Towards 6G Sidelink: Distributed Scheduling and Routing for Reliable Multi-Hop Connectivity

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***Abstract*—Reliable multi-hop communication in 5G New Radio (NR) Vehicle-to-Everything (V2X) communications remains challenging, especially in dynamic, infrastructure-less scenarios. We present a joint framework for distributed scheduling and multi-hop relaying over the Sidelink interface, tailored to dynamic formations such as virtually coupled trains. Motivated by the railway requirement to operate strictly at Layer 2 (i.e., without the ETSI ITS stack), our design integrates sensing based on inter-UE coordination with a proactive routing protocol inspired by B.A.T.M.A.N. that fits the Sidelink MAC model. Unlike approaches that treat routing and resource selection independently, our cross-layer strategy couples the two via a hybrid next-hop metric – a weighted combination of Signal-to-Interference-plus-Noise Ratio (SINR) and available resource blocks – so that paths can avoid weak links and relays with limited resources. Simulations in a virtual train coupling scenario show high delivery ratios, reduced hidden-node collisions, and robust performance across densities, indicating the suitability of the proposed Layer 2 framework for V2X-enabled train automation and future cooperative mobility systems.**

***Index Terms*—NR-V2X, Sidelink, Multi-Hop Relaying, Resource-Aware Routing, Cooperative Scheduling, Inter-UE Coordination, Virtual Coupling, Distributed Resource Allocation**

I. Introduction

Advanced mobility scenarios – including cooperative driving [1], connected convoys [2], and virtual train coupling [3] – place stringent demands on Vehicle-to-Everything (V2X) communication, requiring scalable, low-latency, and multi-hop support beyond what baseline 5G New Radio (NR)-V2X currently offers. These scenarios demand ultra-reliable, low-latency, and long-range communication, often in environments with limited or no cellular infrastructure. One such domain is railway automation, where dynamic train formations such as virtual coupling require seamless, infrastructure-independent wireless communication between wagons.

The 5G NR-V2X standard introduces Sidelink communication to support direct Device-to-Device (D2D) interactions [4]. Within NR-V2X, Mode 2 handles out-of-coverage resource selection. Mode 2a enables each User Equipment (UE) to autonomously select resources based on local sensing alone. Mode 2b is one concrete realization under ETSI's broader *inter-UE coordination* concept, in which neighboring UEs exchange sensing-derived resource occupancy to extend awareness, mitigate hidden-node effects [5], and improve scheduling decisions [6, 7]. These mechanisms provide strong support for one-hop communication. However, multi-hop relaying is not supported by the current 5G NR-V2X stack, a key limitation for linear topologies like trains where connectivity must span hundreds of meters or more. In ETSI terminology, Modes 2a–2d fall under the inter-UE coordination umbrella, differing in how (and how far) sensing information is shared. Our design operates within this umbrella while adding a proactive Layer-2 multi-hop capability.

Meanwhile, routing in multi-hop environments introduces additional challenges. It must remain resilient to dynamic link conditions, and compatible with autonomous MAC-layer scheduling, especially in dense or delay-sensitive settings. Traditional routing approaches can be categorized as proactive (e.g., OLSR), reactive (e.g., AODV), or hybrid. Proactive schemes maintain up-to-date routing tables at each node but introduce steady control overhead, while reactive protocols discover routes on-demand, incurring additional delays.

Unlike urban vehicular use cases, virtual train coupling imposes a strict constraint: the communication stack must remain within Layer 2, as the railway industry avoids reliance on the ETSI ITS stack, including IP-based protocols or GeoNetworking. Consequently, this paper avoids Cooperative Awareness Messages (CAMs) and Decentralized Environmental Notification Messages (DENMs) and does not assume Layer 3 routing. Instead, we propose a lightweight protocol inspired by Better Approach To Mobile Ad-hoc Networking (B.A.T.M.A.N.) that operates entirely at the MAC level. This protocol offers proactive path discovery without requiring IP addressing or neighbor discovery. This design choice reflects the unique needs of train communications, where topologies evolve slowly, but the reliability and timing constraints are extremely stringent.

Among available routing protocols, B.A.T.M.A.N. is particularly suitable for this context due to its minimal overhead, distributed operation, and ability to maintain robust path knowledge using periodic broadcast messages, such as Originator Messages (OGMs). B.A.T.M.A.N. does not construct full end-to-end paths; instead, each node learns the best next-hop toward every destination using MAC-layer metrics and localized updates, making it naturally compatible with the

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NR-V2X Sidelink model.

To this end, this paper proposes a joint scheduling and multi-hop relaying framework for next-generation 6G Sidelink communications. Our solution integrates inter-UE coordinated scheduling with a proactive routing protocol adapted from B.A.T.M.A.N.. A cross-layer routing metric, defined as a weighted combination of Signal-to-Interference-plus-Noise Ratio (SINR) and available resource blocks, guides relay selection. To ensure robustness under congested conditions, a fallback mechanism enables resource reuse from upstream transmissions, reducing the risk of transmission failure.

Our key contributions are as follows:

- We define a joint scheduling and multi-hop relaying mechanism that enables efficient, distributed, and resource-aware communications for emerging use cases such as virtual train coupling and connected convoys.
- We evaluate the performance of the proposed solution using a state-of-the-art 5G NR-V2X simulation framework that models realistic mobility and radio conditions.
- We assess the proposed solution across different scheduling strategies, including a benchmark random scheduler, the standardized Mode 2a, and the latest inter-UE coordination (Mode 2b), to examine its adaptability and robustness in dynamic scenarios.

The remainder of this paper is organized as follows. Section II provides a review of existing related works. Section III presents the proposed cross-layer framework, detailing the integration of B.A.T.M.A.N.-based relaying and scheduling under NR-V2X Mode 2a and inter-UE coordination. Section IV outlines the simulation environment and discusses the results, focusing on communication reliability, resource utilization, and multi-hop robustness in a virtual train coupling scenario. Finally, Section V concludes the paper and outlines possible future extensions.

II. Related Works

Recent advancements in 5G NR-V2X Sidelink communications have spurred a variety of research efforts aimed at enhancing distributed scheduling, multi-hop relaying, and cross-layer optimization. This section reviews key contributions in these areas.

A. Distributed Scheduling in NR-V2X

The Semi-Persistent Scheduling (SPS) mechanism, particularly in its sensing-based form, has been central to improving distributed resource allocation in NR-V2X systems. Yin and Hwang [8] introduced a Reuse Distance-Aided Resource Selection (RD-RS) strategy, which integrates reuse distance estimation into sensing-based SPS to mitigate resource conflicts and interference caused by random selections. Their approach demonstrated significant gains in Packet Received Ratio (PRR) and reductions in inter-packet gaps.

Nguyen [9] proposed enhancements to wireless resource allocation for 5G NR-Vehicle-to-Vehicle (V2V) communications, designing algorithms that dynamically adapt to varying traffic densities and mobility patterns to improve both resource utilization and communication reliability.

Yoon and Kim [10] addressed the limitations of standard SPS in handling aperiodic traffic. They proposed enhancements that explicitly incorporate traffic stochasticity into the sensing-based reservation process, making resource allocation more responsive to real-world traffic fluctuations.

In a comparative analysis, Lusvarghi et al. [11] evaluated SPS against Dynamic Scheduling (DS) under different traffic types and latency requirements. Their study concluded that SPS is better suited for fixed-size, periodic traffic, while DS performs better under aperiodic or variable workloads. Complementing this, Rolich et al. [12] showed that DS can outperform SPS even for periodic traffic when evaluated using the Age-of-Information (AoI) metric.

Furthermore, He et al. [13] propose a cluster-based UE scheduling scheme that partitions vehicles onto orthogonal resource sets, reducing intra-cluster collisions and boosting packet delivery ratio under dense deployments.

Targeting congested scenarios, Daw et al. [14] enhance SPS with a priority-aware policy (P-SPS) and complementary mechanisms (e.g., probabilistic collision mitigation, grant removal), reporting PRR gains for both high- and low-priority traffic while keeping inter-reception times in check. In structured formations, Cao et al. [15] study resource allocation for NR-V2X platoons, contrasting improved random selection with learning-based control. Their deep deterministic policy gradient approach outperforms randomization in collision probability and schedule stability.

Freshness-centric adaptations have also been studied. From an AoI perspective, Cao et al. [16] analyze how SPS parameters – especially the resource reservation interval – shape expected (peak) AoI across densities, providing guidance on resource reservation interval tuning to maintain information timeliness. For aperiodic traffic, Saad et al. [17] propose an *enhanced* SPS with re-evaluation of reservations, which helps identify available resources more quickly and reduces contention as load fluctuates.

B. Multi-Hop Relaying and Routing Protocols

The role of multi-hop relaying in NR-V2X has gained growing attention, particularly for extending communication range and ensuring reliable data delivery in infrastructure-less vehicular networks. Sanada et al. [18] analyzed the delay distribution of multi-hop relay transmissions in platoon scenarios using Cellular V2X (C-V2X) Sidelink communication. Their results emphasized how relay positioning and hop count significantly influence end-to-end latency, offering guidelines for optimal relay strategies.

Fu and Liu [19] proposed a generalized multi-hop NR Sidelink relay framework designed to support dynamic relay selection and path optimization, particularly under high mobility and rapidly evolving vehicular topologies.

C. Cross-Layer Optimization Strategies

To improve system performance under real-world conditions, cross-layer designs have been proposed to better coordinate interactions across physical, link, and network layers in NR-V2X. Horta et al. [20] developed an analytical model for evaluating the performance of 5G NR protocol stacks, focusing on latency and throughput – metrics critical to safety applications such as remote driving. Their model enables the study of trade-offs under different scheduling and channel configurations.

Rolich et al. [21] presented an AoI-aware congestion control mechanism specifically tailored for NR-V2X systems. By integrating persistence strategies into the access protocol, their design ensures timely and reliable information delivery while managing congestion effectively.

In our previous work [6], we proposed and evaluated a Mode 2b-based inter-UE coordination scheme in a virtual train coupling scenario to reduce the hidden node problem. An extended version of this approach was presented in [7], introducing an awareness mechanism that further mitigates collisions through a network-wide expansion of sensing coverage. Both studies demonstrated consistent improvements in PRR and robustness under infrastructure-less conditions.

D. Summary

While the above contributions provide valuable insights into specific aspects of NR-V2X scheduling or routing, they tend to treat these layers independently. However, emerging use cases – such as virtually coupled trains – require distributed architectures that jointly reason about routing and resource allocation. Our work addresses this gap by proposing a cross-layer framework that combines normalized link quality and resource availability in a unified metric, enabling scalable, reliable multi-hop relaying for NR-V2X Sidelink systems.

III. Joint Relaying and Scheduling Framework

This section presents the proposed framework for joint multi-hop relaying and resource scheduling in NR-V2X Sidelink communication. The solution builds upon the structure of the B.A.T.M.A.N. routing protocol while adapting it to the specific requirements of distributed sidelink scheduling. By integrating resource awareness into the routing process and incorporating fallback mechanisms to address congestion at the time of transmission, the framework achieves a resilient and scalable mechanism suitable for high-mobility vehicular environments such as virtually coupled trains.

A. System Packet Types and Generation Intervals

The proposed framework relies on four distinct packet types, each fulfilling a specific role within the 5G NR-V2X Sidelink Layer 2 protocol stack:

1) **One-Hop Beacon:** Used for channel sensing and resource selection under inter-UE coordination (based on Mode 2a/2b). Each UE broadcasts a beacon periodically, enabling decentralized awareness of Resource Blocks (RBs) occupancy in its neighborhood and supporting collision avoidance during distributed scheduling.
2) **OGM:** Inspired by the B.A.T.M.A.N. protocol, OGMs are relatively small packets that disseminate proactive routing information across the network. Each node periodically broadcasts an OGM carrying the routing metric reflecting path quality, the originator identifier, the transmitting node identifier, a Time-To-Live (TTL) to bound propagation, and a sequence number preventing redundant processing.
3) **Ethernet Train Backbone Node (ETBN) Packet:** Represents the application/control payload (e.g., wagon telemetry or commands) transmitted from wagons toward the locomotive. ETBNs are generated periodically, and are forwarded over the multi-hop path determined by the routing scheme.
4) **ETBN-ACK:** An acknowledgment sent from the destination back to the source upon successful ETBN reception. An ETBN transmission is considered successful only if its ACK arrives within twice the ETBN period. Delayed or missing acknowledgments beyond this bound are counted as failures. ETBN-ACKs are compact, with a typical size of a few tens of Bytes, including source/destination IDs, sequence number, optional timestamp, and a checksum.

B. Inter-UE Coordination and Sensing

The NR-V2X Sidelink specification defines Mode 2 as the mechanism enabling autonomous, out-of-coverage resource selection. Within this mode, the two sub-variants – Mode 2a and Mode 2b – are considered. Mode 2a relies on local sensing, where each UE monitors sidelink activity within a defined sensing window and avoids resources that appear occupied. Mode 2b, on the other hand, builds on Mode 2a by allowing UEs to share their sensed resource occupancy with neighboring nodes. This cooperative behavior can significantly improve awareness beyond one-hop neighbors, particularly in dense environments.

In our prior work [6], we proposed a practical extension of Mode 2a by enabling UEs to piggyback the list of unavailable resources onto the Sidelink Control Information (SCI) broadcast. This allowed resource status to propagate up to two hops via periodic beacons, mitigating the hidden-node problem and improving spatial reuse. That mechanism serves as the basis for the present framework.

In this work, we integrate the output of this sensing process into a broader joint scheduling and routing pipeline. Inter-UE coordinated sensing is reinterpreted as an enabler for informed routing under real-time V2X constraints. Specifically, the number of available resource blocks observed or received from neighbors becomes a key metric input to the routing process. This way, resource availability is no longer considered solely for MAC-layer decisions but is elevated into the route selection logic. As the next subsection will discuss, this sensed information is fused with physical-layer SINR measurements into a unified metric that drives relaying decisions.

C. Routing Metric Calculation and Path Update

To enable efficient multi-hop relaying in NR-V2X Sidelink, each UE maintains a local routing table storing the best-known path to every originator node. This mechanism is inspired by the B.A.T.M.A.N. protocol, which uses periodic exchanges of

OGMs to propagate routing information. In our framework, OGMs serve a dual role: they disseminate route information and carry sensing-based measurements of resource availability and SINR that are used for path selection.

Upon receiving an OGM, a UE evaluates whether the sender offers a better route to the originator based on the following hybrid routing metric:

$$M = \alpha \cdot \frac{\text{RB}_{\text{avail}}}{\text{RB}_{\text{total}}} + (1-\alpha) \cdot \frac{\text{SINR}}{\text{SINR}_0}. \quad (1)$$

Here, RB_{avail} denotes the number of available RBs sensed or inferred at the neighbor node, and RB_{total} is the total size of the candidate RB pool. SINR denotes the signal-to-interference-plus-noise ratio measured at the receiver. SINR_0 is a scaling factor representing the best-case SINR achievable under the assumption of no interference from neighboring UEs. The parameter $\alpha \in [0,1]$ determines the trade-off between MAC-layer resource availability and physical-layer link quality.

The routing metric is updated hop-by-hop using a bottleneck-aware rule:

$$M_{\text{new}} = \min\left(M_{\text{prev}}, M^{(i)}\right), \quad (2)$$

where M_{prev} is the metric received from the previous hop, and $M^{(i)}$ is the routing metric of the current neighbor i, as defined in (1). The use of $\min$ ensures that the path's weakest segment dominates the overall path quality, which helps avoid routing through resource-starved relays.

If M_{new} is higher than the metric stored in the routing table for that originator, the table is updated and the OGM is rebroadcast with the new value. Otherwise, the OGM is discarded. This selective propagation limits redundant updates and ensures that only the strongest routes remain active.

Routing Table Structure: Each UE maintains a routing table $\mathcal{T}$, where each entry corresponds to a known originator node o and stores three key fields: the next-hop node ID (i.e., the neighbor currently offering the best path to o), the cumulative hybrid metric M associated with that path, and a timestamp indicating the most recent update time. The timestamp supports entry aging and cleanup to ensure routing consistency under mobility or topology changes.

Figure 1 illustrates the proposed mechanism for joint relay selection and resource scheduling in a mesh topology.

The next section describes how this routing logic is integrated with resource selection and transmission scheduling, including the fallback behavior when no available resources are sensed at runtime.

D. Resource Reuse in Congested Cases

Although the proposed joint routing and scheduling framework selects paths that are both resource-aware and interference-averse, real-world NR-V2X deployments – especially in dense or bandwidth-limited environments – may still experience temporary RB shortages at transmission time. This mismatch arises because sensing and path selection occur prior to actual forwarding, making local resource availability at relays non-deterministic.

To address this, we introduce a fallback resource reuse mechanism designed to maintain transmission continuity under congestion. Rather than blindly selecting idle RBs, which risks interfering with downstream nodes, the proposed strategy restricts reuse to resources already used by upstream nodes along the selected path $\mathcal{P} = n_0, n_1, \ldots, n_k$. If the current node n_i finds no sensed-free RB, it selects the one previously used by an upstream node n_j (with $j < i$) that yields the highest local SINR:

$$\text{RB}^{(i)} = \underset{\text{RB} \in \text{RB}^{(j)}: j<i}{\text{argmax}} \ \text{SINR}^{(i)}(\text{RB}). \quad (3)$$

This upstream-biased reuse reduces the likelihood of collision at n_{i+1}, preserves directional consistency, and allows for graceful degradation in congested settings without invalidating routes or inducing retransmissions. Implicitly, it leverages the fact that upstream transmissions have likely terminated by the time n_i forwards the packet. For this strategy to operate correctly, nodes must maintain a short-term record of upstream RB usage – either through local logging or lightweight metadata appended to OGMs or control beacons.

By narrowing the selection space to previously-used and directionally safe resources, this fallback mechanism complements proactive routing decisions and enhances reliability under high traffic loads, particularly in linear topologies like virtually coupled trains where timely multi-hop forwarding is critical.

E. Pseudocode Summary

Algorithm 1 presents the proposed joint relaying and scheduling logic executed at each node. It consists of two core procedures: ProcessOGM for routing table updates and TransmitMessage for resource selection.

ProcessOGM*:* Upon receiving an OGM, the node computes $m(n)$ for each neighbor n and compares it with the embedded metric in the OGM using a bottleneck (min) update $M_{\text{new}} = \min\big(m(n), \text{OGM.metric}\big)$. If M_{new} improves

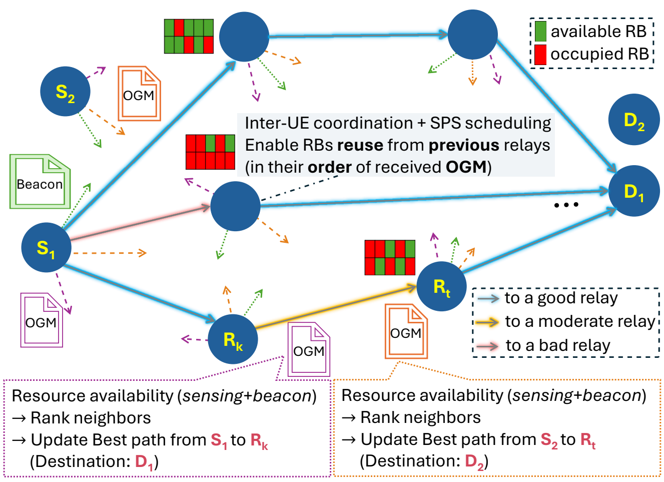

Figure 1. Illustration of joint multi-hop relaying and scheduling in a mesh network. Selection of relays is based on available RBs and the SINR.

the stored entry for the OGM originator, the local routing table is updated and the OGM is rebroadcast with a decremented TTL. This hop-by-hop, bottleneck-aware rule preserves the weakest-segment constraint along the path and suppresses inferior updates.

TransmitMessage: For data forwarding, the node first attempts to use a currently available RB selected by sensing (Mode 2a or inter-UE coordination). If no RB is free at transmission time, the node falls back to reusing an upstream-used RB that maximizes the locally observed SINR according to (3), thereby minimizing interference at the downstream receiver and ensuring continuity under congestion.

This simple yet effective logic continuously adapts route formation and data forwarding to changing conditions, while the fallback reuse policy provides graceful degradation in resource-depleted scenarios.

F. ETBN Transmission

The transmission of ETBN packets begins at the source node, where they are generated periodically to report status or telemetry to the locomotive. To ensure timely and low-overhead access, SPS is employed for their initial transmission, enabling periodic reservation of resources without per-packet signaling.

Beyond the source, packets are forwarded hop-by-hop using dynamic scheduling, where each relay independently selects a resource based on current sensing and inter-UE coordination. This flexibility is crucial for adapting to transient channel occupancy and ensuring robust multi-hop delivery.

Algorithm 1 NR-V2X Joint Routing and Resource Scheduling

T: routing table storing best next-hop and metric per originator
α: weight of available RBs in hybrid metric computation
$\mathcal{N}$: current node's one-hop neighbors
OGM: Originator Message with `metric`, `ttl`, and `originator` fields
R_{avail}: normalized available RBs sensed/inferred at neighbor
$SINR$: normalized SINR of link to neighbor
H: selected path from source to destination

procedure ProcessOGM(OGM)
    if $OGM.ttl = 0$ **then**
        return
    end if
    $OGM.ttl \leftarrow OGM.ttl - 1$
    for all $n \in \mathcal{N}$ **do**
        $m \leftarrow \alpha \cdot R_{avail}(n) + (1-\alpha) \cdot SINR(n)$
        $M_{new} \leftarrow \min(m, OGM.metric)$
        if $OGM.originator \notin T$ or $M_{new} > T[OGM.originator].metric$ **then**
            $T[OGM.originator] \leftarrow (n, M_{new})$
            Rebroadcast OGM with updated metric and TTL
        end if
    end for
end procedure
procedure TransmitMessage(currentNode)
    if no RB available **then**
        $H \leftarrow$ current route from routing table
        $RB_{reuse} \leftarrow \text{argmax}_{j \in \text{upstream}(H)} SINR(RB_j)$
        use RB_{reuse} for transmission
    else
        use best available RB
    end if
end procedure

Upon successful reception, the destination issues an ETBN-ACK toward the source, using the current routing and scheduling logic at each hop. The acknowledgment must arrive within twice the ETBN interval to be valid; otherwise, the transmission is considered failed.

To prevent relay congestion, forwarding of ETBN and ETBN-ACK packets is prioritized over periodic control beacons. Beacons scheduled during such forwarding events are skipped, allowing relays to maintain deterministic delivery even under tight channel conditions. ACKs are forwarded with even higher priority than ETBN, preventing local control traffic from delaying acknowledgment delivery and ensuring end-to-end reliability.

IV. Evaluation and Results

To validate the proposed joint relaying and scheduling framework, we simulate a challenging train depot scenario inspired from [22], featuring dense co-located virtual train formations with high spatial reuse requirements. As depicted in Figure 2, the scenario consists of 10 parallel railway tracks, each populated with a stationary train. The number of wagons per train is varied across simulation runs, taking values in {6, 10, 14, 18, 22}. Wagons are spaced 1 m apart within a train, while adjacent tracks are separated by 10 m, creating a grid of UEs that must establish intra- and inter-train communications under tight spatial constraints.

All UEs transmit over a 20 MHz Sidelink channel centered at 5.9 GHz, using a subcarrier spacing of 15 kHz, and a Modulation and Coding Scheme (MCS) of 5. Fixed packet sizes of 1000 Byte, 40 Byte, 52 Byte, and 1000 Byte are considered for ETBN, ETBN-ACK, OGM, and beacon, respectively. The generation periodicity of each ETBN, OGM, and beacon packet is 500 ms, 1 s, and 100 ms, respectively. An ETBN transmission is considered successful only if the ACK arrives within 1 s of the ETBN's transmission time, in line with railway communication constraints.

All OGMs are subject to a maximum TTL of 7 hops. The transmission power is configured with antenna gains of 3 dBi, a noise figure of 9 dB, and a Reference Signal Received Power (RSRP) sensing threshold of −126 dBm. The propagation model follows the WINNER+ B1 channel with a shadowing variance of 3 dB.

Within each train, we simulate deterministic multi-hop traffic by fixing the source as the head wagon and the

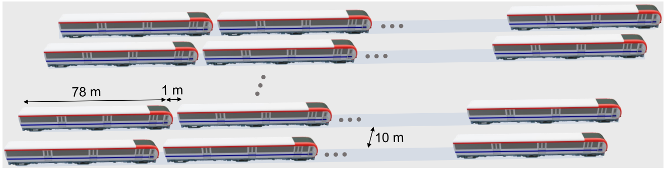

Figure 2. Illustration of the train depot scenario.

Table I
PARAMETER CONFIGURATIONS

System Parameter	Numerical value
Topology layout	Depot on parallel railways
Number of wagons	{6, 10, 14, 18, 22} per lane
Number of railway lanes	10
Inter-lane distance	10 m
Inter-wagon distance	1 m
Antenna gains	3 dBi
Noise figure, N_i	9 dB
Frequency band	5.9 GHz
Bandwidth	20 MHz
Subcarrier Spacing (SCS)	15 kHz
Subchannel size	10 PRBs
MCS	5 (QPSK)
Channel model	WINNER+ B1
Shadowing	Variance 3 dB
Maximum TTL	7 hops
ETBN Packet size	1000 Byte
ETBN-ACK size	40 Byte
Beacon size	1000 Byte
OGM size	52 Byte
ETBN packet generation period	500 ms
Beacon generation period	100 ms
OGM generation period	1 s
Simulation duration	600 s
RSRP sensing threshold	−126 dBm

destination as the tail wagon. This setup ensures full-length intra-train relaying and enables evaluation under maximum path distance.

The simulation spans 600 s, during which our MATLAB-based implementation – extended from the Mode 2a model in [23] – supports our proposed solution. Table I summarizes all the simulation parameters used in our study.

A. Benchmark Methods and Performance Metrics

The following relaying-based schemes are evaluated:

1) **Proposal-2a:** Uses B.A.T.M.A.N.-based routing with a hybrid SINR+RB metric and Mode 2a one-hop sensing for scheduling. Fallback resource reuse is enabled for congestion handling.
2) **Proposal-Inter-UE-Coordination:** Full version of the framework with inter-UE coordination, hybrid routing metric, and reuse strategy.
3) **Proposal-Random:** Same routing as above, but with randomized RB selection. No sensing, coordination, or reuse is applied.

We evaluate each scheme using the following metrics:

- **Packet Delivery Ratio (PDR):** The fraction of ETBN packets for which both the data and the corresponding acknowledgment (ETBN-ACK) are successfully delivered. An ETBN is only counted as delivered if its ACK is received at the source within the designated deadline;
- **Collisions:** The (normalized) number of collisions due to hidden-node problem;
- **Average Hop Count:** The mean number of hops used for message delivery;
- **Average Latency:** The mean duration of the time gap between the generation of ETBN at the source and its complete reception at the destination.

B. Results Analysis

Figure 3 shows how PDR varies with the number of wagons. It is worth noting that *Proposal-Inter-UE-Coordination* achieves the highest PDR in low to medium-density scenarios, owing to its use of two-hop sensing and a hybrid-metric routing strategy. However, at higher densities – specifically at 22 wagons – *Proposal-2a* slightly surpasses it. This shift can be attributed to the inter-UE coordination mechanism, which may conservatively discard potentially usable resources due to its broader two-hop perspective, thereby limiting resource reuse under heavy network load. In contrast, Mode 2a, with its more localized one-hop view, enables more aggressive yet still effective reuse in congested environments. Meanwhile, *Proposal-random*, which lacks any environment-aware resource scheduling mechanism, experiences the sharpest decline in PDR as network density increases, further highlighting the importance of informed and context-sensitive resource selection.

To understand whether PDR loss stems from interference or poor channel conditions, Figure 4 shows normalized hidden-node collisions. Despite its modest PDR lead, *Proposal-Inter-UE-Coordination* achieves far fewer collisions than the other schemes, especially at high densities. This confirms that cooperative sensing effectively suppresses hidden terminal problems. The remaining losses are better attributed to signal degradation. In contrast, *Proposal-2a* and *Proposal-random* show rising collision rates, revealing the limits of one-hop sensing or random access.

Figure 5 shows that hop count increases with the number of wagons, as longer train lengths require traversing more relays to reach the destination. *Proposal-Inter-UE-Coordination* consistently results in fewer hops compared to *Proposal-2a* as it leverages cooperative sensing and a hybrid metric that prioritizes strong, well-connected relays, avoiding weak links

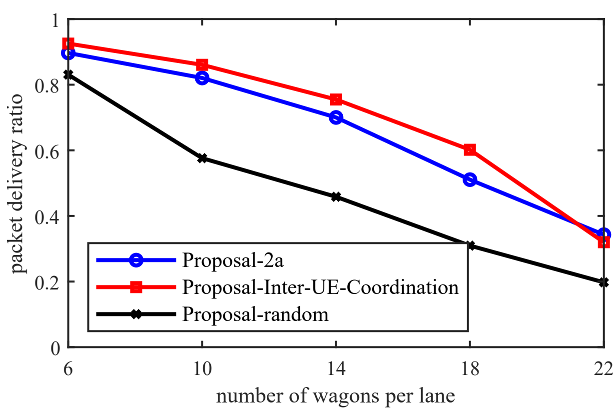

Figure 3. PDR under varying wagon count.

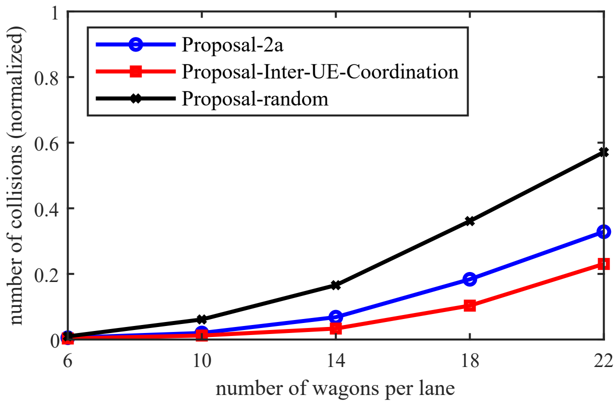

Figure 4. Number of packet collisions (normalized) due to hidden node problem under varying wagon count.

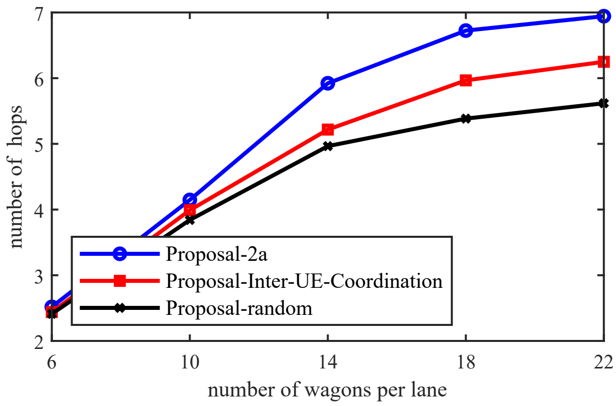

Figure 5. Average number of hops from source to destination under varying wagon count.

and unnecessary detours. *Proposal-2a*, based solely on local sensing, lacks broader awareness and thus yields slightly longer paths. Interestingly, *Proposal-random* exhibits the lowest hop count across all densities – a side effect of its lack of resource reservation. Since it does not mark or exclude resources during selection, routing proceeds through fewer, more direct hops without accounting for contention at intermediate nodes.

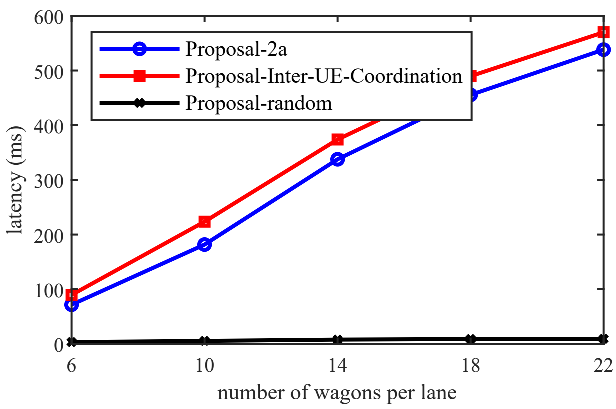

Figure 6. Average latency under varying wagon count.

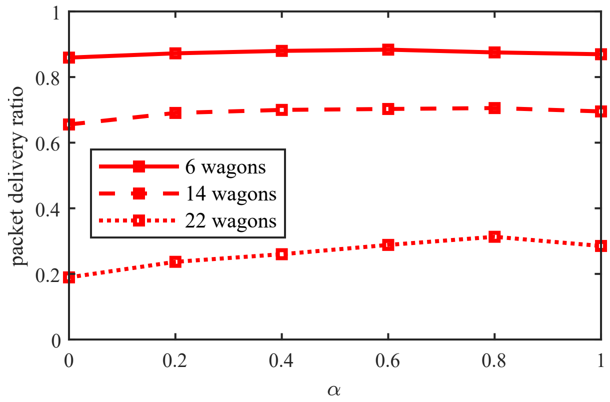

Figure 7. PDR vs. α for the proposed solution with inter-UE coordination with 6, 14, and 22 wagons per lane.

However, this shorter path length comes at the cost of frequent mid-path collisions and poor overall performance.

While the increase in hops is a natural consequence of longer paths and resource scarcity, it contributes to further resource depletion: each additional relay must perform its own resource selection, adding to overall RB occupation. This feedback loop is reflected in the slowing slope of the hop-count curves: as available resources diminish, the system becomes constrained to near-minimal routing configurations, limiting further path elongation. The min-based update logic and TTL constraints help suppress suboptimal routes and stabilize performance under growing load.

Figure 6 reports the average end-to-end latency between source and destination as a function of the number of wagons. Latency increases with network length due to the growing number of relays and the decreasing availability of unoccupied resource blocks per node. As resource contention rises, nodes must wait longer within the allocated NR-V2X Sidelink selection window.

To be noted that latency values across schemes are not directly comparable, as they are computed over different subsets of transmissions. In *Proposal-2a* and *Proposal-random*, a larger number of transmissions suffer from mid-path collisions and fail to reach their destination, and are therefore excluded from the latency calculation. Conversely, the inter-UE coordination scheme achieves a higher delivery rate, and the reported latency reflects a greater share of complete, multi-hop forwarding sequences. As such, the higher latency observed under inter-UE coordination is not necessarily indicative of poorer performance, but rather of a more reliable and congestion-aware forwarding process. Nonetheless, if one considers only the subset of packets that are successfully delivered under all schemes, the coordinated version still tends to exhibit higher latency due to its stricter resource exclusion policies and extended waiting/probing during resource selection. In contrast, *Proposal-2a* may complete transmissions more quickly under light load, while *Proposal-random* incurs the lowest latency overall by skipping the probing process within the selection window and directly picking transmission resources – albeit at the cost of higher collision risk.

Last, Figure 7 shows how PDR varies with the metric weighting parameter α under 6, 14, and 22-wagon scenarios. Intermediate values of α (around 0.6–0.8) yield the best performance, confirming the benefit of balancing SINR and RB availability. Low α (SINR-only) favors crowded high-quality links, while high α (RB-only) may cause detours through poor links. The results highlight the importance of jointly considering both layers in routing decisions.

The proposed framework improves path selection by combining SINR and resource awareness in its routing metric. The inter-UE coordination further enhances spatial awareness, leading to better delivery ratios and shorter paths. Fallback resource reuse helps maintain reliability under congestion. In contrast, simplified schemes using SINR-only routing or random scheduling suffer from reduced performance, emphasizing the benefit of the integrated joint design.

V. Conclusions

This paper proposed a distributed framework for joint multi-hop relaying and resource-aware scheduling in advanced Vehicle-to-Everything (V2X) Sidelink communication. Leveraging inter-User Equipment (UE) coordination from 5G New Radio (NR)-V2X, the design integrates a lightweight, Better Approach To Mobile Ad-hoc Networking (B.A.T.M.A.N.)-inspired routing protocol with a hybrid metric based on resource availability and Signal-to-Interference-plus-Noise Ratio (SINR). While multi-hop forwarding remains outside current standard support, the proposed cross-layer architecture illustrates a viable direction for upcoming 5G releases and 6G Sidelink evolution.

The framework enables each UE to make forwarding decisions that reflect both MAC-layer contention and physical-layer link quality. To ensure robustness under congestion, a fallback mechanism allows selective reuse of upstream Resource Blocks (RBs), minimizing interference with downstream receivers. Simulation results confirm the effectiveness of the approach in delivering reliable multi-hop communication under dense and dynamic conditions.

Future work includes Quality of Service (QoS)-aware routing, support for heterogeneous traffic, and predictive link modeling using mobility or sensing history – all aimed at improving adaptability to emerging 5G mobility scenarios.

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