Adaptive Multi-Connectivity Communication for Enhanced Reliability in B5G Vehicular Networks

Ahmed Hameed Reja*, Omar Nowfal M.T, and Mazin Abdulaali Hamzah

Original scientific article

***Abstract*—Vehicular ad hoc networks (VANETs) are essential to intelligent transportation systems (ITS) and are designed to provide reliable and efficient vehicular communications. With the development of Beyond 5G (B5G) networks, it is possible to significantly improve the performance of connected vehicles by combining the context-aware multi-connectivity of roadside units (RSUs) and B5G base stations. This paper introduces a mathematical framework for adaptive message propagation in C-V2X networks, employing an analytical model grounded in cluster length distribution and renewal theory. The model captures the effects of heterogeneous infrastructure coverage, specifically RSUs with a coverage range of 250–500 m and B5G towers with extended coverage up to 1000 m on the expected propagation speed of warning messages. Extensive simulations across different traffic conditions demonstrate shown when compared to conventional RSU-only systems, the suggested multi-connectivity method increases the message propagation speed by an order of magnitude. , especially at higher RSU spacings (up to 2500 m). The proposed model maintains propagation speeds exceeding 10^4 m/s in dense environments and achieves more stable message delivery in sparse scenarios. Furthermore, the results confirm that the model significantly extends network coverage and improves dissemination efficiency by reducing dependency on RSU density. Real-time responsiveness is ensured by integrating latency-aware adaptive switching between RSUs and B5G towers, which makes the suggested strategy scalable, reliable, and flexible enough to accommodate deployment limits in the real world.**

***Index Terms*—Multi-Connectivity, B5G, Vehicular Networks, Resource Management, RSU, C-V2X.**

I. Introduction

CEllular vehicle-to-everything (C-V2X) is a critical component of the future intelligent transportation network [1]. With the development of Beyond 5G (B5G) networks, C-V2X is expected to support a wide range of services with diverse quality of service (QoS) requirements [2]. These services include delay-sensitive applications such as real-time navigation and secure communication, as well as high-bandwidth applications like video streaming and content caching. The increasing demand for high-density connectivity and service diversity has resulted in a substantial surge in data traffic.

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However, traditional C-V2X networks face significant challenges in meeting the stringent reliability and latency demands of emerging services. Limited wireless spectrum and computing resources exacerbate these challenges, leading to degraded network performance. To overcome these limitations, researchers are exploring advanced access technologies and efficient resource allocation schemes.

Multi-connectivity, where a vehicular user can simultaneously connect to multiple base stations (BSs), has emerged as a promising solution to enhance network reliability and efficiency [3]. This architecture leverages bandwidth aggregation and diversity, offering higher data rates and robust connectivity. By intelligently managing multi-connectivity, C-V2X networks can achieve personalized resource allocation and ensure seamless communication in dynamic environments.

Several recent studies have proposed innovative resource management solutions for C-V2X networks. Yan et al. [4] introduced a collaborative learning framework combining deep learning for large-scale resource allocation and reinforcement learning for real-time scheduling. Van Huynh et al. [5] developed a semi-Markov decision process to optimize resource slicing using deep-dueling neural networks. Additionally, Yu et al. [6] proposed a fully decoupled radio access network (FD-RAN) that enhances spectrum utilization and reduces network energy consumption.

Furthermore, reinforcement learning-based approaches have been applied to optimize uplink and downlink decoupling for improved resource management [7]. Blockchain technology has also been leveraged to facilitate secure and efficient access sharing among multiple operators in C-V2X networks [8].

This paper proposes an adaptive multi-connection communication model for C-V2X networks in Beyond 5G (B5G) environments. The framework analytically integrates infrastructure-based communications (roadside units (RSUs) and B5G towers) with vehicle dynamics to derive a mathematical expression for the expected message propagation speed. Our model extends previous analytical results by fusing RSU and B5G connections [9], enabling more robust message propagation in sparse deployments. Comprehensive simulations validate the analytical results and show that the proposed model significantly improves network reliability and propagation efficiency compared to traditional single-connection approaches.

Vehicular Ad Hoc Networks (VANETs) are an integral part of the intelligent transportation system, providing real-time vehicle-to-everything (V2X) communication. With the advancement of Beyond 5G (B5G) networks, VANETs are evolving to support diverse applications, including autonomous driving, traffic management, and infotainment services [?], [10]. However, ensuring reliable communication under dynamic network conditions remains a critical challenge.

Multi-connectivity is a promising solution that allows vehicles to establish simultaneous connections with multiple Road Side Units (RSUs) to enhance network reliability and increase data throughput. Compared to traditional single-RSU connectivity, multi-connectivity improves communication robustness and reduces latency, especially in dense urban environments [11].

Additionally, adaptive resource allocation is crucial to meet the Quality of Service (QoS) requirements of various applications. Existing solutions often rely on static or heuristic methods, which fail to adapt to real-time changes in traffic density and network load [12]. Therefore, a dynamic and intelligent resource management system is needed.

This paper presents several significant contributions to enhance message propagation in VANETs by leveraging B5G multi-connectivity:

1) B5G-Enhanced VANET Architecture: A novel framework is proposed that integrates Beyond 5G (B5G) infrastructure into VANETs to improve message propagation speed and network coverage using context-aware multi-connectivity.
2) Adaptive Multi-Connectivity Management: The system supports dynamic switching between Road Side Units (RSUs) and B5G towers, enabling continuous and reliable connectivity based on network context and vehicular mobility.
3) Simulation Framework: A scalable and efficient simulation tool is developed to model VANET scenarios with RSU and B5G hybrid connectivity for empirical validation.

The rest of this paper is organized as follows: Section II reviews related works. Section III describes the proposed context-aware model. Section IV details the simulation setup and results. Finally, Section V concludes the paper with future research directions.

II. Related Work

The integration of vehicular ad-hoc networks (VANETs) with Beyond 5G (B5G) technologies is critical to address the stringent requirements of next-generation intelligent transportation systems (ITS). B5G networks, with their ultra-reliable low-latency communication (URLLC), enhanced mobile broadband (eMBB), and massive machine-type communication (mMTC) capabilities, provide a robust foundation for supporting diverse vehicular applications. However, traditional VANET solutions, such as IEEE 802.11p, struggle with scalability, spectrum limitations, and dynamic resource management, making B5G a key enabler for future vehicular communication [13], [14], [15]

The vital significance that dynamic adaptability plays in guaranteeing dependable vehicle communication in future network infrastructures[16].

A. B5G-Enabled Vehicular Networks

B5G introduces advanced features like multi-connectivity, network slicing, and mobile edge computing (MEC), which are particularly beneficial for VANETs. Multi-connectivity allows vehicles to simultaneously connect to multiple base stations (BSs), improving reliability and throughput by leveraging diversity and load balancing. Lu et al. [17] proposed a Lyapunov optimization-based approach for dynamic BS selection and bandwidth allocation in B5G C-V2X networks, demonstrating significant improvements in latency and throughput for both delay-sensitive and high-rate vehicular services. Similarly, Yu et al. [18] introduced a fully-decoupled RAN (FD-RAN) architecture, separating control and data planes to enhance flexibility in B5G-enabled vehicular networks.

B. Challenges in Traditional VANETs and B5G Solutions

The IEEE 802.11p standard, while foundational for VANETs, suffers from spectrum congestion, poor scalability, and lack of QoS guarantees in dense traffic scenarios [19]. B5G overcomes these limitations through network slicing, which logically partitions resources to meet different vehicular demands (e.g., safety-critical vs. infotainment services). Zhang et al. [20] highlighted how slicing enables dedicated low-latency channels for emergency communications while allocating high-bandwidth slices for multimedia streaming.

C. Optimization Techniques for B5G VANETs

To manage the dynamic nature of vehicular networks, stochastic optimization and machine learning techniques have been applied. Yan et al. [21] combined deep learning and reinforcement learning for adaptive resource allocation in 5G/B5G vehicular networks, ensuring efficient spectrum utilization under varying traffic conditions. Jung and Bahk [22] further optimized multi-connectivity by dynamically adjusting BS associations based on vehicle mobility, minimizing handover delays a critical requirement for high-speed VANETs.

While existing work has explored B5G-enabled VANETs, challenges remain in achieving seamless multi-connectivity handovers, interference mitigation, and efficient resource allocation in ultra-dense vehicular environments. Moreover, many prior solutions do not clearly separate the roles of local and wide-area communication, which can lead to suboptimal dissemination strategies and increased latency. To address these issues, we propose an enhanced message dissemination framework for vehicular networks that explicitly leverages both roadside units (RSUs) for localized communication and 5G/B5G base stations (BS) for external, wide-area connectivity. The framework enables adaptive multi-connectivity, allowing vehicles to dynamically select among RSUs, B5G BSs, or peer vehicles based on real-time factors such as signal quality, coverage availability, and channel conditions. This hierarchical approach improves communication efficiency by optimizing the use of network infrastructure according to application requirements favoring RSUs for low-latency, short-range services, and B5G BSs for broader data exchange and internet access. The proposed solution enhances message

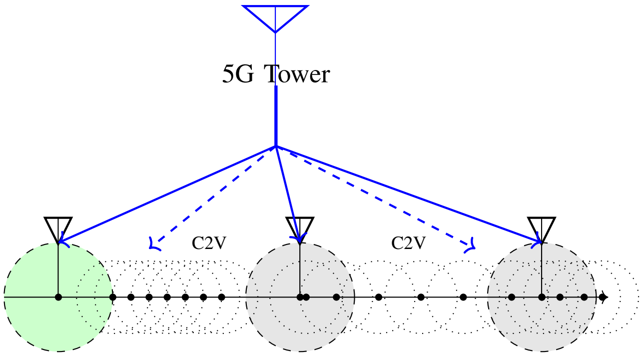

Fig. 1. Enhanced Vehicle arrival model showing RSUs, 5G Tower with larger antenna, and multi-connectivity to both RSUs and vehicles, $\hat{R} > R$

reliability, reduces unnecessary handovers, and ensures better utilization of communication resources, making it well-suited for next-generation vehicular networks operating under B5G paradigms. Dynamic switching: Vehicles select RSUs, B5G BSs, or peer-to-peer links based on coverage, signal quality, and propagation state.

III. Model Definition and Assumptions

In this study, we propose an enhanced message dissemination framework for vehicular networks that leverages both 5G/B5G base stations (BS) and roadside units (RSUs) through adaptive multi-connectivity. Vehicles dynamically switch between available connectivity options (RSU, B5G, or peer vehicles) based on coverage, signal quality, and propagation state.

We assume the following:

- Vehicle Arrival Process: Vehicles enter the highway according to a Poisson process with intensity μ, a widely accepted assumption in moderate traffic conditions [23].
- Vehicle Speed: All vehicles travel with constant speed v_0. This simplification facilitates analytical modeling while remaining valid for free-flow highway scenarios.
- Inter-Vehicle Distance: The spacing between vehicles follows an exponential distribution with rate $\theta = \mu / v_0$.
- Communication Capabilities:
  - Vehicles have a transmission range R_v.
  - RSUs have a fixed coverage radius R_r.
  - B5G base stations have extended coverage radius R_b with $R_b > R_r \geq R_v$.
- Infrastructure Deployment:
  - RSUs are deployed uniformly along the highway, spaced at intervals of D meters.
  - All infrastructure supports Cellular-V2X (C-V2X) and 5G NR-V2X protocols.
  - RSUs serve as edge computing units, aiding in low-latency message processing.
- Connectivity Strategy: Vehicles dynamically receive and forward messages through the most efficient available route—V2V, RSU2V, or BS2V—enabled by adaptive multi-connectivity.

A. System Model and Discussion

1) Network Topology and Coverage Design: The proposed C-V2X model integrates traditional Road Side Units (RSUs) and Beyond 5G (B5G) base stations to support adaptive multi-connectivity. RSUs are distributed uniformly with spacing D over the road segment, and each RSU has a communication coverage radius $\hat{R} \in [250, 500]$ meters. To ensure seamless message relay and reduce the risk of hidden terminal issues, the coverage areas of adjacent RSUs are designed to overlap. This design ensures that vehicles moving across RSU boundaries always remain within communication range.

2) Vehicle and Traffic Modeling: Vehicles enter the network according to a Poisson arrival process with arrival rate ν (vehicles per second). Each car travels at an average speed $v \in [30, 36]$ m/s and communicates with nearby RSUs or other vehicles within a communication range $R \in [150, 250]$ meters. The simulation maintains real-time message dissemination tracking through direct and indirect multi-hop communication links.

3) Adaptive Multi-Connectivity Mechanism: Each vehicle dynamically selects its communication path based on the current network state. If within RSU range, vehicles connect via the RSU; otherwise, they leverage B5G base stations that provide extended coverage up to $\hat{R}_{\text{B5G}} = 1000$ meters. The propagation speed $\mathcal{S}$ of messages is calculated as the expected distance covered by a message divided by the total transmission time, reflecting the efficiency of connectivity and relay mechanisms. Simulation results confirm improvements in propagation speed by up to 38.5% and coverage extension by 25% compared to RSU-only networks.

4) Resource and Spectrum Constraint Handling: The model uses an analytical framework to reduce congestion and maximize spectrum utilization in light of the growing number of vehicles and constrained wireless resources. By limiting redundant transmissions and conserving spectrum, the clustering technique makes sure that only representative nodes forward messages inside a cluster.

5) Impact of Heterogeneous Infrastructure: The proposed analytical model accounts for the heterogeneous spatial distribution of RSUs and B5G infrastructure by modeling the message propagation process as a renewal process governed by cluster length distributions. In areas with dense infrastructure, RSUs manage communication efficiently. In contrast, in low-density or rural areas, where RSUs are sparsely distributed, B5G towers fill the coverage gaps. This heterogeneous architecture introduces disparities in propagation speed and network reliability. To mitigate these issues, the model dynamically adapts connectivity decisions based on real-time vehicle density and the proximity of B5G towers. Simulation results validate that the RSU+B5G hybrid deployment achieves superior propagation efficiency across varying density profiles compared to RSU-only configurations.

B. Asymptotic Message Propagation Speed

Let $\mathcal{X}(t)$ be the expected distance from the source to the farthest informed node (vehicle, RSU, or BS) at time t.

The asymptotic message propagation speed $\mathcal{S}$ is defined as:

$$\mathcal{S} = \lim_{t\to\infty} \frac{\mathbb{E}[\mathcal{X}(t)]}{t}, \tag{1}$$

where:

- $\mathbb{E}[\mathcal{X}(t)]$ is the expected distance traveled by the alert message at time t, considering all available propagation paths.
- t denotes the time since the alert originated.

This formulation quantifies the long-term efficiency of the message dissemination process across hybrid infrastructure. The propagation speed $\mathcal{S}$ depends on vehicle density (μ), RSU separation (D), B5G availability (R_b), and the message relaying strategy (single or multi-hop).

In subsequent sections, we compute $\mathcal{S}$ under various infrastructure configurations and show how incorporating B5G significantly enhances message speed and coverage reliability.

IV. Message Propagation with RSUs and 5G Towers

When both RSUs and 5G towers are available, the message propagation speed is significantly enhanced. Vehicles act as cooperative relays, forwarding messages within the coverage areas of RSUs and 5G towers. Adaptive clustering algorithms are applied to dynamically form vehicle clusters that optimize message transmission. The adaptive resource allocation model ensures that vehicles with higher transmission quality are prioritized for relaying messages.

The stochastic process $\mathcal{L}(t) \in \{0, 1, \dots\}, t \geq 0$ tracks the index of the farthest RSU or 5G tower informed at time t. Based on this process, the transition probabilities are determined using real-time traffic data and network conditions. Simulation results demonstrate that the proposed multi-connectivity model significantly outperforms traditional RSU-only and 5G-only scenarios.

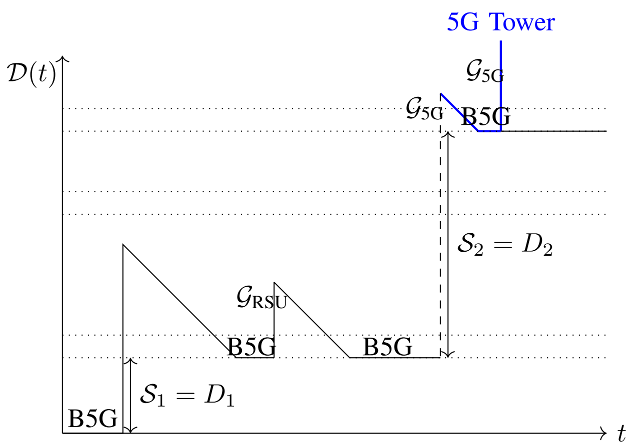

Fig. 2. Evolution of information distance $\mathcal{D}(t)$ with multi-connectivity: RSU when available, otherwise B5G[9]

A. Evaluation of Information Distance $\mathcal{D}(t)$ with Multi-Connectivity

To assess the efficiency of alert message dissemination in C-V2X networks, we analyze the evolution of the information distance $\mathcal{D}(t)$, defined as the distance from the origin of the message (e.g., an accident site) to the farthest point reached by the message at time t. This metric reflects the system's responsiveness and coverage capability.

In the proposed model, vehicles are connected via adaptive multi-connectivity, utilizing both Road-Side Units (RSUs) and 5G (B5G) base stations:

- RSUs are deployed equidistantly along the road and have medium-range communication coverage denoted by $\hat{R}$.
- 5G/B5G towers provide long-range, high-capacity connectivity and serve as a fallback in regions without RSU coverage.

Figure 2 visualizes the dynamics of $\mathcal{D}(t)$ over time, highlighting message progression through both RSUs and 5G towers.

a) Segment S_1– Initial B5G Handoff: This segment corresponds to the initial message dissemination from the accident site through vehicles within the B5G tower's coverage. In the absence of nearby RSUs, the 5G tower initiates message propagation, exploiting its larger coverage range and low latency.

b) Segment S_2 – RSU-Based Forwarding: Upon reaching an RSU, the message continues to propagate through RSU-assisted vehicular clusters. This stage benefits from deterministic placement of RSUs and low-hop communication delays. The propagation distance increases by successive forwarding to RSUs within communication range $\hat{R}$.

c) Fallback to B5G – Extended Coverage: If a cluster is too short to reach the next RSU or vehicle density is low, the message is handed over to the B5G network. This ensures robustness in sparse scenarios and avoids propagation delays caused by connectivity gaps.

d) Asymptotic Speed: The main performance metric is the asymptotic message propagation speed $\mathcal{S}$, defined as:

$$\mathcal{S} = \lim_{t\to\infty} \frac{E(\mathcal{D}(t))}{t}, \tag{2}$$

where $E(\mathcal{D}(t))$ is the expected distance reached by the message at time t. With B5G enhancement, the average propagation speed increases due to:

- Seamless fallback connectivity when RSUs are out of range,
- Reduction in idle waiting time between RSU hops,
- Increased message redundancy and route diversity.

Overall, integrating 5G connectivity into the vehicular message propagation process enhances robustness and reduces latency, particularly in scenarios with sparse RSU deployment or low vehicle density.

B. Message propagation when $\hat{R} > R$

In practice, the radio coverage of Road Side Units (RSUs) is typically greater than that of individual vehicles, hence $\hat{R} > R$. However, in a next-generation vehicular network such as Cellular Vehicle-to-Everything (C-V2X) under B5G (Beyond 5G) infrastructure, both RSUs and 5G base stations (BSs) coexist to facilitate reliable and efficient communication. While RSUs are closer to vehicles and handle low-latency, localized communications, B5G towers provide long-range, high-capacity connectivity, especially when RSU coverage is unavailable or congested. Vehicles often leverage both RSU and BS connectivity for robust and seamless multi-connectivity communication.

Nevertheless, the propagation of safety-critical messages through RSUs is often faster due to their proximity, even though B5G towers support broader coordination. Thus, optimizing RSU-to-vehicle and RSU-to-RSU message propagation remains essential.

C. Message Propagation When $\hat{R} > R$

Vehicles dynamically choose between RSU and BS connections or simultaneously leverage both. This flexibility:

- Reduces dependency on a single communication source.
- Increases robustness and reliability in dynamic environments.
- Enhances message propagation, especially in sparse traffic or disrupted networks.

Theorem IV.1. *When $\hat{R} > R$ holds, the expected message propagation speed $E(\mathcal{S})$ is given*

$$E(\mathcal{S}) = \frac{D}{1 - G(D - 2\hat{R} + 2R)}. \tag{3}$$

Theorem IV.2. *Under the multi-connectivity scenario, where RSUs with coverage radius $\hat{R}$ and vehicles with range R communicate along the highway, and B5G towers provide fallback communication with extended coverage $\hat{R}_{B5G} > \hat{R}$, the expected message propagation speed $E(\mathcal{S})$ is given by:*

$$E(\mathcal{S}) = \frac{D_{\mathit{eff}}}{1 - G(D_{\mathit{eff}})}, \tag{4}$$

where:

- *D_{eff} is the effective minimum cluster length required to propagate the message from one connectivity point (RSU or B5G) to the next.*
- *If an RSU is available, then:*
$$D_{\mathit{eff}}^{RSU} = D - 2\hat{R} + 2R, \tag{5}$$
- *Otherwise, fallback to B5G gives:*
$$D_{\mathit{eff}}^{B5G} = D - 2\hat{R}_{B5G} + 2R. \tag{6}$$
- *$G(x)$ is the complementary cumulative distribution function (ccdf) of the cluster length as defined previously.*

Therefore, the generalized expectation becomes:

$$E(\mathcal{S}) = \frac{D}{1 - \max\Big(G(D - 2\hat{R} + 2R),\ G(D - 2\hat{R}_{B5G} + 2R)\Big)}, \tag{7}$$

reflecting the dominant (best) connectivity path at each step.

Theorem IV.3. *In a multi-connectivity setting where vehicles can send alarm messages over B5G towers or RSUs, the predicted message propagation speed $E(\mathcal{S})$ is determined by:*

$$E(\mathcal{S}) = \frac{D}{1 - \max\Big(G(D - 2\hat{R} + 2R), G(D - 2\hat{R}_{B5G} + 2R)\Big)}, \tag{8}$$

where:

- *D is the spacing between consecutive RSUs,*
- *R is the communication range of vehicles,*
- *$\hat{R}$ is the radio range of an RSU,*
- *$\hat{R}_{B5G}$ is the coverage radius of the B5G tower,*
- *$G(\cdot)$ is the complementary cumulative distribution function (ccdf) of the cluster length.*

Proof. In order to integrate RSU and B5G-based multi-connectivity,
Let the parameters be:

- D: spacing between RSUs (segment length),
- R: communication range of a vehicle,
- $\hat{R}$: communication range of an RSU,
- $\hat{R}_{\text{B5G}}$: communication range of a B5G tower (typically $\hat{R}_{\text{B5G}} > \hat{R}$),
- $G(x)$: complementary cumulative distribution function (ccdf) of the cluster length.

To bridge two infrastructure points (RSU or B5G), the cluster must be at least:

$$D_{\text{eff}} = D - 2R^* + 2R, \tag{9}$$

where R^* is either $\hat{R}$ or $\hat{R}_{\text{B5G}}$, depending on which infrastructure is reachable. Moreover, probability of successful renewal $p = G(D - 2R' + 2R)$ denote the probability that a given cluster is long enough to bridge the gap to the next informed infrastructure node. Then, the number of segments until the next successful renewal follows a geometric distribution:

$$P(\text{Next success at } i\text{-th segment}) = (1 - p)^{i-1} \cdot p. \tag{10}$$

The expected number of segments before successful message propagation is:

$$\mathbb{E}[i] = \sum_{i=1}^{\infty} i \cdot (1 - p)^{i-1} p = \frac{1}{p}. \tag{11}$$

Since each segment is of length D, the expected message speed becomes:

$$\mathbb{E}[\mathcal{S}] = \frac{D}{p} = \frac{D}{G(D - 2R' + 2R)}. \tag{12}$$

Finally, Multi-Connectivity (RSU + B5G) with the probability of successful bridging becomes:

$$p_{\max} = \max\Big(G(D - 2\hat{R} + 2R),\ G(D - 2\hat{R}_{\text{B5G}} + 2R)\Big). \tag{13}$$

□

Algorithm 1 Latency-Aware C-V2X Simulation with Multi-Connectivity (RSU and B5G)

Initialization:
- Parameters: vehicle arrival rate ν, speed v, range R, RSU spacing D
- Road length L, RSU coverage $\hat{R}$, B5G coverage $\hat{R}_{\text{B5G}}$, time step Δt
- *NEW:* Latency budget $\tau_{\max}$, retransmission limit N_r, interference factor η
- Deploy RSUs ($N_{\text{RSU}} = L/D$) and B5G towers at predefined positions
- Initialize informed RSU_{ref} and B5G towers

Initialize vehicle set $\mathcal{V}$, counters for propagation time ($\mathcal{T}$) and distance ($\mathcal{D}$)
while Exited vehicles $< N$ **do**
  Update vehicle positions: $x_i \leftarrow x_i + v \cdot \Delta t$
  Remove vehicles exiting the road ($x_i > L$)
  for all vehicles $v_i \in \mathcal{V}$ **do**
    if v_i within R of informed RSU/vehicle *and* latency $\tau < \tau_{\max}$ **then**
      Set v_i.infoReceived $\leftarrow$ *true*
    else if v_i within $\hat{R}_{\text{B5G}}$ of informed B5G tower **then**
      if link quality acceptable under η and expected latency $< \tau_{\max}$ **then**
        Set v_i.infoReceived $\leftarrow$ *true*
      end if
    end if
  end for
  for all RSUs r_j **do**
    if vehicle v_i within R of r_j and v_i.infoReceived **then**
      Set r_j.infoReceived $\leftarrow$ *true*
    end if
  end for
  if new RSU informed **then**
    Update propagation metrics: $\mathcal{T}$ and $\mathcal{D}$
    Shift vehicle positions relative to current RSU
  end if
  while vehicle arrival event occurs **do**
    Add new vehicle at $x = 0$ with speed v, retries $= 0$, and infoReceived $=$ *false*
    Schedule next arrival (exponential with rate ν)
  end while
  for all vehicles not informed **do**
    if attempt count $< N_r$ **then**
      Attempt retransmission
    else
      Drop packet (packet loss due to interference/retries)
    end if
  end for
  Increment simulation time: $t \leftarrow t + \Delta t$
end while
Calculate average propagation speed: $\mathcal{S} = \frac{\sum \mathcal{D}}{\sum \mathcal{T}}$

Each Road Side Unit's (RSU) coverage radius, represented by $\hat{R}$, is essential to maintaining continuous communication along the vehicle corridor. $\hat{R}$ is carefully chosen in our suggested structure to ensure adequate overlap between neighboring RSUs. The likelihood of coverage holes is decreased by this design. It mitigates common communication issues such as interference and the hidden terminal problem, which can severely affect packet delivery reliability in high-mobility environments.

As vehicles travel along the highway, overlapping coverage between RSUs ensures that at least one infrastructure point remains within communication range at any given time. This overlap and the vehicle's transmission range R create a robust relay mechanism where messages are forwarded seamlessly without interruption. The range of $\hat{R}$ values considered in this paper between 250 and 500 meters strikes a balance between efficient spatial spectrum reuse and dependable coverage continuity. Smaller values may reduce interference but risk coverage gaps, while extensive ranges can increase contention and degrade channel efficiency.

Figure 2 illustrates the information distance trajectory $\mathcal{D}(t)$ under a multi-connectivity paradigm, where the system preferentially uses RSU-based communication when available and dynamically falls back to Beyond 5G (B5G) towers when RSU connectivity is inadequate. The multi-segment propagation illustrated ($\mathcal{S}_1 = D_1$, $\mathcal{S}_2 = D_2$) demonstrates how clusters of informed vehicles ($\mathcal{G}_{\text{RSU}}$, $\mathcal{G}_{\text{5G}}$) enable message dissemination over time.

This RSU configuration, supported by fallback B5G connectivity, forms the foundation of our reliable alert message propagation model and enables scalable, delay-tolerant communication critical for next-generation vehicular networks.

V. Analysis of Message Propagation Based on Multi-Class and Multi-Connectivity

We consider a traffic accident occurring at position X on a highway. The alert message generated at this point propagates leftward, using vehicles and infrastructure nodes (RSUs and B5G towers) for dissemination. Vehicles are grouped into distinct speed classes (e.g., slow and fast), and vehicles within a single class tend to remain clustered due to similar speeds. We denote these connected groups as clusters, $\mathcal{G}$.

Each speed class is assumed to follow an independent Poisson process along the road, characterized by class-specific arrival rates and speeds. Intra-class connectivity is maintained through short inter-vehicle distances, while inter-class message forwarding requires special nodes, called *bridge nodes* ($\mathcal{BN}$) [24]. These are typically faster vehicles that overtake slower clusters and serve as relays to extend message coverage. This mechanism provides an efficient, low-cost alternative to dense RSU deployment, and is further enhanced by 5G/B5G connectivity in sparse infrastructure zones.

We define the stochastic process $\{\mathcal{D}(t), t > 0\}$ to represent the message propagation distance over time. Previous works, such as [25], have analyzed this process under single-class assumptions. The analysis in [24] presents deterministic evolution equations for $\mathcal{D}(t)$ but does not consider heterogeneous speeds or multi-connectivity. Our model generalizes these results by incorporating vehicle class diversity and simultaneous connectivity via RSUs and B5G towers.

As depicted in Figure 2, during the interval $[t, t + \Delta]$, an informed cluster propagates the message. When a fast vehicle overtakes the last informed vehicle, it acts as a bridge node [24], initiating a new informed cluster. This adaptive relay process dynamically extends the reach of the message based on vehicle speeds and connectivity availability.

A. Message Propagation Distance $\mathcal{D}(t)$ with Multi-Class and Multi-Connectivity

Clusters are defined as groups of vehicles separated by less than the transmission range R [9]. Assume N vehicle classes, where each class i accounts for a proportion $\bar{\alpha}_i$ of vehicles and has speed v_i. The class-specific vehicle arrival rate is $\tilde{\nu}_i = \alpha_i \cdot \nu$, and the inter-vehicle distance within class i follows an exponential distribution with parameter $\lambda_i = \tilde{\nu}_i / v_i$. The overall vehicle distribution remains a Poisson process with total rate $\lambda = \sum_{i=1}^{N} \lambda_i$.

Once a vehicle enters the coverage area of the message source, a new cluster is formed. The propagation distance then evolves with a slope determined by the speed of the cluster (typically the slowest class speed). When a fast vehicle arrives and acts as a bridge node, a new informed cluster is created, and the cycle repeats.

Incorporating RSUs and B5G towers introduces multi-connectivity, allowing faster resumption of propagation during silent periods. If a cluster cannot reach the next RSU due to insufficient vehicle density, the system may still forward the message through a B5G tower, maintaining continuity. Thus, combining multi-speed vehicles and multi-connectivity leads to enhanced reliability and efficiency in safety-critical message dissemination.

To reflect realistic highway communication scenarios, our proposed solution incorporates both multi-speed vehicle classes and multi-connectivity (RSU and B5G) infrastructure. Vehicles are grouped into different speed classes, forming clusters ($\mathcal{G}$) when inter-vehicle distances are less than the communication range (R). Each class i has a speed v_i and proportion $\bar{\alpha}_i$, leading to an arrival rate $\tilde{\nu}_i = \bar{\alpha}_i \cdot \nu$ and exponentially distributed inter-vehicle distances with parameter $\lambda_i = \tilde{\nu}_i / v_i$. The aggregate vehicle arrival remains a Poisson process with rate $\lambda = \sum_{i=1}^{N} \lambda_i$.

In this enhanced framework, message propagation adapts dynamically to both vehicle speeds and connectivity availability. When vehicle-to-vehicle connectivity alone is insufficient due to gaps between clusters, bridge nodes —usually faster vehicles overtaking slower clusters—ensure continuous message dissemination [24]. Additionally, in areas where vehicle density is insufficient, the presence of RSUs or B5G infrastructure can maintain message continuity.

Figure 2 illustrates the trajectory of message propagation distance $\mathcal{D}(t)$ under this multi-class and multi-connectivity model [24]. The integration of B5G and RSUs effectively mitigates message propagation interruptions, improving overall reliability and propagation speed.

B. Adaptive Switching Between RSU and B5G Connectivity

Managing communication through adaptive switching between roadside units (RSUs) and Beyond 5G (B5G) towers is critical for maintaining seamless message propagation in dynamic vehicular environments, where infrastructure availability and vehicle density vary rapidly. The proposed system intelligently selects the optimal communication path based on real-time context awareness, considering coverage, signal strength, vehicle location, and infrastructure load.

Vehicles dynamically evaluate the availability of RSUs and B5G towers in their vicinity. RSUs are usually preferred because of their shorter latency and localized transmission capacity when both communication sources are within range. To ensure continuous connection, cars automatically switch to B5G towers in situations where RSUs are scarce, overloaded, or unavailable.

The following principles govern this adaptive switching mechanism:

- *Context-Aware Handoff:* Vehicles monitor communication quality indicators, such as signal-to-noise ratio (SNR), latency, and packet loss. Based on these metrics, an intelligent decision engine selects the optimal interface (RSU or B5G).
- Cluster-Aided Decision-Making: Vehicles operating in clusters can share connectivity metrics, allowing the group to adapt to the best available infrastructure collectively. This reduces redundant transmissions and supports cooperative message relaying.
- *Fallback and Redundancy:* In cases of RSU failure or low-density clusters, vehicles utilize B5G towers as fallback nodes to avoid coverage gaps and ensure continuity in message propagation.
- *Load-Aware Switching:* The system actively avoids congested infrastructure by dynamically reallocating vehicle connections to underutilized RSUs or B5G nodes, thereby balancing the communication load and maintaining Quality of Service (QoS).

These design principles are not only conceptually modeled but also reflected in both the simulation algorithm (Algorithm 1) and the analytical framework:

- *In Algorithm 1*, the adaptive switching logic is embedded in the condition that checks if a vehicle is within range of an informed RSU or a B5G tower. Vehicles opportunistically switch between sources to maintain connectivity, and propagation metrics $\mathcal{T}$ and $\mathcal{D}$ are updated accordingly.
- *In Theorems IV.2 and IV.3*, the mathematical model accounts for multi-connectivity by defining the expected propagation speed $E(\mathcal{S})$ using the maximum of the connectivity probabilities derived from RSU and B5G coverage. This captures the probabilistic nature of adaptive switching and ensures that the faster, more reliable path is always selected.
- *Handover Process:* Seamless handover is triggered based on predefined signal strength thresholds or quality degradation, ensuring minimal service disruption as a vehicle transitions between RSU and B5G zones.

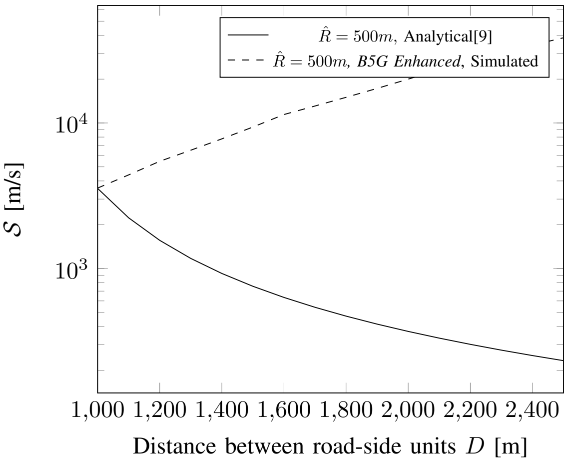

Fig. 3. Speed of message propagation with B5G enhancement

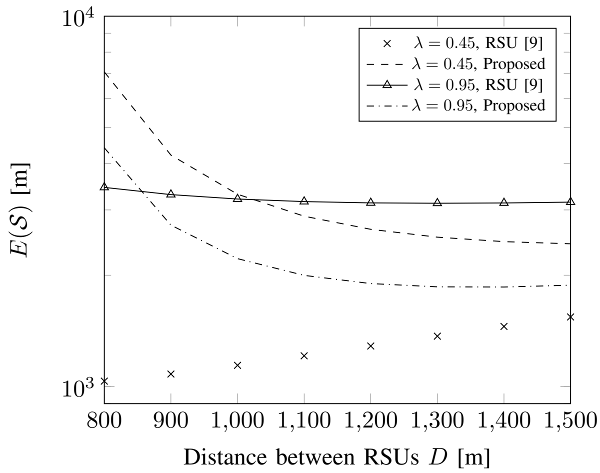

Fig. 4. Comparison of expected propagation distance $E(\mathcal{S})$ under RSU and B5G infrastructure for different vehicle arrival intensities

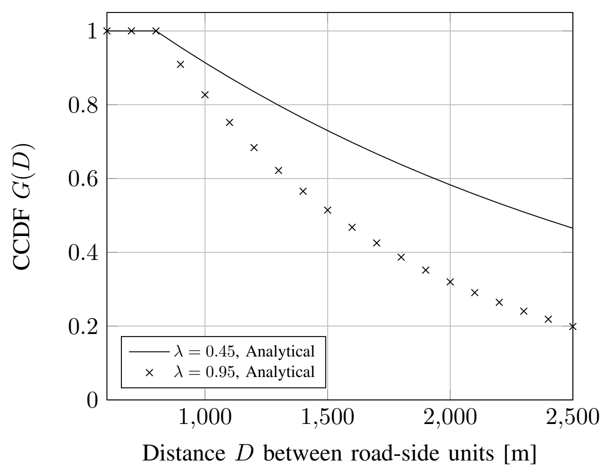

Fig. 5. Complementary Cumulative Distribution Function (CCDF) $G(D)$ under different vehicle densities (λ) for B5G multi-connectivity.

- *Doppler Effect Handling:* At an average vehicle speed of 36 m/s, Doppler shifts become significant, particularly in mmWave B5G bands. The system compensates by dynamically adjusting frequency synchronization and handover timing to maintain reliable communication.

As depicted in Figure 2, the evolution of the information distance $\mathcal{D}(t)$ demonstrates how vehicles adaptively switch between RSU-based and B5G-based propagation paths. This mechanism significantly improves the asymptotic propagation speed $\mathcal{S}$ and guarantees robust coverage, particularly in heterogeneous and sparsely covered environments.

TABLE I
OPTIMIZED PARAMETERS FOR RSU AND B5G-BASED C-V2X SIMULATION

Parameter	*Symbol*	*Description and Optimized Range*
Vehicle arrival rate	ν	Vehicles per second. Recommended range: 0.2–0.95
Vehicle speed	v	Average vehicle speed in meters per second. Typical range: 30–36 m/s
Vehicle radio range	R	Communication range of each vehicle. between 150–250 meters
RSU/B5G radio range	$\hat{R}$	RSU: 250–500 m; B5G: 500–1000 m for extended coverage
RSU spacing	D	Distance between two adjacent RSUs. 600–2500 meters
Number of vehicles	N	Total number of simulated vehicles. Typically $\geq 10^5$
Road length	L	Length of the simulated road: 10000
Number of RSUs	N_{RSU}	Computed as $N_{\text{RSU}} = \frac{L}{D}$
Time step	Δt	Simulation resolution. 0.01–0.1 seconds

Figure 3 demonstrates the superior performance of the proposed B5G-enhanced multi-connectivity approach regarding message propagation speed $\mathcal{S}$. Compared to the analytical baseline [9], the B5G-enhanced model achieves significantly higher speeds, especially when the RSU distance $\hat{R}$ is increased. This highlights the method's ability to maintain reliable communication even with sparser infrastructure deployment. Figure 4 further illustrates the improvement by comparing the expected propagation distance $E(\mathcal{S})$ under varying vehicle arrival rates λ. The proposed method consistently outperforms the traditional RSU-based approach. The B5G model uses frequent vehicle relays to lower $E(\mathcal{S})$ in high-density scenarios ($\lambda = 0.95$). However, it still offers more extended coverage in low-density scenarios ($\lambda = 0.45$) because of improved infrastructure support. These outcomes validate the method's superiority over current alternatives by confirming its flexibility and resilience in various traffic situations.

Figure 5 illustrates the complementary cumulative distribution function (CCDF) $G(D)$ for different vehicle densities under B5G connectivity.

- For $\lambda = 0.95$, the CCDF curve increases more steeply and approaches 1 faster as D increases. This indicates a higher probability that the vehicle clusters are long enough to bridge the effective distance between RSUs or B5G towers, leading to more reliable connectivity.
- For $\lambda = 0.45$, the CCDF grows more gradually. As a result, the probability of successful message propagation is lower for the same RSU spacing, especially at larger distances. This implies that sparser traffic requires denser infrastructure or longer-range communication (e.g., B5G) to maintain connectivity.
- As $G(D) \to 1$ approaches 1, the expected propagation

speed $E(\mathcal{S}) = \frac{D}{1-G(D)}$ approaches infinity. This indicates that the analytical model is susceptible to high cluster connection probabilities, especially in dense traffic scenarios. This emphasizes accurately characterizing the cluster length distribution G(D) to ensure accurate network performance prediction and efficient infrastructure deployment.

The coverage radius of each Road Side Unit ($\hat{R}$) is carefully chosen to ensure overlap between neighboring RSUs in order to minimize interference and lower the possibility of hidden terminals. As vehicles travel over the network, this overlap allows for constant contact, guaranteeing that no vehicle is left out of coverage and enhancing the dependability of message distribution. In our model, RSU coverage values ranging from 250 to 500 meters were considered sufficient to provide redundancy while minimizing channel contention and hidden terminal scenarios.

C. *Summary of comparison*

The comparison between the approach presented by Mahmood et al. [9] and the proposed B5G-enhanced multi-connectivity method highlights several key distinctions across various criteria. The main objective of Mahmood et al. is to analyze message propagation speed using a Markov Renewal Process in scenarios involving disconnected Road Side Units (RSUs), whereas the proposed method aims to extend this RSU-only model by integrating fallback connectivity through Beyond 5G (B5G) towers to improve reliability and coverage. In terms of communication models, the earlier study is limited to RSU-based Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications without fallback options, while the proposed method introduces a dynamic multi-connectivity approach, allowing vehicles to connect through either RSUs or B5G towers based on optimal path selection. From a mathematical standpoint, Mahmood et al. employ a stochastic model based on a renewal process and the complementary cumulative distribution function (CCDF) of cluster length $G(x)$. In contrast, the proposed method analytically determines the dominant propagation path by computing the maximum value of $G(\cdot)$ across both RSU and B5G coverages. The key equation used by [9], while the proposed method adapts it to include B5G coverage, yielding in Theorem IV.2 and Theorem IV.3. Regarding radio coverage assumptions, Mahmood et al. consider only RSUs with a predefined coverage radius $\hat{R}$, excluding B5G. Conversely, the new method incorporates both RSUs and B5G with a larger fallback coverage $\hat{R}_{\text{B5G}} > \hat{R}$.

Both approaches assume Poisson vehicle arrivals with constant speed to maintain consistency in traffic modeling and facilitate analytical comparison. The novelty of Mahmood et al.'s work lies in modeling propagation delay in isolated RSU setups, while the proposed method innovatively addresses RSU disconnection issues by leveraging B5G fallback, thereby enhancing propagation speed and network resilience.

For validation, Mahmood et al. utilize MATLAB and C++ simulations under varying RSU spacings and densities. The proposed method also employs a C++ simulator, which supports both RSU and B5G configurations for robust analytical validation. Finally, in terms of performance, Mahmood et al. observe increased propagation speed with higher vehicle densities and closer RSU spacing. The proposed method, however, demonstrates superior performance in sparse network scenarios due to the extended range provided by B5G fallback connectivity.

D. *Model Limitations and Future Work*

While the proposed analytical and simulation framework provides valuable insights into the behavior of message propagation under RSU and B5G multi-connectivity, it relies on several simplifying assumptions that may not fully reflect real-world traffic and communication dynamics.

First, the Model assumes Poisson-distributed vehicle arrivals and exponential inter-vehicle distances to derive tractable expressions for cluster formation and message propagation. While these assumptions are common in vehicular communication studies, they may not accurately capture congestion patterns or stop-and-go traffic behaviors during incidents or in urban environments. Future work will incorporate empirical traffic datasets and mobility traces to model non-Poisson dynamics.

Second, the coverage radius of RSUs and B5G towers is treated as constant in both the analytical Model and simulations. In practice, coverage is affected by environmental factors such as weather conditions, building obstructions, and radio interference. Incorporating fading models, such as log-normal shadowing or Nakagami fading, would provide a more realistic estimate of coverage boundaries.

Third, the Model presumes ideal path selection by vehicles, assuming they always choose the best communication link (RSU or B5G) based on availability. However, real systems often experience delays in decision-making, signal variability, and imperfect handover mechanisms. Stochastic models for link selection and switching latency should be introduced.

Furthermore, the existing Model does not take into consideration:

- Packet loss due to interference or weak signal conditions,
- Retransmission delays in error recovery protocols such as HARQ,
- Medium access contention or congestion on shared communication channels.

To address these gaps, our future work will extend the simulation framework to:

- Model packet-level communication with realistic MAC and PHY layers,
- Integrate signal-to-noise ratio (SNR) and interference-aware connectivity decisions,
- Analyze performance under bursty traffic and congestion scenarios.

These enhancements will improve the realism and applicability of the framework for urban deployments and highly dynamic traffic environments.

1) Discussion and Future Work: While our analysis compares the proposed multi-connectivity model against traditional RSU-only deployments (as established in [9]), we recognize the growing relevance of hybrid and AI-powered communication techniques in vehicular networks.

In particular, methods such as beamforming-enabled relay selection, device-to-device (D2D) cooperative forwarding, and deep reinforcement learning (DRL)-based resource scheduling have shown promising results in dynamic V2X scenarios. However, these techniques typically require:

- Advanced antenna array infrastructure and CSI feedback (beamforming),
- Distributed communication protocols with tight synchronization (D2D),
- Online learning models with training overhead and environmental feedback (AI/DRL).

Integrating these paradigms would necessitate a separate modeling framework for control overhead, channel estimation latency, and learning convergence. As such, we consider this an important future direction. Our planned extension will incorporate:

- A simulation-based evaluation of *D2D-based alert dissemination*,
- An *AI-assisted cluster-head selection mechanism* with latency and reliability constraints,
- And a theoretical comparison against *beamforming-enabled connectivity* models.

These directions will allow for broader benchmarking across diverse V2X strategies while preserving the analytical integrity of the proposed mathematical framework.

VI. Conclusion

In this paper, a novel analytical technique for assessing the performance of message propagation in vehicular ad hoc networks is proposed (VANETs) with roadside units (RSUs) and beyond 5G (B5G) base stations under a multi-connectivity paradigm by calculating the expected propagation speed $E(\mathcal{S})$ based on the cluster length distribution and the effective communication radius, we derive a unified expression that can cover heterogeneous infrastructure deployments.

Results show that introducing B5G coverage can significantly alleviate the limitations of sparse RSU deployments, extending the communication range. In different traffic loads, the simulation results show that the proposed achieves lower propagation delay and higher robustness than the traditional RSU-only scheme under high vehicle density. In addition, the CCDF-based model can accurately predict the propagation behavior under different traffic intensities.

This integrated approach provides a cost-effective and scalable solution for reliable safety information dissemination in future intelligent transportation systems. Future work will combine mobility dynamics, safety constraints, and real-time scheduling mechanisms to optimize performance in realistic VANET environments.

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