RUBICONe: Wireless RAFT-Unified Behaviors for Intervehicular Cooperative Operations and Negotiations

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***Abstract*—Just as Caesar declared "alea iacta est" (the die is cast) upon crossing the RUBICONe river, lane change decisions in autonomous vehicles also represent critical points of no return. RUBICONe addresses this challenge by recognizing that lane change decision-making relying solely on a single vehicle's perception would be as precarious as crossing an unknown river alone. By implementing a distributed consensus framework that extends the RAFT algorithm with wireless connectivity, RUBICONe enables multiple vehicles to collectively process and aggregate their perceptions. Using multiple affordable RISC-V microcontrollers as the experimental platform, this study demonstrates how consensus-based decision-making significantly reduces the impact of environmental interference and mitigates the risk of misjudgments of individual vehicles. Just as the RUBICONe marked a point of irrevocable action backed by collective intelligence, RUBICONe ensures that lane change decisions are made with comprehensive situational awareness and distributed consensus, showcasing the reliability gain of consensus in wireless communications.**

I. Introduction

Contemporary mission-critical communications predominantly rely on wired infrastructure, where physical connections provide deterministic performance characteristics and established reliability metrics. Hardwired networks, particularly fiber-optic and high-grade copper interconnects, serve as the backbone for critical operations, offering predictable latency [8] (typically $\leq 1ms$), guaranteed bandwidth [9], and inherent security through physical isolation [1]. However, the emerging paradigm of mobility-centric applications-particularly in autonomous vehicles [10], industrial automation [4] necessitates the exploration of wireless alternatives, despite their inherent challenges in matching the deterministic nature of wired solutions [12].

The transition from wired to wireless domains in mission-critical scenarios represents a fundamental shift in reliability assurance mechanisms by overcoming the uncertainty of wireless connectivity. While wired networks benefit from a stable physical layer and proven protocols, wireless communications introduce stochastic channel variations and environmental dependencies that challenge traditional reliability assumptions [13]. Contemporary wireless solutions typically achieve reliability rates of 99.9% (or 1000 Hours of Mean Time Between Failures) [5] under optimal conditions, falling short of the 99.9999% reliability standard commonly required in mission-critical applications [12]. These constraints become particularly pronounced in applications demanding real-time consensus establishment, such as inter-vehicular communications, where maintaining wired-equivalent reliability becomes paramount for operational safety [17].

This paper presents RUBICONe (RAFT-Unified Behaviors for Inter-vehicular Cooperative Operations and Negotiations), a novel consensus-based architecture that aims to bridge the reliability gap between conventional wired infrastructure and emerging wireless solutions. Our methodology extends the fundamental RAFT algorithm, leveraging cost-effective (priced at $10) *Milk-V* Duo microcontrollers powered by the open-source RISC-V architecture to enable accessible and flexible experimentation. RISC-V's affordability and open design facilitate the development of reliable distributed systems without high costs. Our approach is guided by three key objectives:

- Hardware implementation of a wireless RAFT consensus system for critical decision-making using low-cost RISC-V Open Source System-on-Chip hardware, achieving hyper-reliability.
- Qualitative analysis of RUBICONe's reliability gains through hardware-validated simulations examining consensus scalability among 13 nodes with correlation to Received Signal Strength Indicator (RSSI).
- Quantitative performance evaluation across varying channel conditions, including SNR ranges from -3dB to 3dB, with detailed assessment of consensus convergence latency under diverse wireless environments.

By achieving these objectives, this study contribute to wireless distributed consensus on designing safer and more efficient lane change systems using RUBICONe with low-cost COTS hardware.

II. Related Work

Recent years have witnessed rapid progress in blockchain-based consensus mechanisms [illegible]e Internet of Vehicles (IoV), with research focusing [illegible]hancing trust, efficiency, and security. Notable approaches leverage cloud-edge-end collaborative architectures and hybrid consensus protocols (e.g., WRBFT, weighted Raft, PBFT) to enable reliable data sharing and rapid validation at the edge [7], [15]. Dynamic node selection and streamlined consensus, as in HN-mPBFT, further reduce latency and message complexity, while advanced schemes like PoTC introduce traffic-aware grouping and deep learning-based node assessment to improve security and adaptability [2], [6]. Parallel and hybrid frameworks (e.g.,

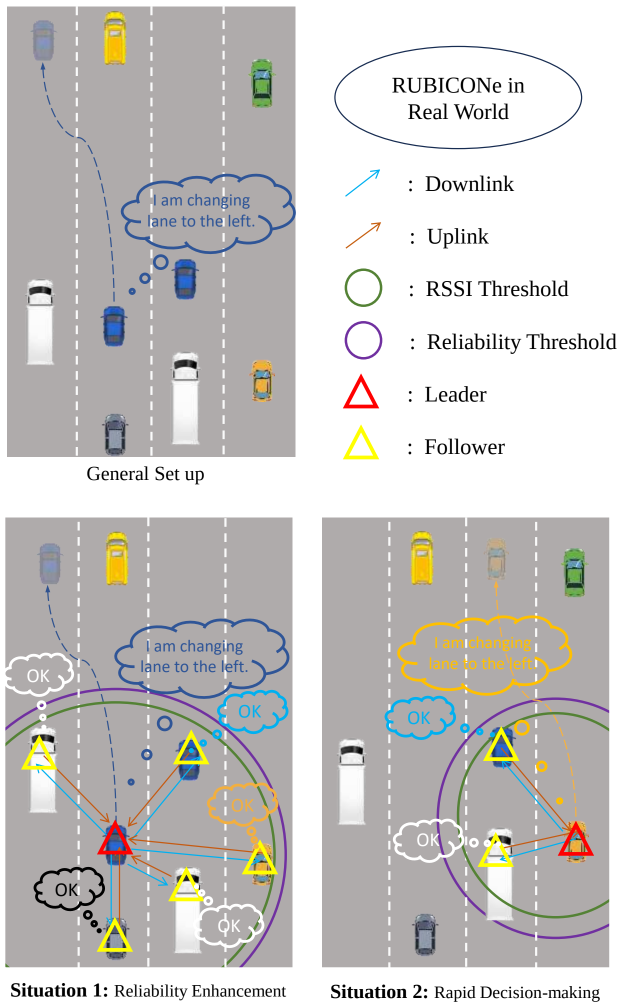

Fig. 1: Lane-change decisions in RUBICONe.

DAG-Lattice PBFT, HCN, ECRaft) have also been proposed to boost throughput and scalability [3], [14], [16].

Despite these advances, most existing solutions share critical limitations in real vehicular environments:

- **Complex Network Mechanisms:** Dynamic sharding, multiphase consensus, and deep learning-based evaluation often result in high coordination and computational overhead, making real-time adaptation to fast-changing topologies difficult.
- **High Computational and Deployment Costs:** Many protocols depend on resource-intensive cryptographic operations or require powerful edge hardware, increasing both deployment and operational expenses.
- **Significant Storage and Communication Overhead:** Maintaining multiple chains or full transaction histories leads to high storage and bandwidth consumption, limiting scalability.

These issues block the practical, low-cost deployment of consensus mechanisms in real IoV scenarios.

Therefore, there is an urgent need for lightweight and low-cost consensus solutions with low complexity, which can be more easily used in resource-constrained vehicular networks. Our work addresses this gap by focusing on the design and implementation of a low-cost, lightweight consensus protocol tailored for IoV environments.

III. System Model

The RUBICONe architecture employs RAFT consensus algorithm to enable reliable lane-change decisions in autonomous vehicle networks. By adopting a RAFT-like coordination strategy, the system allows the acting node and other distributed vehicle nodes to collaboratively manage state transitions through dynamically adaptive RAFT roles (i.e., follower, candidate, leader), ensuring system resilience against the weak link realibiltiy, dynamic topology and latency constraints inherent to open environments.

As depicted in Fig. 1, vehicles relying solely on cameras and LiDAR often fail to detect blocked targets in blind spots, thereby causing collision risks. RUBICONe addresses this challenge by synthesizing voting inputs from all vehicular nodes via downlink (DL) and uplink (UL) channels to derive collision-averse lane-change decisions. For instance, in Situation 1 of Fig. 1, the leader node aggregates multi-node consensus and prioritizes left lane changes over rightward maneuvers to mitigate blind-zone hazards. Concurrently, RUBICONe ensures expedited decision-making under favorable traffic conditions. As demonstrated in Situation 2 in Fig. 1, the leader dynamically selects proximal neighbors through RSSI-weighted adaptive coordination, prioritizing high-signal and reliable nodes to expedite consensus.

By leveraging the distributed consensus framework, RUBICONe effectively mitigates the uncertainties introduced by wireless channel stability. This model not only enhances the overall safety of lane-change maneuvers but also optimizes traffic flow by allowing vehicles to make informed decisions in real-time. The RAFT-unifed approach in high-density traffic scenarios help vehicle communicate effectively and reliably, reducing the likelihood of accidents caused by misjudgments or delayed responses.

IV. RUBICONe: The Algorithm

RUBICONe covers the wireless RAFT decision-making algorithms and the hardware implementation using low-cost hardware. This architecture consists of the following key components:

A. System Organization

The network comprises N distributed nodes, each representing a vehicle equipped with wireless connectivity. Every node is implemented using a *Milk-V* Duo S microcontroller, enabling real-time consensus, local state management, and integrated WLAN connectivity. In the experimental configuration, a specifically designated leader node coordinates initial cluster formation, though in real-world deployments all vehicles would autonomously participate in the distributed consensus protocol without relying on predefined supervisory roles.

The inter-vehicular communication operates over time-varying wireless channels characterized by Rayleigh fading, implementing CSMA/CA for medium access control. This wireless environment introduces inherent challenges including packet loss, variable latency, and signal degradation-factors that the RUBICONe framework specifically addresses through its consensus algorithm.

B. Consensus Protocol

The consensus algorithm functions based on a collection of critical state variables and decision parameters to enable reliable distributed decision-making for lane changes. This design explicitly accounts for vehicular wireless channel characteristics through the following four parts:

- **State Initialization**: Each vehicle node initializes with a local state vector $\mathbf{s}_i = (\mathbf{p}_i, \mathbf{v}_i, \mathbf{h}_i)$, where $\mathbf{p}_i$ and $\mathbf{v}_i$ represent real-time position and velocity, and $\mathbf{h}_i$ captures channel state information (CSI) for wireless link quality assessment. The consensus algorithm processes these parameters through analytical computation, extracting inter-vehicle distances d_{ij} and channel quality indicators γ_{ij}. Nodes periodically broadcast heartbeat messages to discover neighbors and maintain a dynamic topology map $\mathcal{N}_i$, filtering connections based on communication range d_{comm} and channel quality threshold γ_{min}, that is,

$$\mathcal{N}_i = \{j \mid d_{ij} \leq d_{\text{comm}}, \gamma_{ij} \geq \gamma_{\text{min}}\}. \tag{1}$$

  This state information undergoes continuous updates and synchronization throughout the network, ensuring the maintenance of system coherence.
- **Leader Election**: When a follower node detects a leader heartbeat timeout, it transitions to a candidate and initiates a voting process. Candidates broadcast voting requests, and the majority-voted leader assumes responsibility for proposal generation. Notice that the nodes dynamically calculate the timeout threshold based on real-time quality indicators γ_{ij} and neighbor density $\sqrt{|N_i|}$, that is,

$$T_{\text{election}} = \left(1 + \frac{\alpha}{\sum_{i=1}^{|N_i|} \gamma_{ij}}\right) T_{\text{base}}. \tag{2}$$

- **Consensus Execution**: When a vehicle needs to change lanes, the leader aggregates global vehicle states, constructs lane-change proposals and replicates logs to followers. The leader sorts the logs to be replicated according to the following priority formula:

$$\text{Priority}_i = \frac{|\Delta \mathbf{v}_{ij}|}{d_{ij}} + \frac{\lambda}{\gamma_{ij}}. \tag{3}$$

  Here, $\Delta \mathbf{v}_{ij}$ represents the relative velocity, d_{ij} represents the inter-vehicle distance, and λ is the weight coefficient. Followers validate the proposals against safety constraints ($d_{ij} \geq d_{\text{safe}}$) and conflicts via version checks, returning ACKs for the majority confirmation. Upon committing, nodes execute decisions and propagate incremental state updates $(\Delta \mathbf{p}_i, \Delta \mathbf{v}_i)$ to minimize bandwidth overhead.
- **Emergency Response**: When a vehicle node detects an emergency event (e.g. sudden braking), it generates an emergency log and directly broadcasts it to the entire network, bypassing leader coordination. The receiving nodes immediately execute the emergency response, and the leader subsequently issues a formal proposal for synchronization.

The consensus protocol specifically addresses wireless communication challenges through the following:

- Adaptive election timeouts based on channel quality
- Prioritized log replication for safety-critical state updates
- Majority-based decision validation for lane change operations

This protocol enables a comprehensive evaluation of the system's behavior under various operating conditions while maintaining the deterministic performance requirements necessary for safe lane-change decisions in autonomous vehicles.

C. Evaluation Model

To comprehensively evaluate the performance of the RUBICONe in dynamic vehicular networks, an evaluation model is proposed, focusing on three core aspects: communication reliability, consensus efficiency, and robustness.

- **Communication Reliability (η_c):** Communication reliability refers to the probability that the system receives correct lane-change decisions from all nodes, and is defined as following:

$$\eta_c = \sum_{m=N_{\text{real}}}^{N_i} \left(\sum_{\substack{A \subseteq \{1,2,\ldots,n\} \\ |A|=m}} \prod_{a \in A} p_a \prod_{b \notin A} (1 - p_b) \right) + \epsilon, \tag{4}$$

  where p_j denotes the probability of successful communication between node j and the central node, and ϵ represents the system error term, which is associated with factors such as the total number of nodes N_i, the number of successful nodes N_{real}, the channel quality of the central node γ_{ij} and environmental noise.
- **Consensus Efficiency (η_e):** Consensus efficiency refers to the overhead incurred for all nodes to reach agreement. Consensus efficiency considers convergence time (t_c), network overhead (ω_n) and system latency (L_{sys}). It is defined as following:

$$\eta_e = \frac{1}{\alpha t_c + \beta \omega_n + \gamma L_{\text{sys}}}, \tag{5}$$

  where α, β, γ are non-negative coefficients that prioritize different efficiency dimensions.

  It is worth noting that L_{sys} encompasses end-to-end latency from signal transmission to decision validation. This metric is decomposed into three constituent components: signal propagation latency (L_p), computational processing latency (L_c) and stochastic jitter induced by environmental noise (L_j).

- **Robustness (η_r):** Robustness refers to whether a system can maintain stability when subjected to some minor disturbances. It is defined as following:

$$R_b = e^{-\kappa\left(1-\frac{\eta_{\text{now}}}{\eta_{\text{before}}}\right)}, \tag{6}$$

where κ is the interference sensitivity coefficient ($\kappa > 0$),

This study leverages insights from communication studies, emphasizing the role of consensus algorithms like RAFT in ensuring robust decision-making. By addressing current limitations, this paper lays the foundation for safer and more intelligent road traffic systems.

V. Evaluations and Experiments

This section employs experimental validation with hardware and numerical simulation to rigorously verify the model's effectiveness.

A. Experimental Setup and Design

The experiment employs the *Milk-V* Duo S as the primary node platform, featuring dual C906 RISC-V CPUs (primary core at 1 GHz, secondary core at 700 MHz) with 64MB DDR2 memory and integrated IEEE 802.11 b/g/n WLAN connectivity. All inter-node communications utilize the IEEE 802.11 protocol operating in the 2.4 GHz band with a nominal data rate of 54 Mbps, as shown in Fig. 2. An laptop PC with a Cisco switch perform out-of-band control and initiate the program.

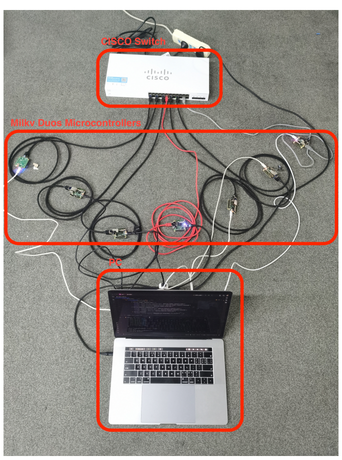

Fig. 2: Experimental equipment of *Milk-V* Duo S SoC.

The experiment integrates hardware-in-the-loop experiments with simulation-based performance analysis using a testbed of *Milk-V* Duo S nodes.

- **Communication Reliability:** To assess the communication reliability of the system, three experiments were designed to evaluate the impacts of the number of nodes, RSSI, and node distance separately. Specifically, experiments were conducted with 1 and 3 nodes configurations in the physical testbed, while simulation results extend to 5, 7, 9, 11, and 13 nodes to evaluate the communication reliability.
- **Consensus Efficiency:**In evaluating consensus efficiency, vehicular cooperative maneuvers (e.g. lane changing) require extremely short decision-making timeframes, thus focusing on latency rather than convergence time and network overhead with less impact. Specifically, the evolution of system latency with increasing node numbers is investigated, while realistic latency distributions are modeled using normal distributions to analyze the effects of different variances on aggregate system latency.
- **Robustness:** To evaluate the system's robustness under different channel conditions, the RSSI was fixed while random fluctuations ranging from -3 dB to +3 dB were superimposed to simulate real-world vehicular environments.

Table I summarizes the key experimental parameters used throughout our evaluation.

TABLE I: System parameters of testbed.

Parameter	Value
Hardware platform	*Milk-V* Duo S
CPU specifications	Dual C906 RISC-V CPUs, (1 GHz primary, 700 MHz secondary)
Wireless standard	IEEE 802.11 b/g/n
RSSI range	-90 dBm to -30 dBm
Channel variation	-3 dB to +3 dB (-89 dBm)
Node configurations	1, 3 nodes (physical) 1,3,5,7, 9, 11, 13 nodes (simulation)
Radius	10 m to 100 m
Experiment duration	At least 1000 runs per experiment

B. Result Analysis

1) Communication Reliability with Varying number of nodes and RSSI: The first simulation experiment evaluated the impact of the number of nodes and the RSSI per node on the communication reliability. Fig. 3 and Fig. 4 respectively illustrate the simulation experimental results under different number of nodes (1, 3, 5, 7, 9, 11, 13) with varying RSSI per node (-30dBm, -40dBm, -50dBm, -60dBm, -70dBm, -80dBm, -90dBm). Meanwhile, Fig. 5 illustrates the physical experimental (Leader on PC, Followers on Milkv Duo S and the connection is built via mobile hotspot WLAN) results under 1 node and 3 nodes with varying RSSI per node (-30dBm, -40dBm, -50dBm, -60dBm). The observations are as follows:

- Under the same RSSI per node (or the same number of nodes), increasing the number of nodes (or the RSSI per node) enhances the Message Delivery Rate (MDR) of the system.
- The smaller the initial number of nodes (or the initial RSSI per node), the more improvement in MDR after adding the number of nodes (or increasing the RSSI per node).
- The systems with low RSSI per node (or small number of nodes) have a greater increase in MDR as the number of nodes (or the RSSI per node) is increased. However,

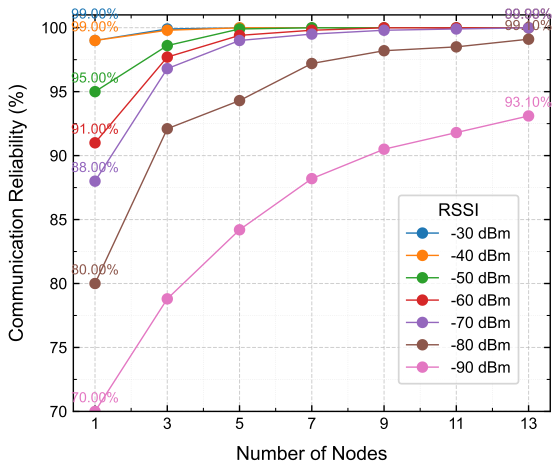

Fig. 3: Communication reliability vs Number of nodes.

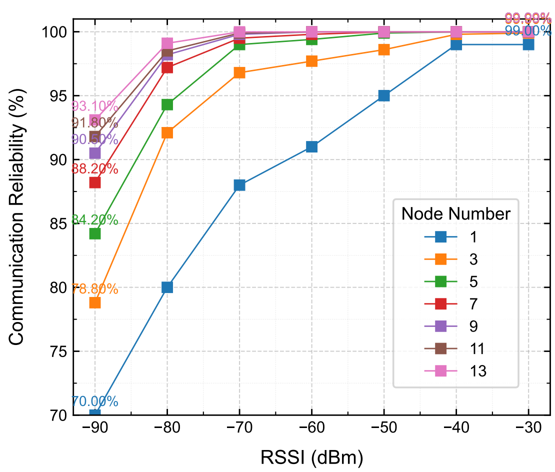

Fig. 4: Communication reliability vs RSSI.

under the same number of nodes (or the same RSSI per node), the MDR of these systems is lower compared to the systems with high RSSI per node (or larger number of nodes).

2) Communication Reliability Under Varying Node Distance in dBm: The second experiment simulates the impact of vehicle spatial distribution on the communication reliability. Within a two-dimensional space of radius R_μ, a certain number n of nodes are generated through the Poisson Point Process (PPP) to simulate vehicle positions. The relationship between spatial distance and signal strength was modeled using the Log-Distance Path Loss Model [11], defined as:

$$PL(d) = PL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma, \tag{7}$$

where $PL(d)$ is path loss at distance d, $PL(d_0)$ is path loss at reference distance d_0, n is path loss exponent, X_σ is Random shadow fading (Gaussian distribution with mean

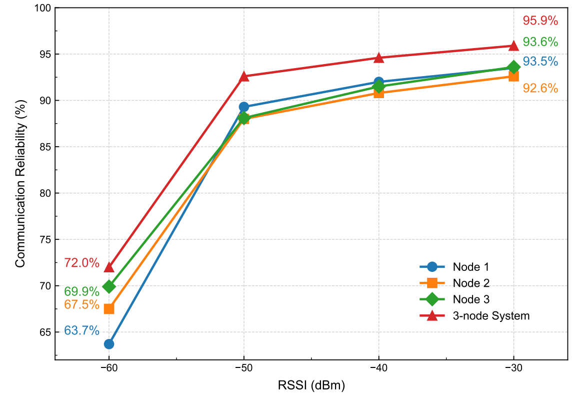

Fig. 5: Communication reliability vs Number of physical nodes.

0 and standard deviation σ). Meanwhile, the relationship between RSSI and path loss is

$$P_r(d) = P_t - PL(d), \tag{8}$$

where P_t is the transmit power. To simplify the discussion, random shadow fading is neglected ($X_\sigma = 0$). Substituting the LDPL formula into the RSSI equation yields the simplified relationship between signal strength and distance:

$$P_r(d) = P_r(d_0) - 10n\log_{10}\left(\frac{d}{d_0}\right). \tag{9}$$

Due to the inherent randomness of node positions in each generation, 1000 position-generating operations are executed. For each generated position, 1000 simulation-based emulations are subsequently conducted. Fig. 6 illustrates system reliability against signal variation for different radius. With $\lambda = 1$ nodes per unit area, it is observed that:

- The system exhibits an inverse correlation between signal strength and coverage radius.
- Network reliability shows monotonic degradation with increasing radial distance.
- For any given radius, the system reliability demonstrates positive dependence on node density. Specifically, within a 100m radius, the 3-node system achieves 79.92% reliability, while the 9-node system reaches 96.2%, representing a 16.28% improvement over the 3-node configuration.

3) Latency Distribution Characterization: The third experiment systematically investigates the impact of network scale on end-to-end system latency. Under practical communication scenarios, heterogeneous data processing capabilities across nodes inevitably introduce latency variations, even among devices of identical specifications. To rigorously account for such inherent variability, nodal latency is explicitly modeled as a normally distributed random variable, as opposed to employing deterministic latency assumptions. Fig. 7 quantitatively characterizes the compound effects of both latency distribution variance and network cardinality on the system latency performance. The observations are as follows.

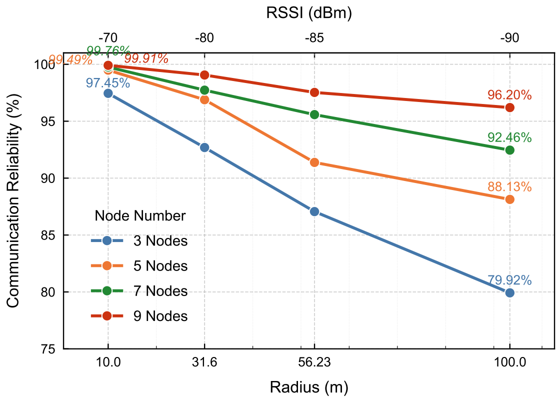

Fig. 6: Communication reliability vs Node distance (m).

- The end-to-end system latency demonstrates a monotonically increasing relationship with respect to network scale.
- Given a fixed mean nodal latency, the aggregate system latency exhibits positive correlation with both the variance of nodal latency distribution and the cardinality of the network.

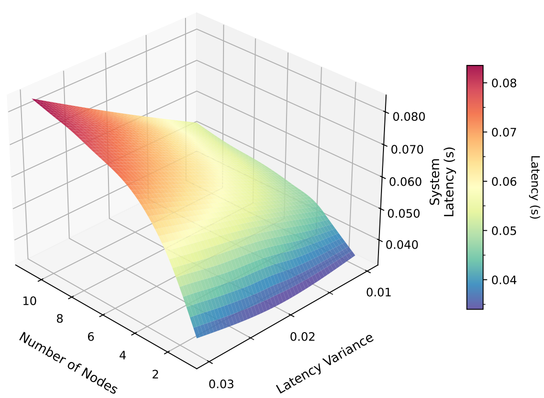

Fig. 7: RUBICONe latency analysis (Number of nodes and Latency variance vs Latency (s)).

4) Robustness Under Interference: The fourth experiment systematically investigates the network robustness. To characterize system performance under diverse communication environments, the interference sensitivity of systems with varying node scales was simulated. The trend of relative gain versus node count was analyzed under $\pm$3dB SNR variations. Using -89dBm as the baseline, the system MDR was measured at both +3dB SNR and -3dB SNR for different number of nodes, as shown in Fig. 8. The observations are as follows.

- At 1 node, the baseline reliability reaches 71%. Under interference (SNR=+3dB), reliability improves to 74%, with a robustness coefficient $R_b = 0.84$.
- Scalability exhibits positive robustness trends: under -3dB conditions, rising from 0.84 at a single node to 0.89 with 13 nodes. Conversely, under +3dB conditions, the robustness coefficient decreases from 1.14 at a single node to 1.03 with 13 nodes.
- Under a -89dBm noise floor, a +3dB SNR enables the system to achieve satisfactory reliability with fewer nodes. Conversely, at a -3dB SNR, indicating a more vulnerable communication link, additional nodes must be deployed to maintain comparable reliability.

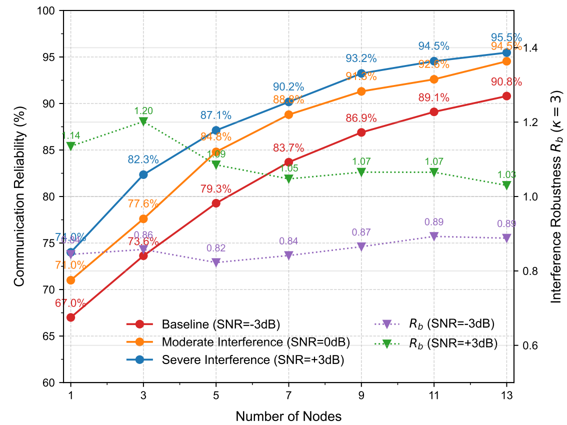

Fig. 8: Communication reliability vs Size of consensus group with SNR = 3dB and SNR = -3dB

C. Discussion

The experimental and simulation results highlight several key aspects of the proposed RUBICONe framework:

- **Low-Cost Feasibility:** The system achieves high reliability and robustness using only affordable, off-the-shelf hardware, demonstrating that dependable vehicular consensus does not require expensive or complex devices.
- **Scalability and Reliability:** Increasing the number of nodes or improving signal strength consistently enhances communication reliability, showing that even simple consensus mechanisms can effectively mitigate wireless channel unreliability in larger groups.
- **Impact of Node Distance and Density:** Reliability decreases with greater node distance, but higher node density can offset this effect, suggesting that practical deployments in dense traffic can maintain strong performance.
- **Consensus Efficiency and Latency:** Although latency increases with network size, the trade-off is modest and remains within acceptable bounds for real-time applications, thanks to the lightweight protocol and hardware.
- **Robustness to Interference:** The system maintains robust operation under varying SNR and interference, and adding nodes further improves resilience, confirming the value of distributed, low-complexity consensus in dynamic wireless environments.

These results suggest that a lightweight, low-cost consensus protocol has strong potential to deliver reliable, efficient, and robust performance in resource-constrained vehicular networks, without relying on advanced or resource-intensive algorithms.

VI. Conclusion

This paper presents RUBICONe, a practical vehicular consensus framework built on PC and low-cost *Milk-V* Duo S nodes. Extensive experiments and simulations show that the system achieves high reliability and robustness in multi-node wireless environments, with only modest increases in consensus latency. Crucially, all results are obtained using simple, low-cost hardware and a lightweight protocol, confirming the feasibility of deploying consensus-based cooperation in real vehicular networks without advanced or complex algorithms.

The main contributions of this work are:

1) The design and implementation of a lightweight, low-cost consensus protocol suitable for vehicular networks.
2) Comprehensive evaluation of reliability, efficiency, and robustness under realistic wireless conditions.
3) Hardware validation on open-source RISC-V platforms. These findings demonstrate that dependable, scalable consensus can be achieved in resource-constrained environments.

Future work will focus on further optimizing consensus performance under dynamic channel states and mobility, enhancing fault tolerance, and reducing convergence time, as well as conducting large-scale field tests and integration with real vehicular platforms to further validate the practicality of RUBICONe.

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