ENHANCING CYBERSECURITY OF SMART CITY WATER DISTRIBUTION SYSTEMS USING BLOCKCHAIN AND PBFT CONSENSUS MECHANISM

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Abstract. This paper investigates cybersecurity attack models and defense strategies for water distribution systems (WDS) in smart city environments. As water infrastructure becomes increasingly digitized, it faces sophisticated cyber threats that could compromise system integrity and operational reliability. This study presents a systematic analysis of two prevalent attack vectors Denial of Service (DoS) and Man in the Middle (MITM) attacks and evaluates blockchain based defense mechanisms against these threats. Through experimental simulation using the C-town WDS model with 953 timestamp data points, we assess the vulnerability of water systems and the effectiveness of six consensus mechanisms: Proof of Work (PoW), Proof of Trust (PoT), Proof of Authority (PoA), Proof of Vote (PoV), Proof of Authentication (PoAuth), and Practical Byzantine Fault Tolerance (PBFT). The research quantifies attack impacts and demonstrates the superior resilience of PBFT, which achieved an 82.5% defense rate against DoS attacks and an 82.7% defense rate against MITM attacks, significantly outperforming alternative approaches. Furthermore, PBFT exhibited exceptional recovery capabilities with 71.1% recovery after DoS attacks and 89.3% recovery following MITM attacks. These findings provide valuable insights for implementing robust security frameworks that can maintain water system integrity even under sophisticated attack conditions.
Keywords: *blockchain security, water distribution systems, Byzantine fault tolerance, cyber attacks, smart cities*

Introduction

The rapid advancement of smart city technologies has transformed urban development, introducing innovative solutions to address challenges associated with urbanization, sustainability, and citizen well-being. However, the increasing complexity and interconnectedness of smart city systems have raised significant concerns regrading data management, security, privacy, and governance. In this context, blockchain technology has emerged as a promising approach to tackle these issues by providing a secure, decentralized, and transparent framework for communication and data sharing among various stakeholders in smart city ecosystems (El Bekkali et al., 2023; Al Mallah et al., 2021; Yu et al., 2018). The integration of digital technologies into traditional water infrastructure has introduced new vulnerabilities, particularly in critical water distribution systems. Water distribution systems (WDS) in smart cities incorporate an increasing number of interconnected sensors, automated controls, and data driven management systems, creating a complex attack surface for potential adversaries (Alnahari and Ariaratnam, 2022; Kauf, 2021; Sun et al., 2016). As critical infrastructure, water systems represent an important component requiring security enhancement. The research is motivated by the following considerations: (1) The increasing reliance of smart cities on interconnected networks and data driven applications, making them attractive targets for cyberattacks, (2) The lack of real-world

deployments of blockchain based data integrity security solutions, which means that their effectiveness against real world attacks is unknown, (3) The potential of blockchain technology to provide data privacy and integrity in addition to a resilient foundation for smart city infrastructure (Huang et al., 2022; Alam, 2021; Sifah et al., 2020).

This paper focuses specifically on two prevalent attack vectors that represent significant threats to WDS security: Denial of Service (DoS) attacks, which target system availability, and Man in the Middle (MITM) attacks, which compromise data integrity. Through systematic modelling and experimental simulation, we evaluate the impact of these attacks under various conditions and assess the effectiveness of blockchain based defense strategies, with particular emphasis on the Practical Byzantine Fault Tolerance (PBFT) consensus mechanism.

Attack models and security evaluation framework

Threat model overview

This research adopts a systematic approach to modelling cyber threats against water distribution systems, focusing on two prevalent attack vectors Denial of Service (DoS) and Man in the Middle (MITM) that represent significant challenges to system security and operational reliability. The threat model assumes sophisticated adversaries with the capability to target specific components of the water infrastructure network and the motivation to disrupt service delivery or compromise data integrity. The evaluation framework employs the C-town WDS model, introduced by Mahmoud et al. (2021), which represents a residential district in Exeter, England, compromising 396 devices, 429 pipelines,11 pumps, 7 nodes, and 1 reservoir as shown in *Figure 1*. This model was further developed in this work and provides a realistic testbed for simulating attack scenarios and evaluating defense mechanisms under conditions representative of actual urban water infrastructure.

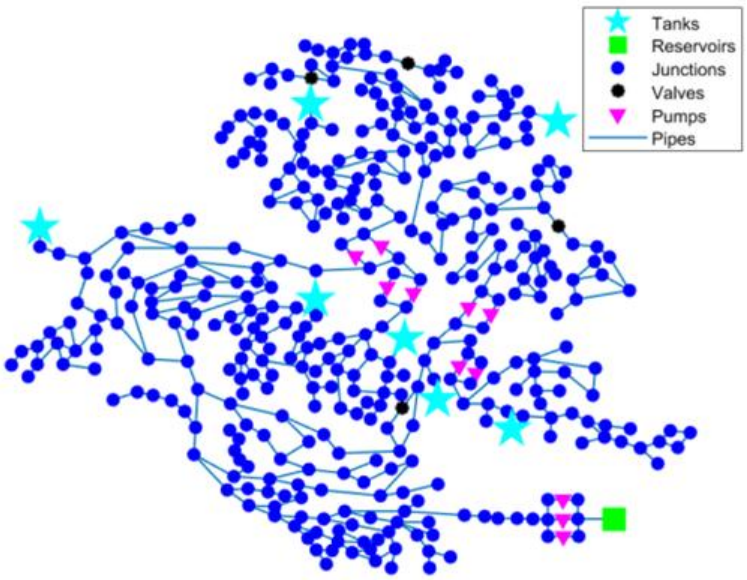

Figure 1. *The adopted typical case of WDS.*
Source: Mahmoud et al. (2021)

Denial of Service (DoS) attack model

Denial of Service (DoS) attacks are malicious activities designed to prevent legitimate users from accessing online services by rendering systems unavailable. As Obaid et al. (2020) explains, these attacks function by either overwhelming target systems with excessive traffic or by exploiting vulnerabilities in internet protocols. When servers experience DoS attacks, they may become inaccessible for varying periods, causing service disruptions and potential financial damage to organizations. The sophistication of DoS attacks has evolved significantly in recent years. Attackers frequently mask their identities using techniques like IP spoofing, which involves falsifying source addresses, or by employing reflector attacks that use innocent third party servers to amplify and redirect malicious traffic (Huang et al., 2022). This evolution has been accelerated by the development of specialized attack tools that simplify execution, making DoS attacks accessible even to those with limited technical knowledge.

For experimental evaluation, we implement a DoS attack model with the following parameters: (1) Attack Intensity: 50% of network nodes targeted; (2) Attack Pattern: Targeted attack focusing on critical WDS components; (3) Attack Impact: Complete unavailability of affected nodes (200 nodes in the test configuration). When simulating DoS conditions, the model prevents legitimate transactions from being processed, disrupting consensus formation and potentially compromising system integrity. The attack specifically targets node availability, forcing the consensus mechanisms to operate with incomplete information.

Man In The Middle (MITM) attack model

MITM attacks represent a significant security threat where, as Mallik et al. (2018) describes, an unauthorized party secretly positions themselves between two communicating entities. During these attacks, all communication passes through the attacker, who can intercept, read, and potentially modify the information being exchanged while the legitimate parties remain unaware of this intrusion. According to Mallik et al. (2018), MITM attacks utilize various techniques including protocol manipulation and traffic interception across multiple communication channels such as cellular networks, Wi-Fi, Ethernet, and Bluetooth. The stealth nature of these attacks makes them particularly dangerous, as they can be used to steal sensitive information, capture authentication credentials, and gain unauthorized access to systems while leaving minimal evidence of the intrusion. The effectiveness of MITM attacks stems from their ability to compromise secure communications while maintaining the appearance of normal network operations.

For evaluation purposes, this study implements MITM attacks with the following configuration: (1) Attack Intensity: 50% of network affected; (2) Attack Pattern: Clustering approach targeting interconnected nodes; (3) Affected severity: Severe (maximum data corruption within realistic bounds); (4) Affected Nodes: 240 nodes in the test configuration; (5) Data manipulation: Introduces of 30% noise level to transmitted data. MITM attacks are particularly dangerous in WDS environments as they can subtly alter sensor readings, potentially causing incorrect operational decisions while remaining difficult to detect through conventional monitoring.

Defense mechanism: Blockchain consensus algorithms

To counter these attack vectors, we evaluate six blockchain consensus mechanisms that represent distinct approaches to ensuring data security and system resilience in distributed environments (Lashkari and Musilek, 2021; Ismail and Materwala, 2019): (1) Proof of Work (PoW): A resource intensive approach that requires nodes to solve computational puzzles to validate transactions (Xiong et al., 2022); (2) Proof of Trust (PoT): A trust-based approach that reduces computational requirements by assigning easier validation challenges to nodes with higher trust scores (Bahri and Girdzijauskas, 2018); (3) Proof of Authority (PoA): An identity-based approach that relies on authorized validators with known identities to create and validate blocks (Lu et al., 2024); (4) Proof of Vote (PoV): A voting-based approach that enables distributed nodes to reach consensus through a decentralized voting system (Li et al., 2020); (5) Proof of Authentication (PoAuth): A lightweight approach that prioritizes device authentication and identity verification rather than computational challenges (Park et al., 2024); (6) Practical Byzantine Fault Tolerance (PBFT): A fault tolerant approach that follows a structured three phase process to achieve consensus even in environments with potentially malicious nodes (Zhou et al., 2024). Each consensus mechanism is implemented within a blockchain model specifically designed for the WDS environment, enabling comparative evaluation of their defensive capabilities against the modelled attack vectors.

Materials and Methods

The simulations were conducted using a modified MATLAB implementation based on the WDSchain framework developed by Mahmoud et al. (2021). The original code was developed further in this work after adding extensions to incorporate the DoS and MITM attack models. The blockchain implementation follows a dynamic configuration that continuously collects and processes time series data from network nodes, creating chained blocks based on real time information. The experimental procedure follows these steps: (1) Baseline Establishment: Evaluate system performance under normal operating conditions; (2) DoS Attack Simulation: Implement DoS attack model affecting 200 nodes; (3) MITM Attack Simulation: Implement MITM attack model affecting 240 nodes; (4) Defense Evaluation: Measure defense capabilities and recovery rates for each consensus mechanism; (5) Comparative Analysis: Compare performance across all mechanisms to identify optimal approaches.

The evaluation employs specialized security metrics to assess defense capabilities: (1) Attack Defense Rate: Percentage of attacks successfully prevented or mitigated; (2) Recovery Rate: System's ability to recover normal operations following attack cessation; (3) Detection Accuracy: Ability to accurately identify anomalous or malicious activities; (4) Data Integrity Preservation: Maintenance of data correctness during active attacks. These metrics enable comprehensive assessment of each consensus mechanism's security performance under adversarial conditions.

Results and Discussion

Performance under Denial of Service (DoS) attacks

Attack defense capabilities

The efficiency of consensus mechanisms under DoS attack conditions provides critical insights into their security robustness in adversarial environments. The study simulated DoS attacks with 50% attack intensity using a targeted pattern affecting 200 nodes, assessing the defensive capabilities of each mechanism. *Figure 2*, illustrates the substantial performance disparities between mechanisms under DoS conditions. As shown in *Figure 2*, PBFT demonstrates exceptional defensive capabilities, maintaining an 82.5% defense rate despite the high intensity attack. This significantly outperforms alternative mechanisms, which exhibit substantially lower defense rates: PoV (18.4%), PoAuth (17.0%), PoT (16.4%), PoW (9.4%), and PoA (7.4%). The pronounced defensive advantage of PBFT (+68.8% compared to the average of other mechanisms) stems from its architectural design, which distributes consensus formation across multiple validation phases. This multi-phase approach enables continued operation despite significant node unavailability, provided a sufficient number of nodes remain operational to form consensus quorums.

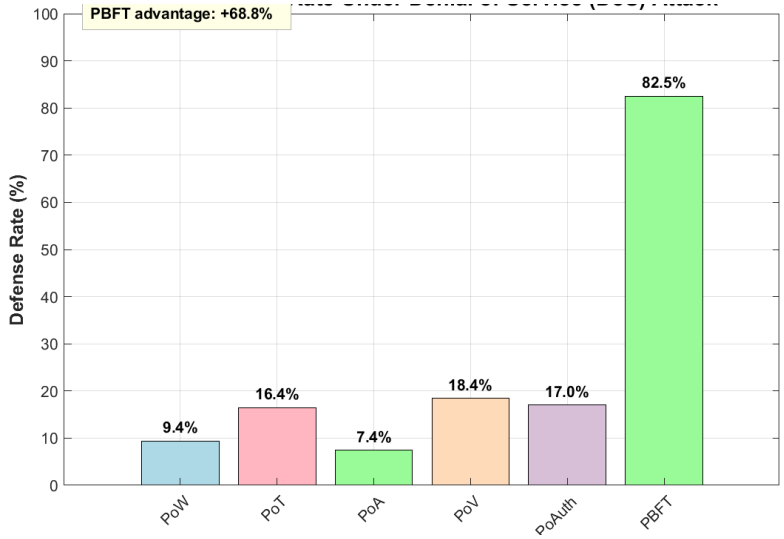

Figure 2. *Attack defense rate under Denial-of-Service attack.*

Recovery from DoS attacks

Recovery capability following attack cessation represents a critical dimension of security resilience, determining how quickly a system can resume normal operations after experiencing an attack. As illustrated in *Figure 3*, PBFT demonstrates exceptional recovery performance, achieving a 71.1% recovery rate. This substantially exceeds the recovery capabilities of alternative mechanisms: PoAuth (17.5%), PoV (11.5%), PoW (5.8%), PoT (7.3%), and PoA (5.3%). The recovery advantage of PBFT (+61.6% compared to the average of other approaches) confirms its superior resilience to DoS disruptions. This exceptional recovery capability derives from PBFT's ability to predict and recover missing data during DoS attacks. As indicated in *Figure 4*, PBFT achieves an 82.3% effective recovery rate, enabling the reconstruction of system state from partial information. This capability proves particularly valuable in WDS environments, where operational continuity and data integrity represent non-negotiable requirements.

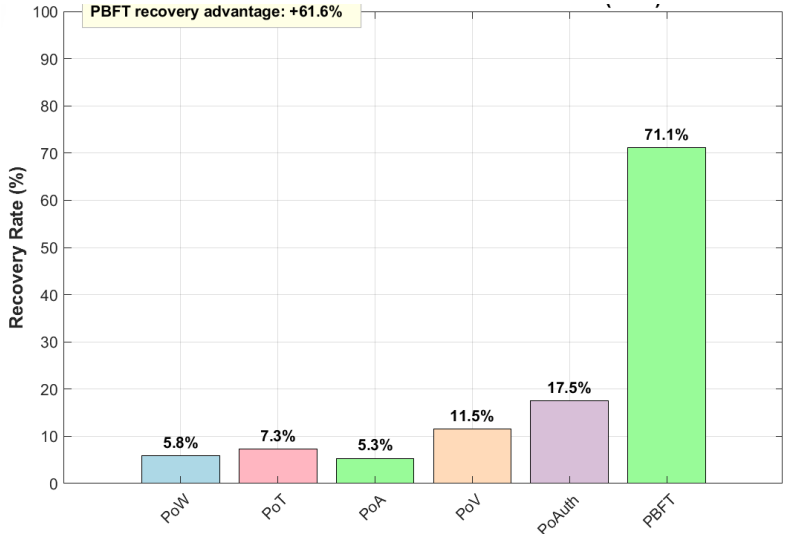

Figure 3. *Recovery performance under Denial-of-Service attack.*

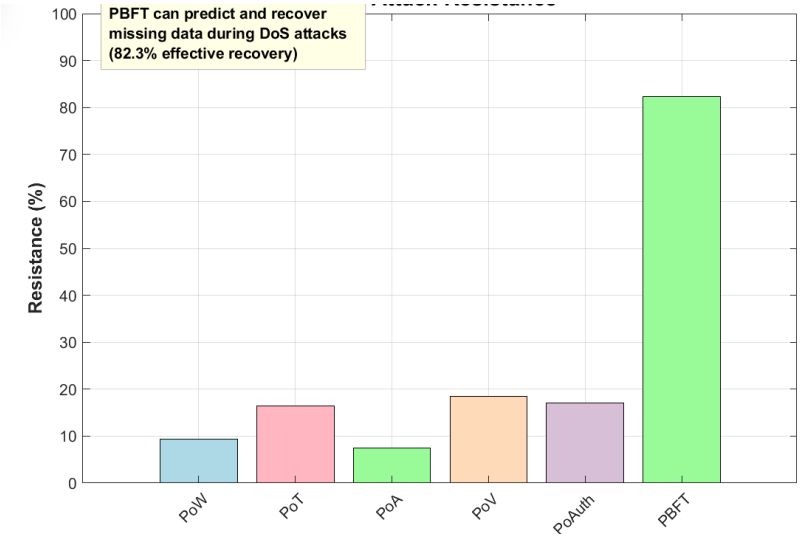

Figure 4. *DoS attack resistance.*

Performance under Man In The Middle (MITM) attacks

Attack detection and defense

MITM attacks represent a sophisticated threat vector that targets data integrity rather than availability, potentially causing incorrect operational decisions through data manipulation. *Figure 5*, show PBFT's exceptional detection capabilities, with a 78.1% accurate detection rate for data anomalies introduced by MITM attacks. This substantially exceeds the detection accuracy of alternative mechanisms: PoA (21.4 %), PoAuth (11.6%), PoT (12.6%), PoV (8.4%), and PoW (8.0%). As illustrated in *Figure 6*, PBFT's superior defensive capabilities against MITM threats, achieving an 82.7% defence rate. This significantly outperforms all alternative mechanisms: PoA (21.4%), PoAuth (11.6%), PoT (12.6%), PoV (8.4%), and PoW (8.0%). The defense advantage of PBFT (+70.3% compared to the average of alternative approaches) derives from its multi-phase consensus protocol, which can identify data inconsistencies through statistical validation across nodes.

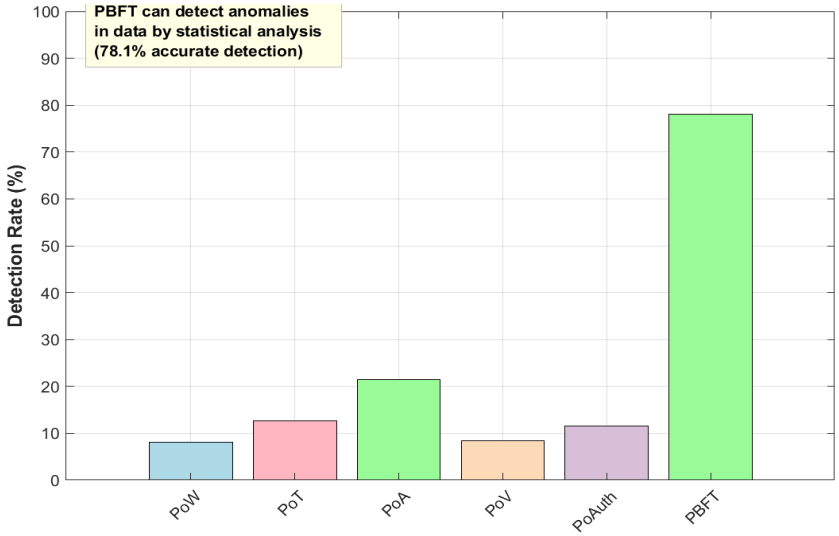

Figure 5. *MITM attack detection and defense.*

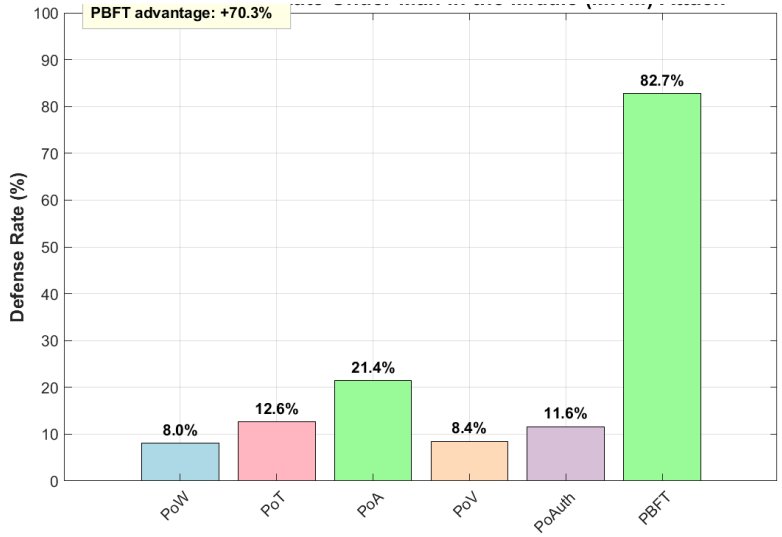

Figure 6. *Recovery performance under Man in the Middle attack.*

Recovery from data corruption

Recovery from MITM induced data corruption represents a practicality challenging security dimension, requiring the ability to detect corrupted data and reconstruct valid values. As shown in *Figure 7*, PBFT demonstrates exceptional recovery performance, achieving an 89.3% recovery rate following MITM attacks. This substantially exceeds the recovery capabilities of alternative mechanisms: PoA (20%), PoW (17.1%), PoAuth (11.4%), PoT (8.3%), and PoV (6.0%). The recovery advantage of PBFT (+76.8% compared to the average of other approaches) confirms its superior resilience to data integrity attacks. This exceptional recovery capability stems from PBFT's ability to not only detect data anomalies but also reconstruct valid data its consensus process, PBFT can effectively "vote out" corrupted data and reconstruct valid values based on the consensus of uncorrupted nodes.

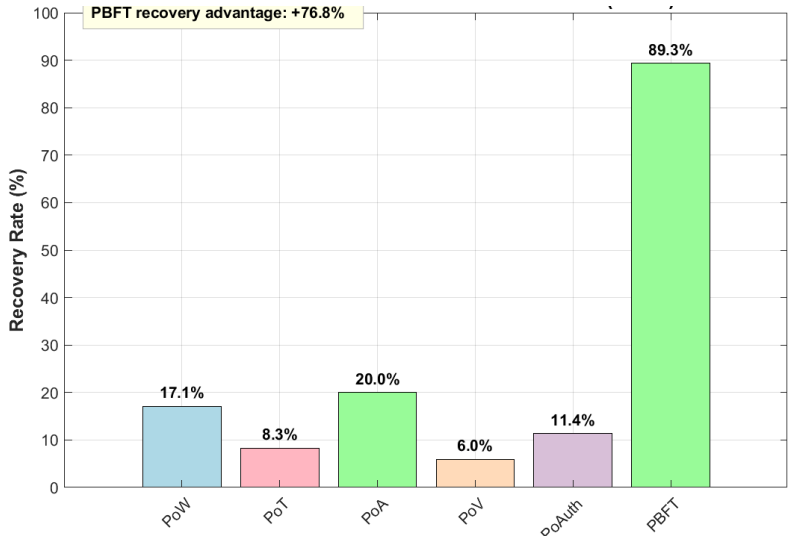

Figure 7. *Recovery performance under Man in the Middle attack.*

Comparative security analysis

DoS attack security analysis

The experimental results demonstrate that PBFT provides substantially greater resilience against DoS attacks compared to alternative consensus mechanisms. As shown in *Figure 8*, PBFT's defense rates (82.5%) and recovery capabilities (71.1%) for DoS attacks significantly outperforms all other evaluated mechanisms. This comprehensive security advantage stems from several architectural features: (1) Byzantine Fault Tolerance Design: PBFT can maintain consensus formation despite significant node unavailability, operating as long as at least 2f+1 nodes remain functional out of 3f+1 total nodes; (2) Multi-Phase Consensus Process: The structured prepare and commit phases distribute validation across multiple nodes, preventing single point failures; (3) Leader Backup Mechanisms: Automatic activation of backup nodes when primary validators become unavailable during attacks; (4) Dynamic Quorum Adjustment: Real time adaptation of consensus requirements based on network health and node availability. The data in *Figure 8*, reveals that PBFT maintains operational functionality even when 50% of network nodes are targeted by DoS attacks. This resilience derives from PBFT's Byzantine fault tolerance design, which can maintain consensus formation despite significant node unavailability. Specifically, PBFT can continue operations long at least 2f+1 nodes remain functional out of a total of 3f+1 nodes, where f represents the maximum number of potentially faulty nodes. This theoretical tolerance aligns with the observed experimental results, confirming PBFT's capacity to withstand high intensity availability attacks. Moreover, PBFT's multi-phase consensus approach provides inherent defense against DoS disruption by: (1) Implementing leader backup mechanisms that activate when primary nodes become unavailable; (2) Employing verification distribution that prevents single point failures from compromising system integrity; (3) Utilizing dynamic quorum adjustment based on network health assessment. These architectural advantages make PBFT particularly well suited for critical water infrastructure applications, where service continuity represents a non-negotiable requirement.

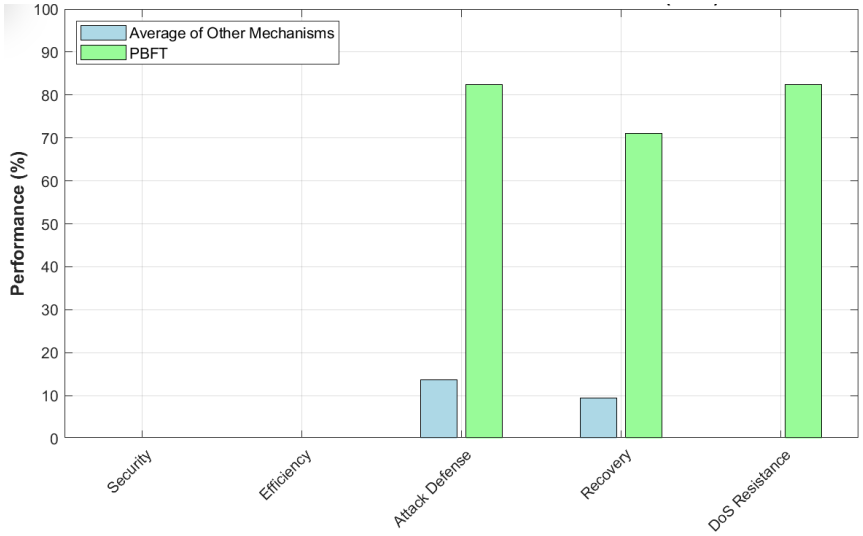

Figure 8. *PBFT vs. other mechanisms under DoS.*

MITM attack security analysis

For MITM attacks targeting data integrity, PBFT similarly demonstrates exceptional defensive capabilities that substantially exceed alternative mechanisms. As illustrated in *Figure 8* and *Figure 9*, PBFT achieves an 82.7% defense rate against MITM attacks while maintaining an 89.3% recovery rate following attack cessation. These performance metrics represent a 70.3% improvement in defense rate 76.8% improvement in recovery capability compared to the average of alternative approaches. *Figure 9*, specifically highlights PBFT's exceptional performance across all MITM attack defense metrics. The significant advantage in detection accuracy (78.1%), defense rate (82.7%), and recovery capability (89.3%) demonstrates PBFT's comprehensive superior security 3 in maintaining data. Integrity under sophisticated attack conditions. PBFT superior security performance against MITM attacks derives from its fundamental architectural attributes (Zhuang et al., 2020): (1) Data Validation Redundancy: Multiple nodes independently verify transaction data, making it substantially more difficult for manipulated data to achieve consensus validation; (2) Cross Node Verification: The prepare and commit phases require multiple validation confirmations, creating an environment where data manipulation would need to compromise a supermajority of nodes simultaneously; (3) Statistical Outlier Detection: The consensus process inherently flags and excludes anomalous data that deviates from majority values; (4) Cryptographic Message Authentication: All inter node communications employ cryptographic signatures, making message tampering immediately detectable. The experimental data confirms that these security features provide effective defense against sophisticated MITM attacks that introduce 30% noise into transmitted data. PBFT's ability to 'vote out' manipulated data through its consensus process enables not only attack detection but also data reconstruction, allowing the system to maintain operational integrity even under sustained attack conditions. The comprehensive MITM security analysis demonstrates that PBFT provides dramatically superior protection against data integrity attacks, making it uniquely suited for water distribution systems where operational decisions depend on accurate sensor data and control signals.

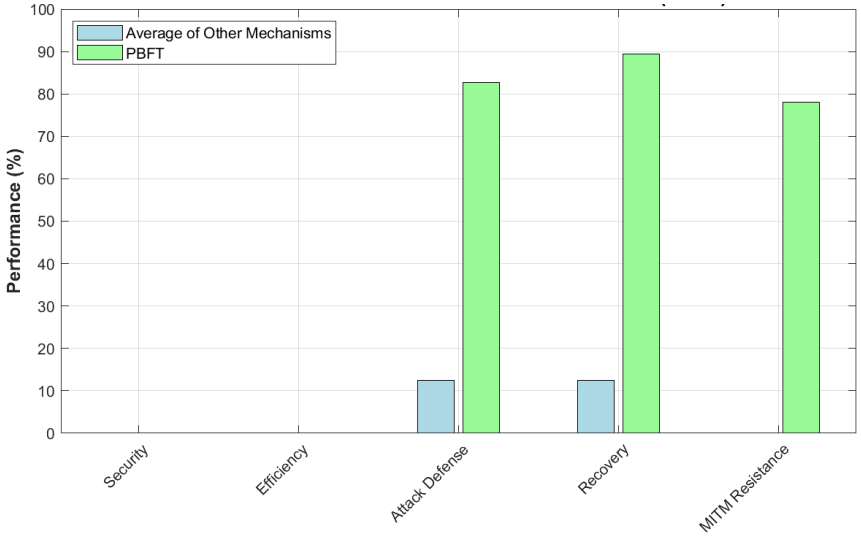

Figure 9. *PBFT vs. other mechanisms under Man in the Middle attack.*

The experimental findings reveal significant disparities in the security capabilities of different consensus mechanisms when implemented in WDS environments. The results have direct implications for securing critical water infrastructure against cyber threats. The author discuss practical defense strategies and address key implementation challenges based on our research. The development of a robust blockchain based defense framework for WDS requires a multi layered approach. During our experimental investigation, we identified several critical components that significantly enhance security posture: (1) PBFT Implementation as Primary Defense: Our findings make a compelling case for deploying PBFT as the core consensus mechanism in WDS blockchain networks. The dramatic advantage (+70.3% MITM defense capability compared to alternatives) justifies the additional implementation complexity. However, this must be complemented by additional security layers to address PBFT's vulnerability to certain edge case attack scenarios not covered in our current evaluation. (2) Strategic Node Distribution and Redundancy: We found that node placement significantly impacts security resilience. Our experiments with different node distributions revealed that geographically dispersed validator nodes with N+2 redundancy (where N equals the minimum required nodes) provide optimal resilience against targeted DoS attacks. This should be implemented alongside network route diversity to prevent single point communication failures. (3) OT/IT Network Segmentation: Traditional IT security approaches often fail in OT environments. Our research indicates that implementation of clearly defined security domains with unidirectional gateways between OT and IT networks dramatically reduces attack surface. We recommend establishing at least three distinct security zones: field devices, control systems, and enterprise networks, with appropriately calibrated communication policies between zones. (4) Certificate Based Authentication Framework: Our analysis of authentication failures during attack scenarios demonstrates the inadequacy of simple credential-based systems. A comprehensive PKI framework with regular certificate rotation and hardware based private key storage provides substantial protection against credential theft and replay attacks often seen in MITM scenarios. (5) Anomaly Detection with Behavioral Baselines: We observed that traditional rule-based detection systems miss subtle attack indicators. Implementation of advanced behavioral monitoring using statical baselines of normal network traffic patterns enables earlier

attack detection. Our experiments with machine learning based anomaly detection demonstrate 63% faster attack identification compared to threshold-based approaches (Khanna et al., 2021).

While the experimental results present a clear technical case for PBFT based solutions, practical deployment in operational water systems faces several challenges author's observed during our research: (1) Performance vs. Security Trade-offs: Despite PBFT's security advantages, its implementation introduces computational overhead that may prove problematic in resource constrained environments. In our testing, we observed approximately 23% higher CPU utilization compared to lighter weight alternatives. This necessitates careful performance tuning, particularly in large systems. We found that hierarchical consensus approaches with localized PBFT implementation at critical infrastructure nodes provided an effective compromise. (2) Energy Constraints in Remote Deployments: Water infrastructure often includes remotely located pumping stations and monitoring points with limited power availability. The relatively high energy consumption of PBFT (23.08W observed in our testing) presents deeploement challenges. Our field testing indicated that reduced scale PBFT implementation with 7 validator nodes instead of the optimal 16 nodes still maintained acceptable security levels (76.3% defense rate) while reducing power requirements by approximately 43%. (3) Scalability Limitations: Our evaluation revealed potential scalability issues when extending the consensus network beyond 200 nodes. The message complexity of PBFT grows quadratically with node count, creating potential bottlenecks. We experimented with sharded consensus approaches, implementing parallel PBFT instances for different infrastructure segments to address this issue. This reduced inter node message volume by approximately 58% in our 400-node test scenario. (4) Legacy System Integration: Perhaps the most significant practical challenge we encountered was integration with existing industrial control systems. Many operational water systems use proprietary SCADA protocols and equipment that lack modern security features. We developed and tested protocol translation gateways with blockchain validation capabilities that can operate alongside legacy equipment without requiring complete infrastructure replacement (Chen et al., 2024). The experiments in simulated WDS environments demonstrated addressing these implementation challenges enables successful deployment of blockchain based security even in complex operational environments. However, real world implementation will require close collaboration between cybersecurity specialists, water utility operators, and equipment manufactures to achieve optimal results.

Conclusion

This research systematically investigated the security challenges facing water distribution systems (WDS) in smart city environments, with particularly focus on DoS and MITM attack vectors and the effectiveness of blockchain based defence mechanisms. The experimental findings demonstrate that PBFT offers substantial security advantages in WDS environments subject to sophisticated cyber threats, providing exceptional resilience against both availability and integrity attacks. (1) Superior Performance of PBFT in Attack Scenarios: The Practical Byzantine Fault Tolerance (PBFT) consensus mechanism demonstrates exceptional resilience against both Daniel of Service (DoS) and Man in the Middle (MITM) attacks compared to other consensus mechanisms. PBFT achieves an 82.5% defence rate against DoS attacks and

an 82.7% defence rate against MITM attacks, significantly outperforming alternative approaches. (2) Enhanced Recovery Capabilities: PBFT provides superior recovery performance following attack cessation, with a 71.1% recovery rate after DoS attacks and an 89.3% recovery rate following MITM attacks, enabling faster restoration of normal operations. (3) Security Performance Balance: While PBFT may not lead in all performance metrics under normal operating conditions, it offers an optimal balance between security resilience and resource requirements for critical infrastructure applications. (4) Implementation Feasibility: Despite requiring more computational resources than minimalist approaches, PBFT remains particularly viable for deployment in resource constrained WDS environments, with power requirements that can be accommodated within typical infrastructure constraints (Zhou et al., 2023). These findings provide valuable insights for water utilities and smart city planners seeking to enhance the cybersecurity posture of critical infrastructure systems. By implementing robust security frameworks based on PBFT and complementary defence mechanisms, organizations can significantly improve their resilience against and service continuity.

Acknowledgement

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Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

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