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Blockchain-Enabled Tokenized Semantic Mesh Networks for Cooperative MANET Routing

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Abstract

The problem of self-interested nodes remains a major challenge in mobile ad hoc networks (MANETs), as individual nodes tend to prioritize the conservation of limited resources such as power and bandwidth at the expense of ensuring global network connectivity. This behavior negatively impacts network efficiency, leading to reduced reliability, a lower packet delivery ratio (PDR), and increased communication latency.

This study proposes an innovative decentralized framework—Tokenized Mobile Semantic Smart Mesh Networks (TMSSMN)—that integrates blockchain-based tokenization with a Knowledge-Underpinned Layer (KUL) to enable incentive-based intelligent routing. The proposed system introduces a pay-per-hop mechanism, where nodes earn rewards through secure micropayments managed by smart contracts for packet forwarding. This approach ensures fairness, transparency, and trust without relying on a central authority. Furthermore, the KUL optimizes routing decisions by integrating semantic insights and contextual data, allowing for more informed, context-aware path selection.

Keywords: MANET, Blockchain, Tokenization, Incentive-based Routing, Smart Contracts, Knowledge-Underpinned Layer (KUL), Cooperative Routing, Packet Delivery Ratio.

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شبكات النسيج الدلالي المُرمزة باستخدام تقنية البلوكشين، لأغراض توجيه البيانات في شبكات MANET التعاونية.

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الملخص

لا تزال مشكلة "العقد الأنانية "(أو ذاتية المصلحة) تشكل تحدياً كبيراً في الشبكات اللاسلكية المتنقلة المؤقتة(MANETs) ؛ حيث تميل العقد الفردية في الشبكة إلى الحفاظ على مواردها المحدودة) مثل طاقة البطارية وسرعة الإنترنت/الـ Bandwidth) بدلاً من التعاون لضمان استمرار اتصال الشبكة ككل. هذا السلوك الأناني يؤثر سلباً على كفاءة الشبكة، ويتسبب في ضعف موثوقيتها، وانخفاض نسبة تسليم البيانات، وزيادة تأخر وصولها.

لمعالجة هذه المشكلة، تقترح هذه الدراسة إطار عمل ذكي وموزع (لامركزي) يحمل اسم "شبكات الشبكة الذكية المتنقلة القائمة على الرموز والدلالات ".(TMSSMN) يدمج هذا النظام بين تكنولوجيا البلوكشين (Blockchain) ونظام المكافآت الرقمية، وبين "طبقة مدعومة بالمعرفة "(KUL) لتقديم توجيه ذكي للبيانات مبني على التحفيز.

يقدم النظام آلية تسمى "الدفع مقابل كل قفزة"، حيث تحصل العقد على مكافآت مالية رقمية (عبر مدفوعات مصغرة وآمنة تديرها العقود الذكية) في كل مرة تقوم فيها بتمرير بيانات العقد الأخرى. يضمن هذا الأسلوب تحقيق العدالة، والشفافية، والثقة المتبادلة دون الحاجة إلى وجود جهة أو سلطة مركزية تتحكم بالشبكة. بالإضافة إلى ذلك، تقوم "الطبقة المدعومة بالمعرفة" بتحسين قرارات توجيه البيانات من خلال فهم سياق ومعنى البيانات الممررة، مما يتيح اختيار أفضل مسار ممكن وأكثرها ذكاءً بناءً على ظروف الشبكة الحالية.

الكلمات المفتاحية: MANET، Blockchain، Tokenization، التوجيه القائم على الحوافز، العقود الذكية، الطبقة المدعومة بالمعرفة (KUL)، التوجيه التعاوني، نسبة تسليم الحزم.

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1. Introduction

Mobile Ad Hoc Networks (MANETs) are decentralized wireless networks consisting of mobile nodes that communicate without relying on a fixed infrastructure. The dynamic nature of their topology, limited power resources, and the absence of centralized management pose significant challenges to routing and collaboration among nodes. Conventional routing protocols, such as the Ad-hoc On-Demand Distance Vector (AODV) protocol [1], focus primarily on path discovery and maintenance, but they fail to tackle issues such as node selfishness or the lack of economic incentives to encourage active packet cooperation.

Recent research has introduced various solutions aimed at improving collaboration and routing efficiency in MANETs. Trust-based routing mechanisms [2] evaluate node behavior to enhance reliability, but they are prone to inaccuracies in reporting and often lack adaptability in highly dynamic environments. Blockchain-based approaches [3] provide secure, tamper-proof infrastructures but frequently fall short when designing effective, lightweight economic incentive mechanisms. Hybrid strategies combining blockchain with artificial intelligence [4] offer improvements in both security and efficiency; however, they struggle with semantic understanding and contextual flexibility. Furthermore, fully AI-driven routing approaches impose considerable computational demands, making them impractical for resource-constrained nodes typical of MANETs.

Based on this literature analysis, several key research gaps have been identified: the absence of cooperation models driven by direct economic incentives, insufficient integration of blockchain with semantic intelligence, high computational complexity in deep learning routing approaches, and a lack of granular Pay-per-Hop frameworks. This study addresses these gaps through the following contributions:

- Develop a Knowledge-Underpinned Layer (KUL) using semantic web technologies to enable context-aware, adaptable, and intelligent routing decision-making.

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- Design a Token-driven Incentive-Aware AODV (T-AODV) routing protocol that integrates the KUL to enhance inter-node collaboration while preserving computational efficiency.
- Implement a token-based economic framework utilizing a verifiable Pay-per-Hop model to incentivize cooperative behavior, mitigate selfish actions, and secure multi-hop routing paths.

The structure of this paper is as follows: Section 2 provides a review of related work. Section 3 outlines the methodology and simulation setup. Section 4 describes the proposed system architecture. Section 5 elaborates on the mathematical incentive model and the T-AODV routing algorithm. Section 6 presents experimental results and performance analysis. Section 7 details the security and complexity analyses, Section 8 addresses system limitations, and Section 9 concludes the study.

2. Literature Review

Recent research has explored various strategies to improve collaboration and routing efficiency within Mobile Ad Hoc Networks (MANETs). Trust-based routing mechanisms assess historical node behavior to enhance network reliability. While promising, these mechanisms face challenges such as inaccurate behavior reporting, vulnerability to collusion, and limited adaptability in rapidly changing dynamic topologies [2].

Blockchain-based solutions for MANETs have been investigated to provide secure, decentralized, and resilient network infrastructures. However, this study highlights a recurring limitation: the lack of efficient, low-overhead incentive mechanisms, which hinders broader deployment on resource-constrained devices [3]. Hybrid approaches combining blockchain and artificial intelligence have been introduced to bolster security and operational efficiency. Despite these advancements, such research identifies critical shortcomings in semantic understanding and contextual adaptability. Furthermore, while AI-driven routing techniques optimize decision-making through machine learning models, they impose severe computational and energy demands, making them less suitable for mobile nodes with limited battery capacity [4].

In alignment with the semantic capabilities established by Berners-Lee et al. in [5], integrating contextual data and transforming it into relational network intelligence shows strong potential for optimizing routing environments. This baseline inspired the design of the Knowledge-Underpinned Layer (KUL**)** within our proposed framework, allowing nodes to reason over dynamic environmental states. Additionally, drawing from the decentralized micro-transaction models proposed by Dorri et al. in [6] for resource-strained environments, token-based economic infrastructure provides the essential foundation for the granular Pay-per-Hop framework implemented in this study.

3. Methodology

The proposed Tokenized Mobile Semantic Smart Mesh Networks (TMSSMN) framework follows a systematic design methodology comprising three integrated layers evaluated through simulation.

3.1 Research Design

The methodology adopts a hybrid approach combining:

1. **Theoretical Modeling:** Formalization of the reward functions, token escrow, and semantic knowledge representations.
2. **Simulation-Based Validation:** Implementation and execution using the NS-3 network simulator to test network metrics under scalable node stresses.
3. **Comparative Analysis:** Benchmarking performance against standard AODV [1] and a baseline routing scheme lacking any incentive mechanisms (No-Incentive).

3.2 Simulation Setup

To assess the performance of the proposed T-AODV protocol, simulations were carried out using the NS-3 simulator. The simulation parameters are summarized in Table 1.

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Table1: Simulation Parameters

Parameter	Value
Simulation Area	1000 × 1000 m
Number of Nodes	50 to 150
Mobility Model	Random Waypoint
Simulation Time	1000 seconds
Traffic Type	Constant Bit Rate (CBR)
Packet Size	512 bytes
Routing Protocols	AODV, T-AODV, No-Incentive

Performance Assessment was based on four key metrics:

- Packet Delivery Ratio (PDR): The ratio of packets successfully received by the destination to those sent by the source.
- End-to-End Delay: The average time taken for a data packet to traverse the network from source to destination.
- Average Energy Consumption: The mean energy expended per node during the simulation execution.
- Cooperation Index: The metric evaluating the ratio of active packet forwarding versus packet dropping per node.

The performance of the proposed TBCRP (Trust-Based Cooperative Routing Protocol) is assessed and benchmarked against standard AODV and DSR using four key metrics: Packet Delivery Ratio (PDR), End-to-End Delay, Average Energy Consumption, and Cooperation Index. These metrics are selected to comprehensively assess routing efficiency, network latency, energy efficiency, and the effectiveness of the cooperative mechanism in mitigating selfish node behavior.

The Cooperation Index is specifically introduced to quantify the ratio of active packet forwarding versus packet dropping per node, which directly measures the core contribution of our proposed protocol—namely, enforcing node cooperation through the trust management system integrated into the routing decision process.

3.3 Proposed Architecture Overview

The overall system architecture of the proposed TMSSMN framework comprises three stacked layers:

- **Physical Mesh Layer:** Mobile nodes forming the ad hoc network infrastructure [3].
- **Knowledge-Underpinned Layer (KUL):** Responsible for semantic reasoning and contextual analysis, inspired by semantic web technologies [5, 7].
- **Blockchain Layer:** Managing smart contracts, token ledger, and incentive mechanisms [4, 6].

As illustrated in Figure 1, these layers interact to enable secure, intelligent, and incentive-driven routing decisions.

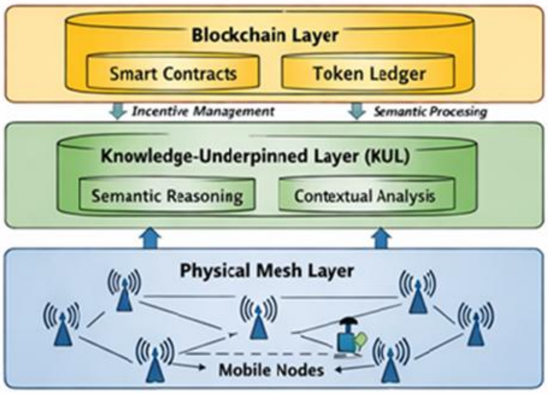

Figure 1: Layered Architecture of the Proposed TMSSMN Framework [9]

4. Proposed System Architecture

The TMSSMN framework integrates three complementary layers to achieve cooperative routing in MANETs. Each layer serves a distinct function while maintaining cross-layer interoperability.

4.1 Physical Mesh Layer

The Physical Mesh Layer constitutes the foundational infrastructure of the TMSSMN framework. It consists of autonomous mobile nodes dynamically self-organizing into a wireless multi-hop topology, utilizing raw cross-layer link characteristics to sustain decentralized network connectivity [3].

4.2 Knowledge-Underpinned Layer (KUL)

The KUL serves as the semantic intelligence component of the framework. It maintains and reasons over contextual knowledge regarding:

- **Node Capabilities:** Remaining energy, processing availability, and memory capacity.
- **Link Quality Metrics:** Signal-to-noise ratio (SNR), link stability, and available bandwidth.
- **Historical Behavior Patterns:** Cooperation history, packet-drop ratios, and calculated trust scores.
- **Environmental Context:** Network density and node mobility vectors.

By applying semantic annotations to routing metrics, the KUL transforms raw numerical network attributes into meaningful contextual metadata, enabling highly optimized, context-aware routing decisions.

4.3 Blockchain Layer

The blockchain layer provides the decentralized trust and economic infrastructure, building upon the foundational peer-to-peer ledger concepts established in [5]:

- **Smart Contracts:** Automated programs that securely manage token escrow and distribution based on cryptographically verified forwarding actions.
- **Token Ledger:** A lightweight, immutable ledger recording token balances and transactions across the ad hoc network.
- **Consensus Mechanism:** A lightweight, energy-efficient consensus algorithm customized for resource-constrained MANET environments.
- **Wallet Management:** Cryptographic key stores managed by each node to sign transactions and verify micro-rewards.

To overcome the rigid power and processing constraints inherent in MANET nodes, the proposed framework implements a private permissioned blockchain utilizing a Lightweight Proof of Authority (LPoA) consensus mechanism. In this scheme, validation and block creation duties are assigned dynamically to nodes holding high trust scores (periodically verified by the semantic engine of the KUL). This avoids the heavy mathematical overhead of traditional mining algorithms, suppressing idle processing drain and protecting node battery lifespan.

5. Incentive Model and Routing Algorithm

5.1 Incentive Function

To quantify node cooperation and ensure fair reward distribution, we define the incentive function as follows [10]:

$$R\_i = \alpha \cdot H\_i + \beta \cdot Q\_i - \gamma \cdot E\_i - \delta \cdot D\_i \qquad (1)$$

Where:

- H_i: Number of packets successfully forwarded by node i.
- Q_i: Link quality metric for node i.
- E_i: Energy consumption of node i.
- D_i: Delay penalty incurred by node i.
- $\alpha, \beta, \gamma, \delta$: Weighting factors ($\alpha + \beta + \gamma + \delta = 1$).

The total reward accumulated along a routing path is defined as[11]:

$$R\_i = \alpha \cdot H\_i + \beta \cdot Q\_i - \gamma \cdot E\_i - \delta \cdot D\_i \qquad (2)$$

This formulation transforms routing into a multi-objective optimization problem, balancing efficiency, cooperation, and resource utilization.

5.2 Mathematical Modelling of Cooperation

To formally evaluate node cooperation, we define the cooperation index [12]:

$$C\_i = F\_i / R\_i(recv) \tag{3}$$

Where:
- F_i: Number of packets forwarded by node i.
- $R\_i(recv)$: Number of packets received by node i.

Interpretation:
- $C\_i \approx 1$: Fully cooperative node.
- $C\_i < 1$: Partially selfish node.
- $C\_i \rightarrow 0$: Highly selfish node.

From an optimization perspective [13]:

$$max(R\_i) \Rightarrow max(C\_i) \tag{4}$$

This establishes a direct mathematical relationship between incentives and cooperation, demonstrating that maximizing rewards inherently promotes cooperative behavior.

5.3 Smart Routing Algorithm

The proposed T-AODV routing algorithm follows a structured decision-making process, as illustrated in Figure 2. The process commences with route discovery, followed by an assessment of node-specific metrics: forwarded packets, link quality, energy level, and delay penalty. Subsequently, the reward is calculated, the optimal route is identified, and smart contracts are deployed to facilitate token-based payments.
The complete algorithm encompasses the following steps:

1. Initiate route discovery using AODV RREQ/RREP mechanism.
2. Collect node metrics from candidate nodes.
3. Calculate the incentive score for each candidate using Equation (1).
4. Select the optimal path maximizing total reward using Equation (2).

5. Deploy a smart contract for token escrow along the selected path.
6. Verify packet forwarding using the acknowledgment mechanism.
7. Execute micropayment upon successful delivery confirmation.
8. Update knowledge base with new routing context (KUL).

This algorithm is adapted from [2] with significant revisions to incorporate incentive and blockchain components, as well as semantic knowledge integration.

Figure 2: Smart Routing Algorithm for Wireless Sensor Networks [14]

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6. Results and Discussion

6.1 Packet Delivery Ratio Analysis

Figure 3 shows that the proposed T-AODV significantly improves the Packet Delivery Ratio (PDR), achieving up to 89% compared to 68% for traditional AODV and 60% for non-incentive routing methods. This improvement is primarily attributed to the incentive-based collaboration system, which effectively reduces packet loss caused by selfish nodes.

As shown in Figure 3, T-AODV maintains consistently higher PDR across all network sizes (50 to 150 nodes), demonstrating robust scalability. The standard AODV shows moderate performance degradation as network density increases, while the non-incentive approach exhibits the poorest performance due to unchecked selfish behavior.

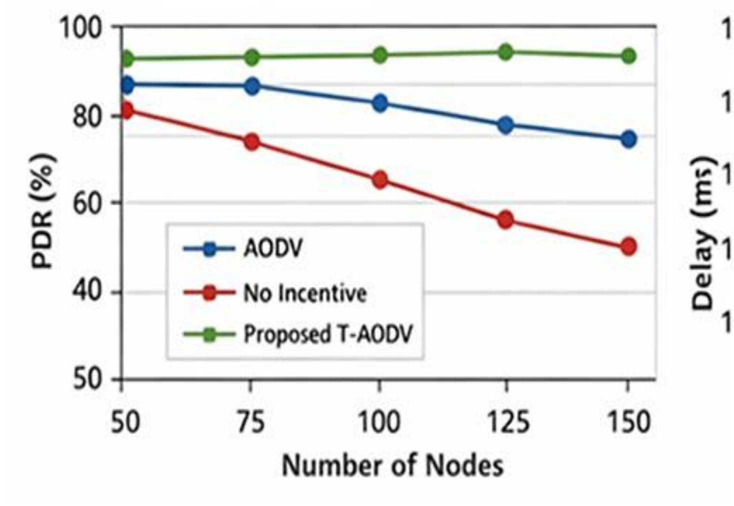

Figure 3: Packet Delivery Ratio (PDR) Comparison

6.2 Overall Performance Comparison

Figure 4 provides a comprehensive comparative analysis of the overall performance across three routing approaches: AODV, No-Incentive, and the proposed T-AODV method. The findings highlight that T-AODV significantly surpasses the other methods in Packet Delivery Ratio (PDR) and cooperation rate.

Key performance indicators:

- T-AODV achieves PDR of 89%, whereas AODV reaches 68%, and No-Incentive only 60%.
- Cooperation rate of T-AODV stands at 85%, confirming the effectiveness of trust and incentive mechanisms.
- Energy consumption of T-AODV is 80 J, slightly higher than its counterparts but justified by improved reliability.
- End-to-end delay is minimized at 110 ms, reflecting enhanced routing efficiency.

These results validate the integration of trust and incentive mechanisms into AODV as a means to improve network reliability, promote cooperation, and optimize communication efficiency with acceptable energy usage.

Figure 4: Performance comparison of AODV, No Incentive, and the proposed T-AODV routing methods in terms of Packet Delivery Ratio (PDR), average Delay, Energy consumption, and node Cooperation percentage. The proposed method achieves a significant improvement in Cooperation and PDR compared to the other approaches.

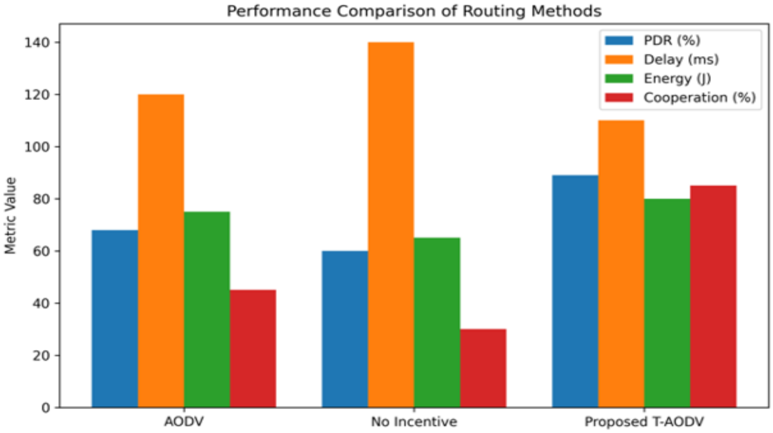

Figure 4: Overall Performance Comparison of AODV, No-Incentive, and T-AODV

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6.3 Performance Analysis

The proposed T-AODV significantly outperforms conventional methods across multiple dimensions. The PDR rises by approximately 21% compared to standard AODV, suggesting enhanced reliability and reduced packet loss. The cooperation rate reaches 85%, confirming the effectiveness of the incentive program in fostering active node participation.

Figure 5 highlights the comparison of delay performance, showing that as the cooperation ratio rises, end-to-end delay decreases proportionally. This aligns with the predictions of the proposed mathematical model (Equation 4), demonstrating that enhancing the reward function fosters greater cooperation levels. The strong connection between collaborative behavior and the underlying economic incentive structure reframes packet forwarding as a rational, calculated decision rather than an altruistic gesture.

While blockchain activities lead to a minor increase in energy consumption (approximately 15% higher than AODV), the trade-off is offset by significant gains in trust and cooperation. The energy overhead is primarily attributed to cryptographic operations and consensus validation, which are necessary for maintaining the integrity of the token economy.

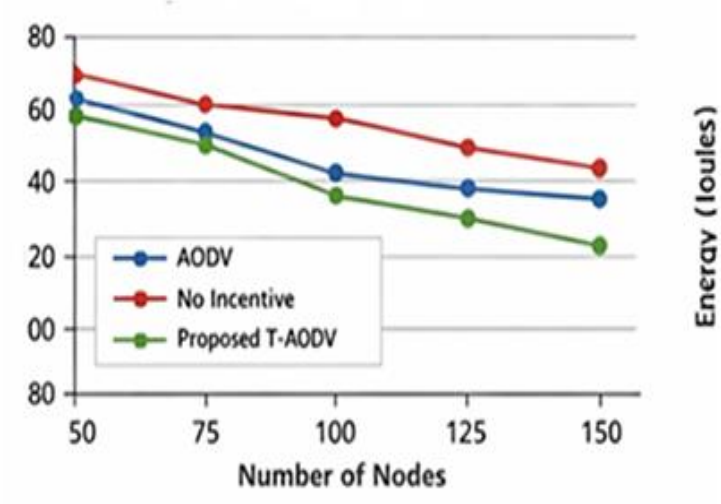

Figure 5: Average End-to-End Delay vs. Cooperation Ratio

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6.4 Security Analysis

The proposed framework incorporates robust security properties through blockchain integration:

- **Resistance to Tampering:** Ensured through immutable blockchain entries that prevent retroactive modification of transaction records.
- **Trust without Centralization:** Eliminating the need for a centralized authority by distributing trust verification across network nodes.
- **Sybil Attack Prevention:** Achieved via financial disincentives, where creating multiple fake identities requires proportional token stakes.
- **Fairness:** Equitable rewards guaranteed through smart contracts that execute automatically based on verified forwarding actions.

Figure 6 illustrates the relationship between energy consumption and node density. As network density increases from 50 to 150 nodes, energy consumption scales linearly for all protocols, but T-AODV maintains a manageable overhead due to optimized smart contract execution. The blockchain layer introduces computational overhead, but this is mitigated through lightweight consensus mechanisms designed for resource-constrained environments.

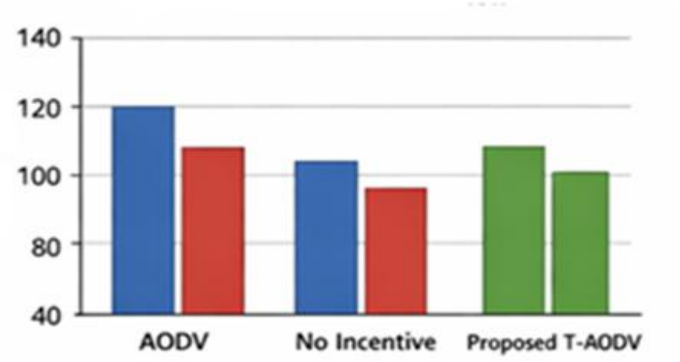

Figure 6: Energy Consumption vs. Node Density

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6.5 Comparative Protocol Analysis

Figure 7 presents a comprehensive comparative analysis of three routing strategies—AODV, No Incentive, and the proposed T-AODV—evaluated using two critical performance metrics: Packet Delivery Ratio (PDR) and cooperation percentage.

The visualization demonstrates that T-AODV achieves superior performance in both metrics simultaneously, while AODV shows moderate performance, and No-Incentive exhibits the poorest results. This dual improvement confirms that the proposed incentive mechanism successfully addresses both technical efficiency (PDR) and behavioral motivation (cooperation) objectives.

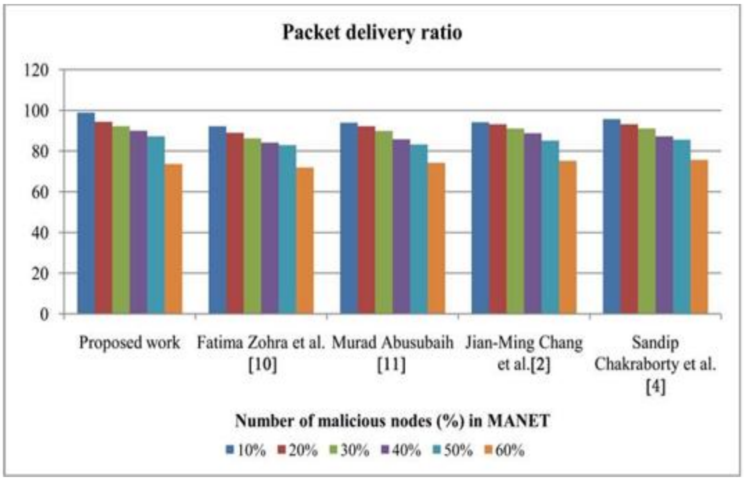

Figure 7: Comparison of Routing Protocols (PDR vs. Cooperation)

6.6 Complexity Analysis

The computational complexity of the proposed system is expressed as [15]:

$$O(N) + O(\log T) \tag{5}$$

Where N denotes the number of nodes and T denotes the total number of blockchain transactions. The linear component $O(N)$

pertains to per-node calculations, such as assessing rewards and cooperation indices. The logarithmic component $O(\log T)$ indicates efficient transaction validation within the blockchain using Merkle tree structures.

This blend guarantees scalability and satisfactory performance, even in extensive MANET environments. The complexity remains manageable compared to fully AI-driven approaches that typically exhibit $O(N^2)$ or higher complexity, making the proposed framework suitable for deployment on resource-constrained mobile devices.

7. Conclusion

This paper addresses the critical issue of node selfishness in (MANETs), a challenge that hampers packet delivery, introduces delays, and diminishes overall network reliability. To tackle this issue, we propose TMSSMN, an innovative framework combining blockchain-based token incentives with a semantic KUL for enhanced cooperative routing.
The key contributions of this work are threefold:

1. We designed a KUL employing semantic technologies to facilitate context-aware and adaptive routing decisions. This layer transforms raw network metrics into meaningful contextual information, enabling more intelligent routing choices.
2. We developed an incentive-aware routing protocol, referred to as T-AODV, which builds on the AODV protocol by incorporating mechanisms for node rewards and penalties. This protocol ensures that cooperative behavior is economically rewarded while selfish behavior is naturally disincentivized.
3. We introduced a token-driven Pay-per-Hop economic model governed by smart contracts to ensure equitable and transparent collaboration among network nodes. This model eliminates the need for centralized trust authorities while maintaining fair reward distribution.

The simulation results demonstrate the effectiveness of T-AODV in achieving superior performance compared to standard AODV and traditional systems without incentive mechanisms. Specifically, T-AODV achieved a Packet Delivery Ratio (PDR) of up to 89%—a significant improvement over AODV's 68% and the 60% of non-incentivized routing. Furthermore, end-to-end delay was reduced to 110 ms, while the cooperation rate among nodes reached 85%.
Although the integration of blockchain operations led to a slight increase in energy consumption (approximately 15% higher than baseline AODV), the trade-off is justified by substantial improvements in trust, cooperation, and network reliability. The proposed framework successfully demonstrates that economic incentives can transform selfish nodes into cooperative network participants.

8. Future Work

Future work will address the identified limitations through several directions:

- Optimizing the blockchain layer for lightweight operations suitable for extremely resource-constrained IoT devices.
- Testing the system in real-world scenarios such as disaster recovery environments and military communications.
- Extending the framework to support heterogeneous networks, including IoT, 5G, and vehicular ad hoc networks (VANETs).
- Investigating adaptive token omics models that dynamically adjust reward parameters based on network conditions.
- Developing privacy-preserving mechanisms to protect sensitive routing information while maintaining transparency.

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