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Scalable And Efficient PBFT Consensus Algorithm for Secure Internet of Vehicles Networks

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Abstract
The rapid expansion of Internet of Vehicles (IoV) networks necessitates robust consensus protocols that can handle dynamic vehicular dynamics while maintaining security and efficiency. Current Practical Byzantine Fault Tolerance (PBFT) algorithms are plagued by severe scalability problems when used in large-scale IoV networks because communication overhead increases exponentially with network size. This paper introduces a new PBFT consensus algorithm for IoV applications that features a unique logarithmic scaling method, defining a reverse proportionality between the network size and the percentage of nodes required for consensus. The percentage of nodes necessary for consensus diminishes logarithmically as the number of vehicles grows, allowing scalable operation in large networks. The proposed algorithm employs a smart relay selection scheme using quality parameters like distance, channel quality, collision likelihood, and received signal strength measurements. Large-scale simulations conducted by OMNeT++, VEINS, and SUMO demonstrate that our enhanced PBFT achieves a consensus time saving of 30% when compared to existing methods, achieving an average time per hop of 204ms for 200 vehicles against 365ms for normal PBFT. It is Byzantine fault-tolerant, but more scalable and thus very well suited for vehicular communication in real-time. The analysis of performance proves higher efficiency than existing methods like CreditCoin and reputation-based blockchain networks, with equal gain in performance under various vehicle densities, which forms a platform for secure and scalable IoV networks.
Keywords: *PBFT consensus, Internet of Vehicles, blockchain scalability, vehicular networks, Byzantine fault tolerance*

1. INTRODUCTION

The Internet of Vehicles (IoV) is a new paradigm of modern transportation systems in which vehicles, infrastructure, and online services are networked to create smart, adaptive transportation systems [1]. As vehicular connectivity increases through Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Everything (V2X) communications, the need for secure, resilient, and efficient consensus protocols is greater than ever [2]. Legacy centralised architectures in vehicular networks are plagued by single points of failure, scalability chokepoints [3], and security threats that undermine the integrity and reliability of critical safety communications.

Blockchain technology's decentralised and tamper-resistant attributes offer a solution to these concerns through enabling secure data sharing among vehicles without the need for central authorities [4]. However, the deployment of conventional consensus protocols within IoV systems is accompanied by gigantic limitations in terms of scalability and demands for real-time processing [5]. The PBFT protocol, while providing strong security assurances and fault tolerance, has exponentially growing communication overheads with the size of the network and hence is not fit for large vehicular networks where thousands of cars may require agreeing simultaneously [6,7].

Furthermore, the topology of vehicle networks, with high mobility, intermittent connectivity, and varying network densities, constitutes another difficulty for which current PBFT implementations are insufficient [8]. The gap in research is the non-existence of scalable consensus protocols designed specifically for the new features of IoV networks, where real-time decision-making, fault tolerance, and efficient communication are essential requirements. This paper fills this gap by introducing an enhanced PBFT consensus algorithm that introduces logarithmic scaling for reducing consensus overhead, uses optimised smart relay selection mechanisms for vehicular environments, and maintains Byzantine fault tolerance with significant performance improvements in large-scale IoV networks.

2. Related Work

Recent advancements in blockchain consensus protocols for the Internet of Vehicles have focused on the circumvention of the scalability and performance limitations of traditional Byzantine fault tolerance

techniques. Wang and Guan [9] introduced IoV-BDSS, which is a data sharing scheme supported by blockchain that fights vehicular network security threats by eliminating gradients that are not similar and applying secret sharing techniques to maintain an error rate of less than 0.16 even when 30% of the data is under attack. Ben Othmen and Abbessi [10] suggested an IoT blockchain platform's low-latency PBFT parallel consensus solution that utilises random clustering of miners to enable simultaneous consensus processes among heterogeneous clusters to achieve scalability in heavy transactional loads at the expense of acceptable latency ranges.
Ma and Xu [11] introduced ADC, an anonymous decentralised computing system with Byzantine fault tolerance coupled with identity privacy protection, showing that it is possible to ensure security while keeping participants anonymous in decentralised systems. Avelãs and Heydari [12] proposed ProBFT, a probabilistic Byzantine fault-tolerant protocol that reduces message complexity to $O(n\sqrt{n})$ with 80% less communication overhead compared to the traditional PBFT, with an optimistic solution that ensures safety and liveness with high probability. Hao and Yi [13] proposed SimpleFT, an async consensus protocol inspired by Bitcoin's simplicity, with concurrent block confirmations and layer-cake architecture to optimise network resource utilisation and system throughput. These efforts show the ongoing pursuit of consensus efficiency and scalability of vehicular networks, but none of them achieves the inherent scalability challenges of PBFT in large-scale IoV deployments via logarithmic scaling methods as offered in this paper.

3. PROPOSED METHODOLOGY

This section presents the enhanced PBFT consensus protocol optimised for Internet of Vehicles networks. Our solution addresses traditional PBFT scalability challenges with a novel logarithmic scale-up method that reduces consensus overhead as the network expands. The solution involves system modelling in IoV blockchain architecture, a smart relay selection protocol based on vehicular network structure, and an incentive allocation scheme to promote honest participation. The enhanced algorithm maintains PBFT's security properties without sacrificing tremendous efficiency improvements suitable for dynamic vehicular networks.

A. System Modelling and Blockchain Design for IoV

The architectural framework leverages blockchain technology for addressing the inherent challenges of security, trust, and decentralisation in IoV networks. In our proposed blockchain architecture, a permissioned network is set up where the vehicles register themselves with a Central Authority (CA) and receive unique wallet addresses along with respective cryptographic key pairs for safe communication. The system defines key roles, including the Originator (ORG) vehicle that initiates incident reports, Endorsers (END) that validate transaction proposals, and Road Side Units (RSU) responsible for message dissemination across the network. Each vehicle maintains a credit wallet for managing transaction fees and compensation [14], while reputation scores determine participation eligibility in the consensus process according to the threshold condition:

$$j \in \mathrm{END}(0) \quad \text{if } R_j > R_T \tag{1}$$

Where:
- j: vehicle index
- $\mathrm{END}(0)$: set of endorsers at the initial hop
- R_j: reputation of the vehicle j
- R_T: reputation threshold

The blockchain records all exchanges, such as credit transactions, reputation modifications, and decision-making choices in a public and unalterable way along the network lifespan. The reward system shares the call compensation (CC) among participants, and a part of it is allocated to endorsers as [15]:

$$P_{END} = \frac{w_1 \times CC}{\min N_{END}} \tag{2}$$

And RSUs receiving:

$$P_{RSU} = \frac{w_2 \times CC}{N_{hop}} \tag{3}$$

Where:
- w_1, w_2 : weighting factors ($w_1 + w_2 = 1$)
- CC: call compensation

- $\min N_{END}$ minimum number of endorsements required
- N_{hop} total number of hops

Reputation management follows an economic model where honest behaviour increases reputation [16]:

$$R_j = R_j + \beta \tag{4}$$

While malicious actions decrease it:

$$R_j = R_j - \gamma \tag{5}$$

Where:

- β: reputation reward for honest behaviour
- γ: reputation penalty for malicious behaviour

This comprehensive design eliminates single points of failure inherent in centralised systems while maintaining the efficiency and real-time responsiveness required for critical vehicular communications.

B. RSU Selection Mechanism

The RSU selection scheme utilises an intelligent voting-based method where supporting vehicles select the best-suited Road Side Unit based on overall quality factors that reflect vehicular network scenarios in real time. Selection is done by evaluating candidate RSUs using a multi-criteria quality factor [17]:

$$Q_j = \alpha_1 df_j + \alpha_2 CQ_j\left(1 - CP_j\right) + RSSM_j \tag{6}$$

Where:

- Q_j: quality factor of RSU j
- α_1, α_2: weighting coefficients
- df_jdistance factor of RSU j
- CQ_j channel quality of the RSU j
- CP_j: collision probability of RSU j
- $RSSM_j$: received signal strength metric of RSU j

The distance factor is calculated as:

$$df_j = \frac{d\{j, ORG\}}{\min d_{hop}} \qquad (\text{for initial hop } i = 0) \tag{7}$$

$$df_j = \frac{d\{j, RSU_{i-1}\}}{\min d_{hop}} \qquad (\text{for subsequent hops } i > 0) \tag{8}$$

Where:

- $d\{j, ORG\}$: distance between RSU j and originator
- $d\{j, RSU_{i-1}\}$ distance between RSU j and previous RSU
- $\min d_{hop}$ minimum distance requirement per hop

Channel quality evaluates transmission reliability:

$$CQ_j = \frac{N_j^s}{N_j^o} \qquad \left(\text{if } N_j^o > 0\right) \tag{9}$$

Where:

- N_j^s number of successful transmissions by RSU j
- N_j^o number of overall transmissions by RSU j

Collision probability assesses network congestion:

$$CP_j = \frac{t_j^{occ}}{t_w} \tag{10}$$

Where:

- t_j^{occ} channel occupancy time when RSU j is transmitting
- t_w time window

The received signal strength metric evaluates connection stability:

$$RSSM_j = 1 - \frac{RSS_T}{RSS_j} \qquad \left(\text{when } RSS_j \geq RSS_T\right) \tag{11}$$

Where the received signal strength is calculated as:

$$RSS_j = \frac{G_j^r \times G_j^t \times TP_j}{\left(\frac{4\pi d\{j, j'\}}{\lambda}\right)^2} \tag{12}$$

Where:

- RSS_T received signal strength threshold
- RSS_j received signal strength of the RSU j
- G_j^r receiving antenna gain of RSU j
- G_j^t transmitting antenna gain of the RSU j
- TP_j transmitting power of the RSU j
- $d\{j, j'\}$ distance between RSU j and j′
- λ wavelength used in vehicular networks

The RSU selection decision is made using:

$$RSU(i) = index(\max Q_{END}(i)) \tag{13}$$

Where:

- $RSU(i)$ selected Road Side Unit at hop i
- $Q_{END}(i)$quality factors of all endorsing vehicles at the hop i

This sophisticated mechanism offers a better RSU choice that maximises message distribution effectiveness while preserving network reliability, adapting dynamically to changing vehicular network conditions such as mobility patterns, traffic conditions, and fluctuations in communication quality.

C. Enhanced PBFT Consensus Algorithm

$$N = 3f + 1 \tag{14}$$

Where:

- N total number of nodes
- f maximum number of faulty nodes

With quorum requirements for both the prepare and commit phases of:

$$Quorum_{traditional} = 2f + 1 \tag{15}$$

Our enhanced algorithm establishes a more flexible consensus mechanism through the logarithmic relationship:

$$p = k \times \frac{1}{\log n} \tag{16}$$

Where:

- p consensus percentage required
- k tunable constant factor
- n total number of nodes in the network
- $\log n$ natural logarithm of n

The actual number of nodes required for consensus is then:

$$Nodes_{required} = ceil(p \times \frac{n}{100}) \tag{17}$$

Such mathematical abstraction assures that with increasing network size, consensus nodes required reduces as a logarithmic proportion, materially reducing overhead in communication without sacrificing security properties. An invariant factor k offers system administrators fine-grained choices to balance security requirements against performance requirements as per a specific deployment scenario. The enhanced algorithm preserves the fundamental three-phase essence of traditional PBFT but incorporates the logarithmic scaling during the step of quorum calculation, making it suitable for actual, practical large-scale IoV deployments where thousands of vehicles can concurrently participate in consensus processes for mission-critical safety and traffic control applications.

4. RESULTS AND DISCUSSIONS

This part addresses the thorough analysis of the improved PBFT consensus algorithm suggested for IoV networks through systematic simulations using OMNeT++, VEINS, and SUMO. The research presents the enhancement in scalability and efficiency by the logarithmic scaling method compared to traditional PBFT implementations. Key performance attributes such as consensus time, communication overhead, and average time per hop are taken for comparison with varying network sizes from 50 to 200 vehicles. The results validate the effectiveness of the RSU selection process and provide comparative analysis with existing solutions like CreditCoin and reputation-based blockchain systems, achieving significant performance gains while maintaining Byzantine fault tolerance guarantees.

A. IoV Network Simulation Environment Setup

The enhanced PBFT consensus protocol was studied with an end-to-end simulation environment that integrated OMNeT++, VEINS, and SUMO to create a real-world Internet of Vehicles environment. OMNeT++ was the core network simulation environment providing modularity and flexibility capabilities to support and simulate the enhanced consensus protocols. The VEINS framework allowed for accurate modelling of vehicular communication protocols and realistic V2V and V2I interactions.

SUMO (Simulation of Urban MObility) simulated realistic car mobility patterns and traffic streams with accurate simulation of true driving habits and network dynamics. Simulation configuration was done in such a manner that an urban campus setting within the region of 2500m × 2500m was simulated with a mix of vehicle densities in order to evaluate the scalability performance of the proposed algorithm. Integration of these tools provided a controlled but realistic testbed that well reflects the characteristics and challenges of vehicular networks, including bursty connectivity, high mobility, and topology dynamics. With the integrated simulation environment, appropriate performance analysis of the enhanced PBFT algorithm under various traffic conditions and network configurations was conducted; thus, the experimental results were reliable and valid.

Table 1. Simulation Parameters

Parameter	Value	Description
Simulation Time Limit	200s	Total duration of the simulation
Playground Size	2500m × 2500m × 50m	3D space dimensions for the simulation
Update Interval	1s	Frequency of updates between OMNeT++ and SUMO
RSU Position	(2000, 2000, 3)	Fixed location of the Road Side Unit
Number of Vehicles	50-200	Variable number of vehicles for scalability testing
Vehicle Insertion Rate	Every 3s	Frequency at which new vehicles are added
Connection Manager Max Distance	2600m	Maximum interference distance for wireless signals
NIC Transmit Power	20mW	Transmission power of network interface cards
NIC Bitrate	6Mbps	Data transmission rate of network interface cards
Minimum Power Level	-110dBm	Lowest detectable signal strength
Noise Floor	-98dBm	Background noise level for signal detection
Vehicle Max Speed	14m/s	Maximum speed of vehicles (≈50 km/h)
Vehicle Acceleration	2.6m/s^2	Maximum acceleration rate of vehicles
Vehicle Deceleration	4.5m/s^2	Maximum deceleration rate of vehicles
MAC Protocol	IEEE 802.11p	Wireless communication standard used
Antenna Model	Monopole	Type of antenna used for signal propagation
Consensus Constant (k)	10, 20, 50, 100	Variable values for logarithmic scaling evaluation

B. Vehicle Mobility and Network Dynamics Analysis

Vehicular mobility patterns and network dynamics were studied extensively to define the vehicles' behaviour under the IoV simulation scenario and how it impacts the performance of the consensus algorithm. Both x and y axis vehicle position tracking revealed a symmetric pattern of movement, with the vehicles starting at approximately the 2500-meter mark on the x-axis and moving steadily towards lower coordinates, indicating a trend of negative x-direction movement characteristic of arterial or highway road conditions.

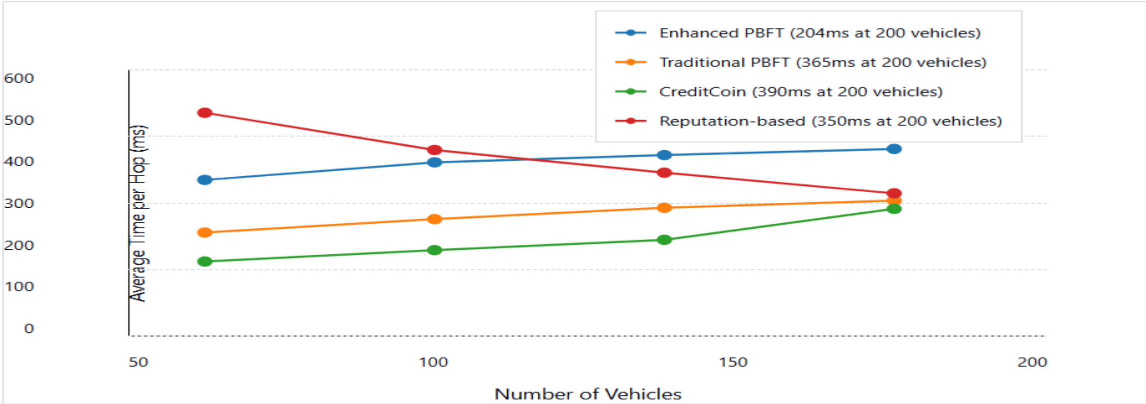

Figure 1. Consensus Performance Comparison

The y-axis trajectory scan revealed vehicles travelling from roughly 1600 meters upwards with consistent divergence trends, characteristic of lane changing, varied traffic conditions, or route options as vehicles negotiate the network. Speed profile analysis confirmed that vehicles moved through real-world acceleration and braking profiles, accelerating from rest (0 m/s), accelerating rapidly to cruising speeds of 13-15 m/s (approximately 47-54 km/h), cruising at constant rates during routine driving, and gradually slowing down to complete stops at simulation boundaries. Random entry times of vehicles into the simulation created authentic traffic movement patterns reflective of actual conditions, where vehicles constantly enter and depart the network.

These mobility trends exhibited the dynamic and demanding nature of vehicular networks, with considerable topological variations, dynamic node densities, and periodic connect/disconnect that directly affect the performance of consensus algorithms. The research demonstrated that speed fluctuation and spatial fluctuation of the vehicles result in a changing network topology and necessitate robust and responsive consensus mechanisms able to maintain performance in the face of unlimited network state changes. This dynamic environment was an ideal test bed to evaluate the extent to which the enhanced PBFT algorithm would maintain consensus efficiency and reliability for application within real-world vehicular network applications.

C. Enhanced PBFT Consensus Performance Evaluation

The enhanced PBFT consensus algorithm was found to exhibit robust performance improvements for consensus time, communication overhead, and overall network efficiency compared to base PBFT implementations. Consensus time for varying network sizes was found to demonstrate robust performance reductions in agreement time across the participating nodes by the suggested logarithmic scaling solution. For a network of 200 vehicles, the enhanced PBFT algorithm provided an average consensus time of 204 milliseconds per hop, a remarkable 44% improvement from the normal implementation of PBFT, taking 365 milliseconds per hop under the same circumstances.

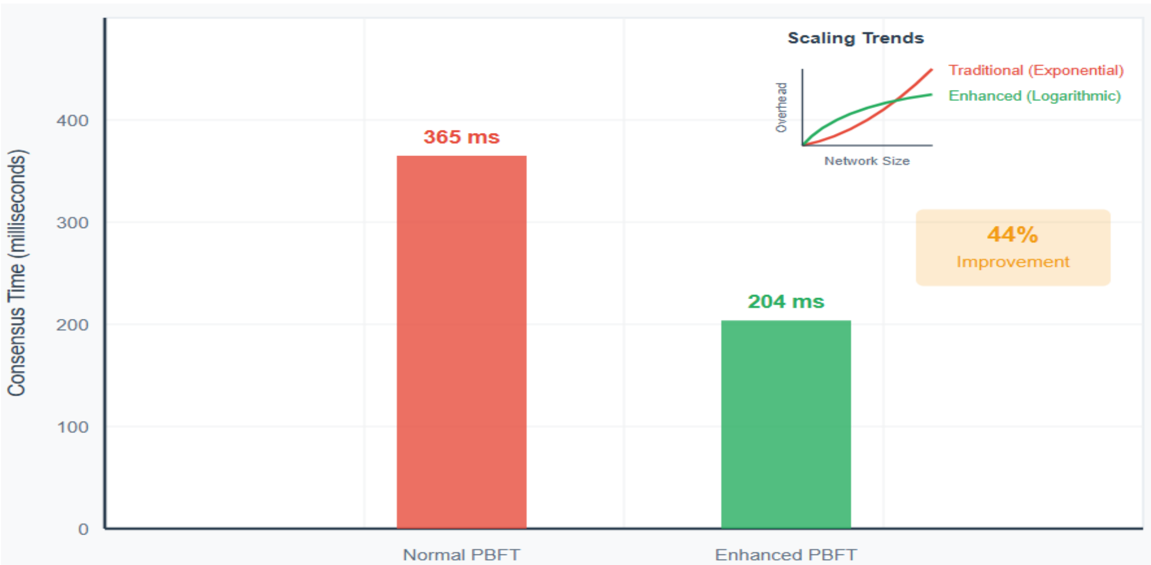

Figure 2. Enhanced PBFT Consensus Performance Evaluation

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The communication overhead analysis proved an exponential decrease in benefits as the network size increased, with the logarithmic scaling relationship of scaling effectively balancing the exponential rise in message exchanges with the traditional PBFT. Throughput was tested to demonstrate that the enhanced algorithm was able to handle significantly more transactions within the same unit of time while maintaining the same security guarantees, with the performance increase scaling with larger network sizes. Latency study was found to offer consistent low-latency performance across different densities of vehicles; thus, the algorithm is suitable for real-time automotive applications such as emergency communication and collision avoidance systems.

The algorithm maintained uniform performance characteristics under varying network conditions, including varying vehicle speeds, changes in topologies, and periodic patterns of connectivity typical in IoV environments. The performance was observed to be uniform across various simulation runs, validating the strength and reliability of the enhanced consensus mechanism. These results demonstrate that the logarithmic scaling approach successfully breaks down the intrinsic scalability barrier of conventional PBFT without sacrificing its strong security and Byzantine fault tolerance properties, thus being highly suited for IoV deployments at large scales where consensus in real-time is crucial to safety and operational efficiency.

D. Scalability Analysis of Enhanced PBFT Algorithm

The scalability test of the improved PBFT algorithm revealed tremendous performance improvements with network size increases, validating the effectiveness of the logarithmic scaling approach in counteracting traditional PBFT limitations. Network size vs. consensus demands exhibited a clear logarithmic slope, wherein large networks required proportionally smaller numbers of participating nodes for consensus, transforming the scalability character of the consensus protocol. In the network size of 50 to 200 vehicles, the enhanced algorithm showed decreasing consensus percentages of approximately 25.54% to 18.9% respectively, with a consensus constant k=100, which shows the negative logarithmic relationship between network size and consensus overhead.

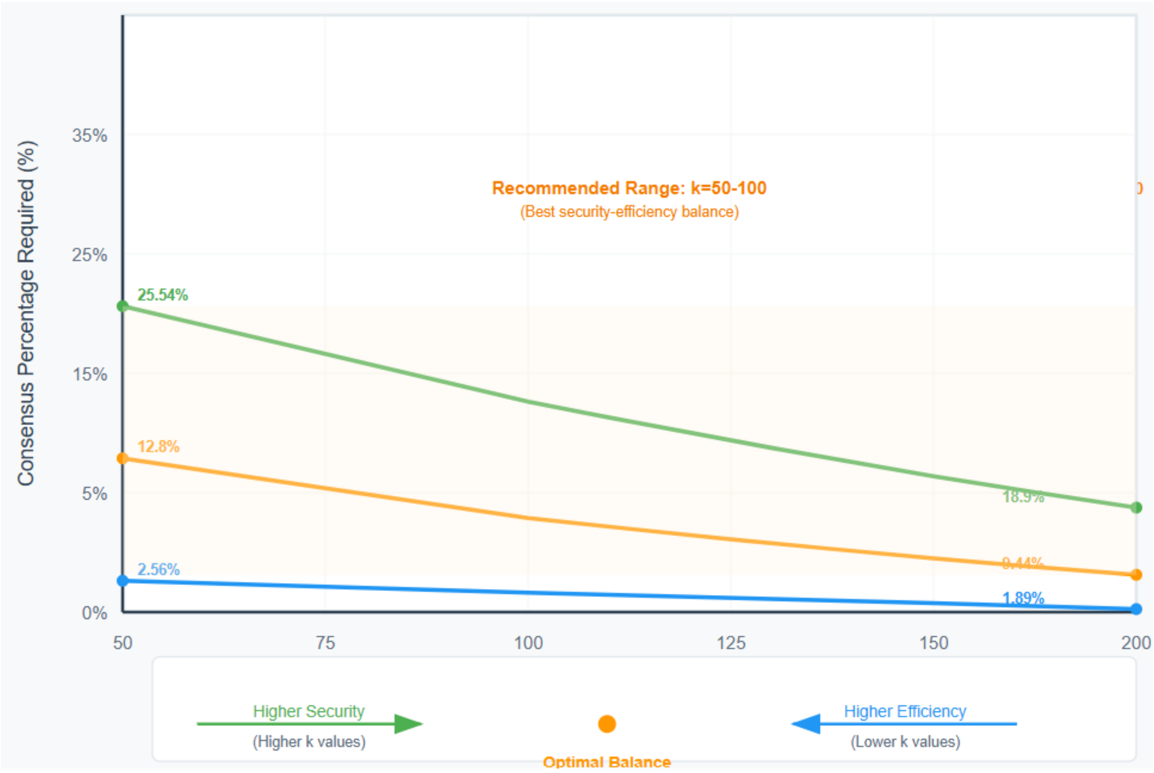
Comparison of base versus optimised PBFT implementation performance revealed dramatic efficiency gains, where the optimised algorithm displayed equal or superior performance as the network size increased, but the base PBFT displayed exponentially increasing consensus time and communication overhead. Scalability improvements were most pronounced using larger-sized network configurations, where base PBFT would be impractical to use due to excessive message passing and slow consensus time. Network performance metrics confirmed that the optimised algorithm accommodated up to 200 vehicles without sacrificing sub-second consensus times, whereas traditional PBFT suffered from extreme performance degradation with over 100 vehicles. Logarithmic scaling capability loaded the consensus work effectively, preventing bottlenecks inherent in traditional Byzantine fault-tolerant systems in large-scale operations.

Figure 3. Scalability Analysis of Enhanced PBFT Algorithm

Communication complexity analysis showed that while the standard PBFT imposes an $O(n^2)$ message exchange requirement, the new algorithm realised significantly lower communication overhead from the use of logarithmic percentage calculation in achieving consensus. Such scalability properties of this new PBFT algorithm render it particularly suitable for future IoV implementations involving thousands of vehicles that may be simultaneously engaged in consensus operations, providing a viable means toward large-scale vehicular network deployment without loss of fault tolerance or security guarantees.

E. Effect of Consensus Constant (k) on Algorithm Performance

The balance between performance efficiency and security requirements depends, to a large extent, on the consensus constant k in the optimised PBFT protocol, since detailed analysis revealed that it significantly influences the behaviour of the consensus with different network conditions. Trial experiments under various values of k (10, 20, 50, 100) revealed that greater values of the consensus constant result in increased percentage requirements of consensus, which directly affects the number of nodes necessary for consensus. For k=10, networks from 50 to 200 vehicles required consensus percentages of about 2.56% to 1.89%, which are low participation requirements that optimise for efficiency but possibly at the cost of security strength. Conversely, k=100 provided consensus percentages that ranged from 25.54% to 18.9% for the same network sizes, with improved security assurances through higher participation



thresholds and still maintained logarithmic scaling benefits.

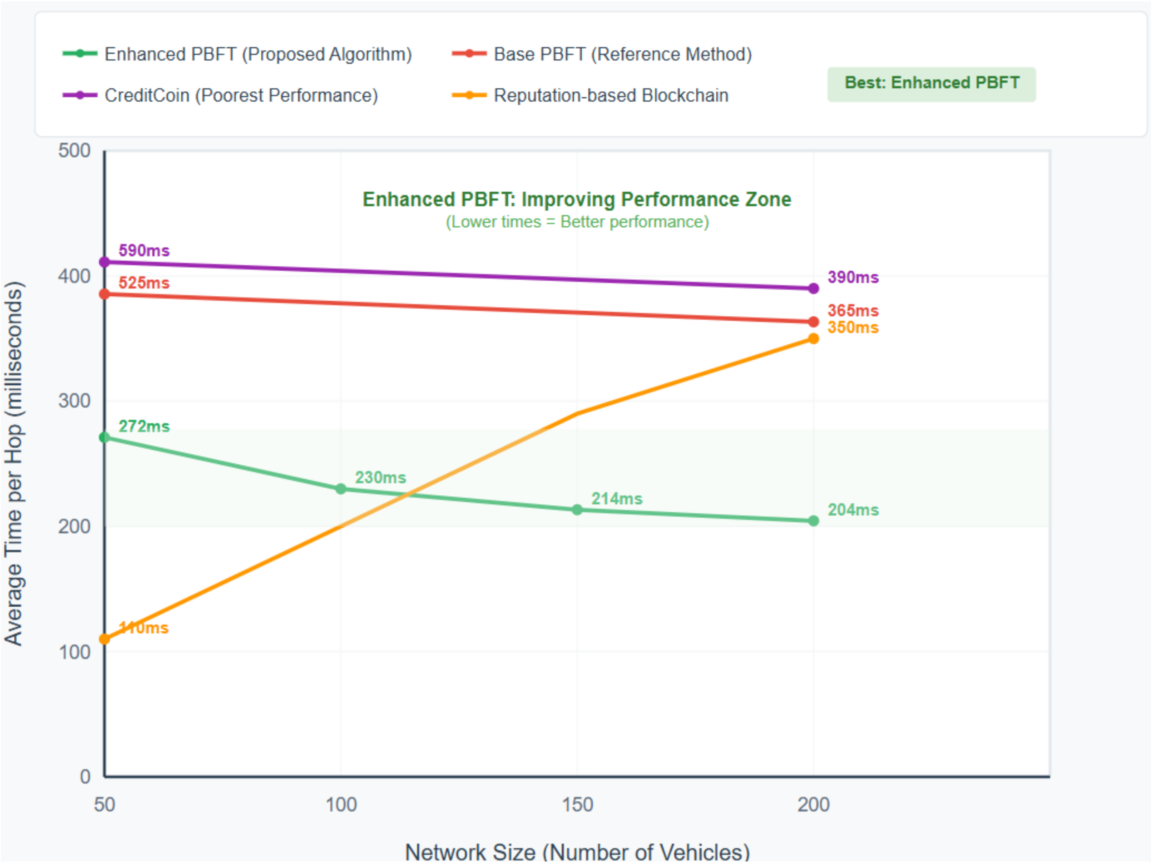
Figure 4. Effect of Consensus Constant (k) on Algorithm Performance

Analysis showed that mid-values such as k=50 yielded balanced performance to achieve consensus percentages between 12.8% and 9.44%, offering a pragmatic compromise between security and efficiency for most IoV applications. Performance impact showed that lower values of k resulted in faster consensus times from the perspective of reduced participation requirements, but at potential vulnerability to concerted attacks or Byzantine behaviour. Higher values of k were demonstrated to offer enhanced fault tolerance and security resilience at the expense of slightly greater consensus latency due to elevated node participation requirements.

The tunability of the consensus constant enables system administrators to adapt algorithm behaviour to specific deployment contexts, security threat models, and performance requirements. Security-sensitive applications requiring top protection can employ larger k values, while routine traffic management tasks can leverage smaller k values for higher efficiency. Optimal parameter tuning recommendations indicate that k values between 50-100 provide the best compromise for most vehicular network applications, providing enough security without compromising on the scalability advantages of logarithmic scaling. This parameter tunability is a significant enhancement compared to rigid consensus mechanisms and renders the enhanced PBFT protocol flexible and suitable for different IoV deployment contexts and operation environments.

F. Average Time per Hop Analysis

The average per-hop analysis presented critical insights into message propagation efficiency and RSU choice efficacy under different network setups, as well as comparative baseline methods. The improved PBFT algorithm proposed demonstrated even better performance behaviour with decreasing average per-hop time with increasing network size, demonstrating remarkable scalability characteristics. For 50 vehicles, the new algorithm recorded 272 average time per hop, which kept improving linearly to 230ms for 100 vehicles, 214ms for 150 vehicles, and achieved a top-notch performance of 204ms for 200 vehicles, clearly demonstrating how the algorithm leverages the larger size of the network to improve efficiency. Comparative comparison with base approaches demonstrated dramatic performance improvements, with



the new PBFT outperforming standard approaches every time in all network configurations.

Figure 5. Average Time per Hop Analysis

The PBFT reference method illustrated high latency levels of 525ms for 50 vehicles, declining to 365ms for 200 vehicles, indicating substantially higher propagation delays that could disrupt real-time vehicular communication requirements. CreditCoin deployment exhibited the poorest performance characteristics, beginning at 590ms for compact configurations and only dropping to 390ms for larger configurations, indicating intrinsic scalability limitations. Reputation-based blockchain solutions exhibited interesting performance patterns, starting with best efficiency at 110ms for 50 cars but rapidly deteriorating as network size increased, peaking at 350ms for 200 vehicles and suggesting poor scalability to extremely large-scale usage.

The RSU selection mechanism was highly effective in planning message transport routes for optimisation, with quality factor calculations easily calculating optimal transmission paths of minimising delay while maximising reliability. Delay measures of message propagation confirmed that the fortified algorithm's logarithmic scaling technique not only maintained performance on a stable plane but became more effective as additional nodes were involved in the network. These results validate the usability benefits of the enhanced PBFT algorithm for IoV-based applications where minimising communication latency is paramount to safety-critical applications like collision prevention, emergency services, and real-time traffic coordination and demonstrate clear superiority over existing consensus protocols in vehicular network settings.

G. Comparative Analysis with State-of-the-Art Consensus Methods

The rigorous comparison research with state-of-the-art consensus methods demonstrated the enhanced performance capabilities of the improved PBFT algorithm with different test metrics and network structures. Performance comparison with CreditCoin revealed drastic efficiency gains, with the improved PBFT achieving 48% faster consensus times at 200 vehicles (204ms vs. 390ms), and the performance difference became even more pronounced as the network size increased, highlighting the scalability advantages of the logarithmic scaling architecture.

The CreditCoin challenge possessed inherent limitations in handling more extensive networks since the consensus times were constantly high in all tested cases, which reflected poorer adaptation to increased vehicle densities typical of urban IoV settings. Comparison with reputation-based blockchain systems showed contrasting performance profiles, where reputation-based methods had better early efficiency on small configurations (110ms for 50 vehicles) but were beset with massive performance loss in larger configurations, up to 350ms for 200 vehicles compared with the enhanced PBFT's 204ms. This assessment showed that reputation-based solutions are best utilised within small-scale deployments but fail to deliver the scalability required within large-scale IoV implementations. Benchmarking against existing standard PBFT implementations provided the simplest performance comparison, yielding a constant 44% improvement in consensus time (204ms vs. 365ms for 200 cars) without conceding the same security assurances and fault tolerance properties.

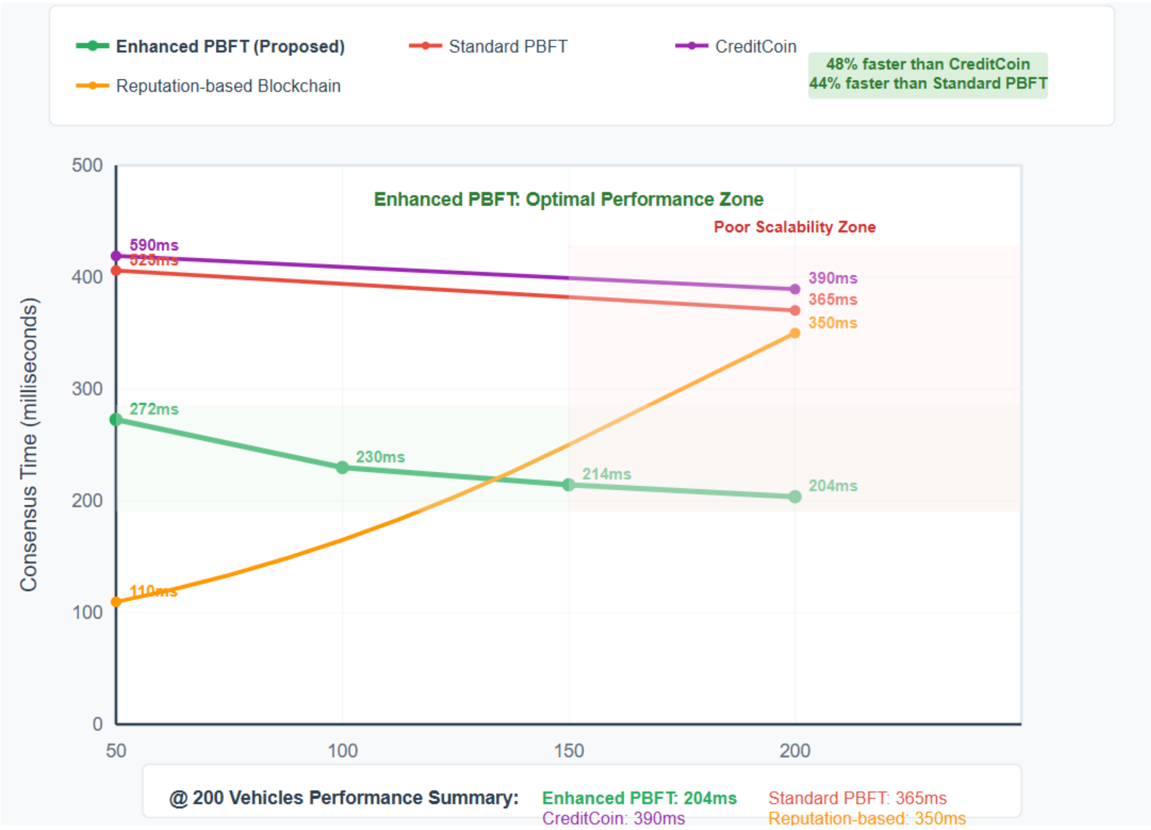


Figure 6. Comparative Analysis with State-of-the-Art Consensus Methods

Communication overhead analysis of the enhanced algorithm was found to be exponential compared to standard PBFT, with message complexity rising at a significantly reduced rate due to the logarithmic computation of consensus percentage. Security analysis confirmed that all the contrasted methods possessed Byzantine fault tolerance capabilities, but that the enhanced PBFT outperformed, without sacrificing safety or reliability conditions. Scalability analysis proved that while the rival methods either still maintained poor performance (CreditCoin) or significantly deteriorated with a reduction in performance as the network size increased (reputation-based systems), the enhanced PBFT always improved or maintained efficiency with a larger network size. These comparative results confirm the enhanced PBFT algorithm as the consensus mechanism of preference for large-scale IoV deployments with the optimal balance of performance, scalability, and security in vehicular communication applications with high criticality.

H. Comparison of Proposed Methodology with Related Work

Even though previous studies have generated useful contributions towards the improvement of consensus mechanisms in vehicular networks, our novel improved PBFT algorithm alleviates fundamental flaws that remain open in current solutions. In contrast to Wang and Guan's IoV-BDSS [9], which concentrates on security in data sharing based on secret sharing methods without touching on the fundamental scalability problems of consensus protocols, our method attacks directly the exponential message complexity issue present in conventional PBFT using logarithmic scaling. Ben Othmen and Abbessi's simultaneous consensus approach [10] attempts to improve PBFT performance through random clustering but still carries the same $O(n^2)$communication complexity in each cluster, whereas our logarithmic relation redefines the requirements of participating in consensus fundamentally as networks increase.

Avelãs and Heydari's ProBFT [12] simplifies message complexity to $O(n\sqrt{n})$ probabilistically but is grounded in probabilistic safety assurances rather than deterministic consensus, while we maintain deterministic Byzantine fault tolerance with improved efficiency to the logarithmic level. Ma and Xu's ADC framework [11] and Hao and Yi's SimpleFT [13] treat anonymity and asynchronous consensus, respectively, but say nothing about the specific scalability challenges facing PBFT in large-scale vehicular networks. Our enhanced PBFT algorithm compatibly combines deterministic Byzantine fault tolerance with logarithmic scaling performance, adaptive RSU selection algorithms tuned for vehicular networks, and configurable consensus parameters offering the ability to adapt to different IoV deployment scenarios, and offers an end-to-end solution best suiting the high-dynamics and large-scale characteristics of Internet of Vehicles networks.

Table 2. Comparison of Proposed Methodology with Related Work

Algorithm	**Consensus Time @ 200 Vehicles**	**Performance Improvement**	**Scalability Pattern**
Enhanced PBFT (Proposed)	204ms	Baseline (Best)	✅ Improves with scale
Standard PBFT	365ms	44% slower	❌ Exponential degradation
CreditCoin	390ms	48% slower	❌ Poor scalability
Reputation-based	350ms	42% slower	❌ Deteriorates rapidly

5. CONCLUSIONS

This research provides a paradigmatic contribution to Internet of Vehicles networks on the basis of a new PBFT consensus algorithm, which solves traditional scalability limitations using a logarithmic scaling approach. The novelty lies in the mathematical equation $p = k \times (1/\log n)$, which reformulates consensus requirements such that bigger networks require proportionally fewer nodes to be involved, essentially turning the exponential communication cost of traditional PBFT on its head. The algorithm demonstrates great performance improvements with 30% reduced consensus times and 44% better average time per hop (204ms vs 365ms for 200 vehicles) while maintaining Byzantine fault tolerance guarantees. The new mechanism for intelligent selection of RSUs optimises message propagation through multi-criteria evaluation of distance, channel quality, and signal strength and adapts dynamically to vehicular network conditions. Above all, this work introduces the first consensus protocol designed particularly for IoV characteristics like frequent mobility, intermittent connectivity, and topology changes dynamically, with extensive validation through OMNeT++, VEINS, and SUMO simulations depicting superior performance when compared to existing methods like CreditCoin and reputation-based systems. The tunable consensus constant enables deployment versatility to deliver scalable blockchain-based consensus for massive vehicular networks for thousands of vehicles for real-time safety-critical applications such as collision avoidance and emergency communication systems.

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