Cross-Layer Inter-UE Coordination: A Facilities Layer Approach to NR-V2X Mode 2 Scheduling

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***Abstract*—This paper proposes a cross-layer Inter-UE Coordination (IUC) mechanism for 5G New Radio (NR)-Vehicle-to-Everything (V2X) Mode 2 communications to mitigate the hidden-node problem in decentralized sidelink scheduling. Unlike standard 3GPP Release 17 IUC, our approach piggybacks midterm resource reservations onto standard Cooperative Awareness Messages (CAMs). By extracting scheduling information from Sidelink Control Information (SCI) and disseminating it via CAMs, we enable cooperative spectral awareness on Release 16-compliant hardware. We implement the framework in the high-fidelity MS-VAN3T simulator and evaluate it within a virtual train coupling scenario. Results demonstrate significant improvements in Packet Reception Ratio (PRR) and reveal a critical trade-off between the look-ahead reservation window and protocol overhead.**

***Index Terms*—NR-V2X, Sidelink Mode 2, Inter-UE Coordination (IUC), Hidden-node problem**

I. Introduction

Next-generation distributed applications in Cooperative Intelligent Transport Systems (C-ITS) rely heavily on 5G New Radio (NR)-Vehicle-to-Everything (V2X) Sidelink (SL) communications. Under 3GPP Release 16, Mode 2 serves as the primary decentralized resource allocation mechanism, where User Equipments (UEs) sense the channel and select sub-channels within a selection window without network infrastructure support [1, 2]. However, this decentralized approach suffers from the hidden-node problem, i.e., transmitters that cannot sense each other may select identical resources, leading to collisions at a common receiver. This limits the reliability of Mode 2 in high-density or obstructed environments [3].

This work-in-progress paper proposes a visionary shift in addressing this gap through an alternative to the standard Inter-UE Coordination (IUC) mechanism. While 3GPP officially introduced IUC in Release 17 [4], the standard implementation primarily relies on Layer 2 MAC control elements or the Physical Sidelink Feedback Channel (PSFCH) to exchange coordination information. This requires modifications to the lower layers and is not directly applicable to legacy Release 16 deployments. In contrast, we propose a lightweight, cross-layer mechanism integrated into the ETSI ITS Facilities layer. Our approach is not intended to replace access-layer IUC, but to complement it by embedding future resource reservation information into standard Cooperative Awareness Messages (CAMs) using an *optional container*. This allows for a software-defined deployment, enabling IUC-like capabilities on Release 16-compliant hardware without requiring modifications to the 3GPP access layer or the physical SL feedback architecture.

Related Works: The evolution of NR-V2X SL has been extensively documented, with recent surveys highlighting the transition from basic safety services to advanced 5G-Advanced and 6G group communications [5, 6]. These works emphasize that while 3GPP Release 17 introduced architectural enhancements like resource re-evaluation and pre-emption, managing SL group resources and mitigating inter-cell interference remain significant challenges for maintaining Quality of Service in dense environments [5].

Technical efforts to mitigate packet collisions in Mode 2 have recently focused on refining the Semi-Persistent Scheduling (SPS) algorithm. For instance, recent studies propose combining vehicle position data with immediate reselection triggers to address hidden-node and half-duplex limitations [7]. However, most existing solutions, including the standard IUC schemes, primarily operate at Layer 2. Our work differs by shifting the coordination intelligence to the ETSI Facilities layer, offering a cross-layer, software-defined alternative that is compatible with legacy Release 16 deployments.

Evolution and Technical Novelty: The research presented here builds upon our previous work [3], where we first proposed a preliminary IUC mechanism using a MATLAB-based link-level simulation. While that study confirmed the theoretical benefits of reservation sharing, it lacked the architectural fidelity required for real-world protocol assessment. The novelty of this paper can be summarized as follows:

- We implement and evaluate the IUC mechanism within MS-VAN3T [8], an ETSI-compliant, high-fidelity 5G NR-V2X simulation framework. This allows for a more rigorous analysis of protocol latencies and overhead.
- Unlike standard coordination schemes, our method extracts Sidelink Control Information (SCI) data and embeds it into the CAM optional container. A dedicated helper manages this additional information via a Time-to-Live

(TTL) mechanism, filtering the local candidate resource set before transmission.
- We evaluate this mechanism in a simple toy scenario to establish a baseline for performance gains and identify architectural limitations.

II. Background on NR-V2X Mode 2

In 5G NR-V2X Mode 2, SL communication occurs directly between UEs. Each data transmission on the Physical Sidelink Shared Channel (PSSCH), triggered at the Application or Facilities Layer, is preceded or accompanied by SCI information transmitted on the Physical Sidelink Control Channel (PSCCH). The SCI is split into two stages:

- **1st-stage SCI (SCI format 0-1):** Transmitted on the PSCCH, containing information necessary for sensing, such as priority, frequency resource assignment, and Resource Reservation Interval (RRI).
- **2nd-stage SCI (SCI format 0-2):** Transmitted on the PSSCH resources, containing metadata like the Modulation and Coding Scheme (MCS) and Hybrid Automatic Repeat-Request (HARQ) details.

Mode 2 utilizes two modes for resource scheduling and allocation: SPS or Dynamic Scheduling (DS). With DS, resources are selected for a single transport block (and its potential HARQ retransmissions). SPS allows a UE to reserve a set of periodic resources for a specific duration by signaling the RRI in the SCI. A UE continuously monitors the PSCCH to decode SCIs from all neighbors.

The resource selection process includes the following steps:

1) **Sensing Window:** The UE maintains a history of decoded SCIs to identify which resources are reserved by others.
2) **Selection Window** $[T_1, T_2]$**:** When an application requests a packet transmission, the MAC layer identifies a window of available slots.
3) **Resource Exclusion:** The UE excludes any candidate resource if it overlaps with a reservation signaled in a decoded SCI, provided the Reference Signal Receive Power (RSRP) of that neighbor exceeds a specific threshold.
4) **Selection:** The UE randomly selects a resource for its transmission, from the remaining "clean" candidates.

While this mechanism effectively prevents collisions among nodes that can "hear" each other, it fails in partial visibility scenarios. Because the exclusion logic depends entirely on successfully decoding an SCI, a UE cannot exclude resources reserved by a hidden neighbor. This leads to simultaneous transmissions on the same resource, resulting in collisions at a common receiver.

III. Proposed IUC Method

The proposed methodology enhances the standard NR-V2X Mode 2 sensing by introducing a cross-layer IUC mechanism. Unlike the standard 3GPP Release 17 IUC, which requires new physical layer signaling, our approach operates at the ETSI Facilities Layer, leveraging the existing periodicity of CAMs to bridge the visibility gap caused by hidden nodes. This proposal aims to extend a UE's awareness of resource occupancy beyond the range of direct physical sensing while maintaining minimal signaling overhead.

The core of the proposal is the IUC Helper, a cross-layer entity that interfaces between the MAC layer and the Facilities Layer (CAM application). As shown in Figure 1, the Helper performs two distinct roles depending on the data flow:

- **Transmission (Data Aggregation):** It monitors local SCI decodes and aggregates future reservations into a compact IUC container, which is included as an optional sub-container within the mandatory High Frequency (HF) container of the CAM. This design ensures interoperability with legacy hardware, as nodes that do not support the IUC mechanism will simply ignore the unrecognized optional field while continuing to process standard CAM data.
- **Reception (Cooperative Filtering):** It maintains a database of coordination information received from neighbors to assist the MAC layer during resource selection.

A key novelty of our approach is the definition of a mid-future look-ahead window, defined by the parameter w. While standard sensing (described in Section II) is highly effective at identifying occupied resources in the immediate future and in the one-hop neighborhood, this information is often outdated by the time a CAM is generated and received, i.e., the resource occupancy information is propagated at two hops.

Our method specifically filters for reservations that fall within a window $[T_{now} + \Delta, T_{now} + w]$, where Δ is a small offset to account for processing and transmission latency. By sharing these mid-term reservations, we provide hidden nodes with sufficient lead time to adjust their future scheduling, which is not possible with standard sensing alone.

Figure 2 shows the extended CAM structure. The IUC container encodes a compact representation of future reservations, including parameters such as Sub-Frame Number (SFN), subchannel index, and reservation periodicity (RRI). To limit overhead, only reservations within the defined look-ahead window are included. Depending on the window size w and traffic conditions, a single CAM can carry multiple reservation entries, with the container size dynamically adapting to the number of relevant future transmissions.

The most significant departure from the standard Mode 2 procedure occurs during the Resource Exclusion phase. In a standard resource selection procedure, the candidate resource set is pruned based only on SCIs decoded directly from the PSCCH. In the proposed method, the Helper modifies this step:

1) The UE receives a CAM from a neighbor containing an IUC container.
2) The Helper extracts the periodic reservation patterns, such as period, timing, SFN, and stores them with a TTL.
3) When the MAC layer initiates a selection window $[T_1, T_2]$, the Helper provides a blacklist of resources based on the aggregated CAM data.
4) The UE excludes resources that are either sensed locally via PSCCH or reported as reserved in the Helper coordination database.

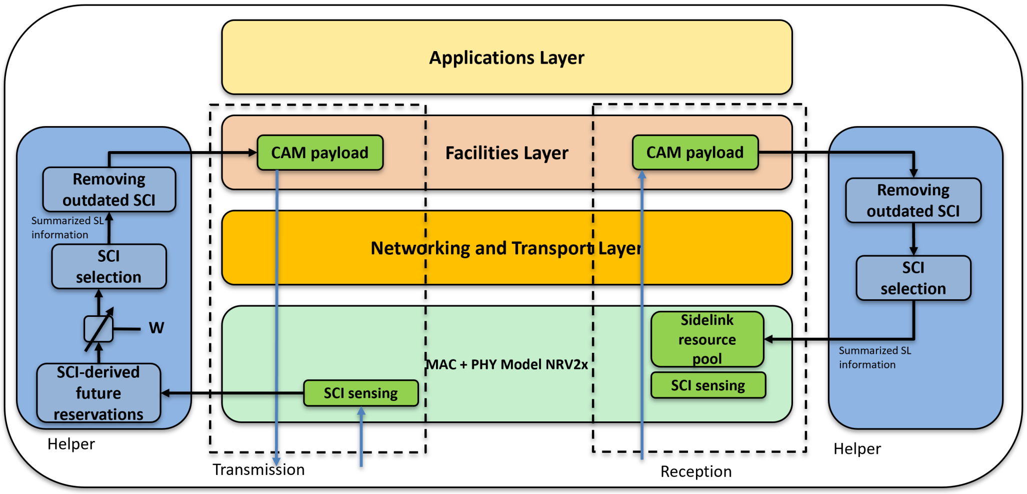

Figure 1. High-level architecture of the proposed CAM-aided IUC framework in MS-VAN3T.

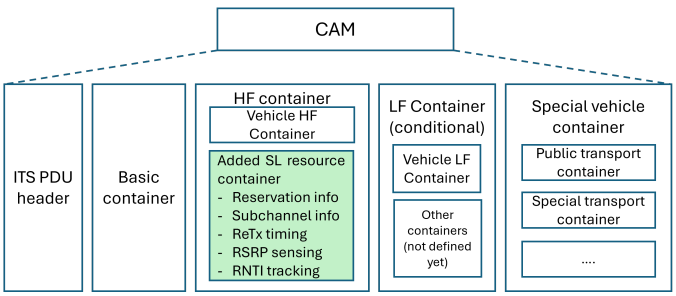

Figure 2. Proposed ETSI-compliant CAM structure featuring the custom IUC container for SL resource reservation sharing.

IV. Implementation and Experimental Setup

Integration in MS-VAN3T: We implement and evaluate the proposed mechanism using MS-VAN3T [8], a high-fidelity simulation framework that integrates SUMO for traffic mobility and ns-3 for the NR-V2X protocol stack. This framework provides an ETSI-compliant environment, enabling the modeling of the full C-ITS station architecture.

The IUC Helper is integrated as a cross-layer module between the MAC and Facilities layers. In the transmission path, the Helper monitors the MAC-layer sensing results and extracts the SFN, sub-channel index, and periodicity of decoded SCIs. These are converted into an IUC Container and passed to the Facilities layer for CAM generation. On the reception path, the Helper decodes received CAMs and extracts the IUC Container. This information is used by the ns-3 5G NR-V2X MAC to update the SL resource pool, allowing it to perform the enhanced resource exclusion logic described in Section III.

Experimental Setup: To evaluate the effectiveness of CAM-aided scheduling in partial visibility conditions, we design a "toy" scenario based on virtual train coupling [9, 10]. This use case is a visionary railway application where multiple trains maintain a coordinated platoon via SL communication.

We simulate three trains (T_1, T_2, T_3) moving along a linear track. T_1 and T_3 are positioned such that they are hidden nodes to one another, i.e., they are outside each other's physical sensing range but both within the communication range of the middle train, T_2. This setup creates a controlled environment to observe persistent collisions at T_2 caused by the simultaneous, uncoordinated resource selection of T_1 and T_3. By sharing reservation hints via CAMs (which may be relayed or simply heard by the central node), we test if T_1 and T_3 can proactively avoid spectral overlap. The main simulation parameters are summarized in Table I.

Table I
KEY SIMULATION PARAMETERS.

Parameter	Value
Numerology	$\mu = 0$ (slot duration $1/2^{\mu}$ ms)
Selection window	$[T_1, T_2]$ ($T_1 = 2$, $T_2 = 33$)
RRI	100 ms
Transmission Power	23 dB
Bandwidth	20 MHz
SL sensing window	1100 ms
MCS	14 (QAM)
Prob. of keeping the resource	0.8
Channel model	Tapped model
Retransmissions	1
TTL	100 ms

V. Results and Discussion

This section evaluates the performance of the proposed CAM-aided IUC mechanism against the standard NR-V2X Mode 2 baseline. We focus on two primary metrics: Packet Reception Ratio (PRR), to assess communication reliability and collision mitigation, and CAM size, to monitor the protocol overhead. These metrics are analyzed as a function of the look-ahead window size w. To ensure statistical confidence, each simulation configuration is repeated 60 times with different random seeds, and we report the results with 95 % confidence intervals.

Figure 3 illustrates the average PRR for both the standard Mode 2 and the proposed IUC method. The results demonstrate a clear reliability gain when using the IUC helper, particularly for window sizes between 300–600 ms. We observe a peak performance improvement at approximately $w = 450$ ms, where the PRR is significantly higher than the baseline. This

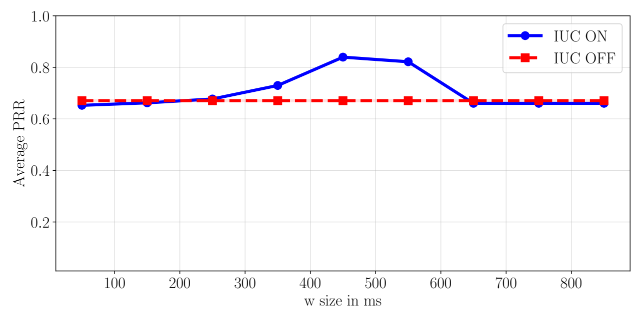

Figure 3. Average PRR vs. look-ahead window size w, comparing the standard NR-V2X Mode 2 baseline with the proposed CAM-aided IUC method.

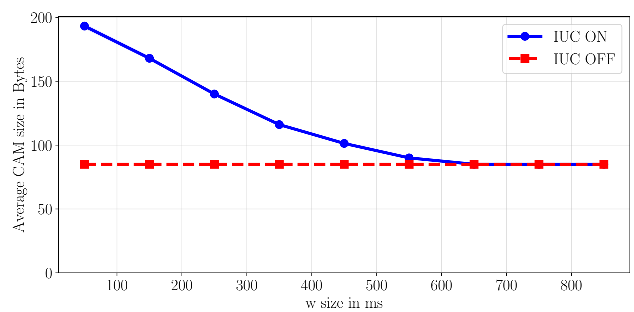

Figure 4. Average CAM payload size as a function of the window size w.

indicates that sharing mid-term reservations provides hidden nodes with the optimal lead time to proactively avoid resource conflicts at the common receiver (T_2).

However, for $w < 250\,\text{ms}$ and $w > 650\,\text{ms}$, the performance of the IUC method converges toward the baseline. The reasons for this behavior are twofold and highlight a fundamental trade-off in the mechanism. When w is small (near-future), the IUC container must carry a high density of immediate reservation data. As shown in Figure 4, this leads to a sharp increase in CAM size, which injects additional load into the channel. This overhead can lead to resource exhaustion, where the increased collision risk from higher channel busy ratios cancels out the benefits of coordination.

The CAM size results in Figure 4 confirm the relationship between the look-ahead horizon and protocol overhead. As w increases, the number of "imminent" reservations that meet the filtering criteria decreases, leading to a smaller IUC container. At very high values of w (e.g., $> 650\,\text{ms}$), the coordination information becomes extremely sparse – often empty – resulting in a CAM size equal to the standard baseline.

In these far-future cases, the IUC mechanism becomes ineffective because the shared information is either too limited to assist in current scheduling or is filtered out before it can be used for resource exclusion.

These preliminary results suggest that a sweet spot for IUC exists where the information freshness is maximized without compromising channel capacity. While the 3-train toy scenario provides a controlled environment to isolate the hidden-node effect, these findings are a first step. Detailed simulations involving larger network topologies, varying vehicle densities, and different mobility patterns (e.g., urban intersections) are required to further generalize these bounds. Nevertheless, the results confirm that a Facilities-layer cross-layer approach is a viable and pragmatic alternative to complex Layer 2 coordination signaling.

VI. Conclusion and Future Work

This paper presented a cross-layer IUC mechanism for 5G NR-V2X Mode 2. By leveraging the ETSI ITS Facilities layer to piggyback mid-term reservation hints onto standard CAM payloads, we address the hidden-node problem without the complex MAC/PHY modifications required by 3GPP Release 17. Our high-fidelity evaluation in MS-VAN3T demonstrates that this approach significantly enhances reliability in partial-visibility scenarios, such as virtual train coupling.

The core finding is a fundamental trade-off between the look-ahead window (w) and protocol efficiency. We identified a performance "sweet spot" at $w \approx 450\,\text{ms}$, where reservation information is fresh enough to be actionable but compact enough to avoid channel congestion. This provides a pragmatic path for enhancing legacy Release 16 hardware via application-layer intelligence. Future work will investigate dynamic window adaptation based on local channel busy ratio and evaluation in high-density urban environments.

Acknowledgments

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