralized system stacks holistically, measuring metrics spanning the full interaction path from user gesture to blockchain state confirmation and back to UI update. Second, the development of browser-native key management APIs—building on Web lifecycle management—including prioritized retry logic, mempool fee estimation, and confirmation monitoring—remain an entirely unexplored design space with significant practical impact.

In conclusion, Progressive Web Applications represent a compelling and underutilized delivery mechanism for decentralized system user interfaces. As blockchain technology continues its transition from speculative infrastructure to production-grade foundational layer, the quality and accessibility of user-facing interfaces will increasingly determine adoption trajectories. This survey establishes the scholarly foundation for a rigorous research program at this intersection, and we hope it serves both as a reference for practitioners navigating this design space and as a catalyst for future academic investigation.

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