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Semantic Vehicle-to-Everything (V2X) Communications Towards 6G

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***Abstract*—Semantic Communication (SEM-COM) has emerged as one of the disruptive technologies facilitating the evolution towards sixth-generation (6G) wireless networks. This article presents the potential of SEM-COM to transform Vehicle-to-Everything (V2X) communications, with a particular emphasis on its ability to enhance communication efficiency and intelligence. We discuss the core components and metrics that characterize SEM-COM, providing insights into its operational framework within the context of V2X communications. We illustrate the applicability and practicality of SEM-COM through real-world vehicular use cases, demonstrate the potential of SEM-COM to enhance aspects of intelligent mobility, such as communication efficiency and decision-making. Finally, the article identifies key open research questions for SEM-COM V2X, pointing to areas that require further exploration and thus setting a foundation for future work in this evolving domain.**

***Index Terms*—6G, Semantic Communications, V2X, Vehicular Networks.**

I. Introduction

Semantic communications, often referred to as SEM-COM, are one of the emerging tenets of 6G, aiming to provide a more intelligent and context-aware network. SEM-COM departs from the traditional data-centric paradigm by encompassing a broader interpretation of communication, including linguistic meanings and visual data. It proposes a shift from the conventional 'transmit first, then understand' approach to a more judicious 'understand first, then transmit' methodology. This signifies a dual shift — technical as well as conceptual — as it transitions away from Shannon's longstanding emphasis on data volume, focusing instead on the meaningfulness of the information exchanged [1].

It is envisioned that SEM-COM will be applicable to a broad spectrum of applications, ranging from augmented reality to autonomous vehicles and advanced healthcare. In the realm of vehicular networks, SEM-COM could play a crucial role. This environment is highly dynamic, necessitating a communication system that can adapt rapidly to frequent changes in road conditions and vehicle speeds. The burgeoning number of vehicle sensors and advanced use cases requiring high reliability and low latency pose significant challenges for communications. These factors contribute to the scarcity of wireless resources, intensifying the need for efficient communication systems [2]. Moreover, privacy stands out as a critical issue in vehicular communications, Semantic communication enhances network security by transmitting only the necessary data while relying on the recipient's background knowledge to decode semantic information. This approach reduces the amount of data transmitted, thereby limiting the exposure of potential eavesdroppers. In addition, the semantic information extracted through encryption enhances the security of the transmitted data [3]. Given that V2X communication data may contain personal details such as license plates or images of individuals in urban settings, SEM-COM can potentially enhance privacy. For instance, instead of transmitting an image that could potentially identify a person, SEM-COM processes and transmits only essential semantic information, such as the presence of a person, which is sufficient for the context. This approach significantly reduces privacy risks by limiting the amount of sensitive data shared.

Efficiency in V2X communication does not just hinge on detailing only some environmental elements; it also depends on the timely and appropriate response to ever-changing scenarios. The utility of SEM-COM lies in its focus on the 'meaning' and 'context' of communication. 'Meaning' relates to the interpretation of content linked to the specific lexicon and semantics of the message, while 'context' involves the situational aspects of communication, such as the participating entities, their intentions, and the timing. These components are essential for understanding the message and ensuring that responses are both rapid and contextually appropriate [4]. SEM-COM is adept at transmitting fewer, yet more pertinent, data while facilitating improved decision-making, thus addressing the pressing demands of contemporary V2X communications, such as the need for high reliability, low latency, and enhanced security. SEM-COM is designed to enhance communication by effectively conveying a message's meaning and context, which could lead to clear and unequivocal communication—a critical need in the intricate domain of intelligent transportation systems. While promising, these capabilities are currently in developmental stages and represent aspirational goals [5], [6].

The remainder of this article offers an in-depth exploration of SEM-COM within a V2X wireless network context. We provide an overview of semantic communications, highlighting the four foundational types and their potential to redefine conventional communication paradigms. Subsequently, we introduce the hierarchical network structure of SEM-COM V2X, which serves as a blueprint for integrating semantic layers into existing vehicular networks. Subsequent sections consider performance metrics like Age of Information (AoI) and its variants, which, while not exclusive to SEM-COM, are closely related and crucial for assessing the effectiveness of V2X communications. Following this, we outline four SEM-COM use cases, presenting their practical applications and

showcasing practical applications and the benefits they bring to intelligent mobility. Finally, we present an analysis of the current challenges within this domain, pointing to future research and development needs in SEM-COM as we step towards the 6G frontier.

II. Overview of Semantic Communications

This section provides a brief overview of SEM-COM, initially focusing on its core components, followed by an analysis of the four distinct SEM-COM types. This demonstrates that the V2X example is used to illustrate semantic communication in general.

A. SEM-COM Components

In the context of semantic communications, semantic features are the identifiable elements within data, while semantic information details how these features interact or relate. A key starting point is understanding its core components. State-of-the-art works offer various definitions, while combining in [7], [8] offer varied definitions for the types of semantic communication, there is a consensus that some of the necessary architectural components, namely 'Semantic Encoder/Decoder' mechanisms and 'Background Knowledge.'

A. **Semantic Encoder:** Responsible for capturing the most information embedded in the source data and filtering out unnecessary redundancies. The focus is on accurately and efficiently encoding and transmitting the semantic information to ensure that the machine retains and understands its meaning, which is eventually extracted as semantic features. e.g., extracted from an image the current state of the light, filtering out background information such as the sky and pedestrians on the ground.

B. **Semantic Decoder:** Inverse process of semantic encoding, where source data is recovered based on semantic information through various techniques. The focus is improving the receiver's ability to successfully infer semantic information from the communication data (semantic features). In some scenarios, semantic decoders may be unnecessary. e.g., in the multi-user collaborative vehicle ID retrieval scenario presented in [9], the executor of the task can directly use the semantic features for ID retrieval without the need to recover the complete vehicle image, so the semantic decoder is omitted to improve the operational efficiency of the system.

C. **Background Knowledge:** This is a pre-existing information base as well as a contextual understanding of the transmitter and receiver that is accurate in interpreting and processing semantic content. It ensures that communication exceeds technical accuracy and delves into contextual relevance and meaning. There are two prevailing implementations: one using knowledge graphs and the other using advanced artificial intelligence techniques [10].

B. Type of SEM-COM

Recent studies broadly categorize Semantic Communication (SEM-COM) into distinct types that address the varied demands of modern network systems. These include Semantic-Oriented communication, which focuses on the precision of semantic processing; Goal-Oriented communication, aimed at semantic accuracy and operational targets; Semantic-Aware communication, which augments task-oriented communication by improving shared knowledge; and Context-Aware communication, which integrates environmental understanding into strategy [7], [8].

The core differences between them are illustrated in Fig. 1, showing a common scenario. The view is obscured by a large truck in front of the vehicle. To safely navigate the junction, the obstructed vehicle requires data from the truck's front camera. The various SEM-COM systems, each with their unique approach, will communicate differing information relevant to this situation. The situation visible to the human eye includes several key details: the traffic light is red, indicating the need to stop; pedestrians are actively crossing the road, requiring drivers to yield; and the right turn indicator of the first vehicle in the opposite lane is on, signaling an intent to turn. For the vehicle behind the truck to safely cross the junction, the critical information it requires through SEM-COM systems includes the red light status to prompt slowing down, the presence of the pedestrian to signal, and waiting until the pedestrian has fully cleared the crossing. The activation of the turn indicator on the opposing vehicle suggests when it is safe to pass the junction.

A. **Semantic-Oriented:** This type prioritizes the accurate interpretation of significant observable elements, such as traffic lights and pedestrian movements, to ensure that the transmitted message maintains the original data's integrity. It focuses on the fidelity of the semantic content to ensure clear and precise communication.

B. **Goal-Oriented:** This system translates environmental observations into executable commands, aligning the vehicle's actions with situational demands. It ensures that the vehicle receives succinct instructions for immediate and appropriate responses, facilitating on-time execution of driving maneuvers.

C. **Semantic-Aware:** By integrating data from other smart devices at the intersection, this approach enhances decision-making processes. It accounts for the mobility of pedestrians and adjusts vehicular actions accordingly to maintain smooth traffic flow and heightened safety.

D. **Context-Aware:** This type takes into account a broader set of data, including current traffic conditions, historical behavior patterns, and environmental factors. It synthesizes this information to develop comprehensive strategies for navigating intersections, enabling vehicles to make informed movements based on a thorough understanding of the environment.

In light of the preceding exposition on SEM-COM types, it becomes clear that each approach carries its distinct set of challenges when applied within V2X environments. The 'Semantic-Oriented' approach, while prioritizing the fidelity

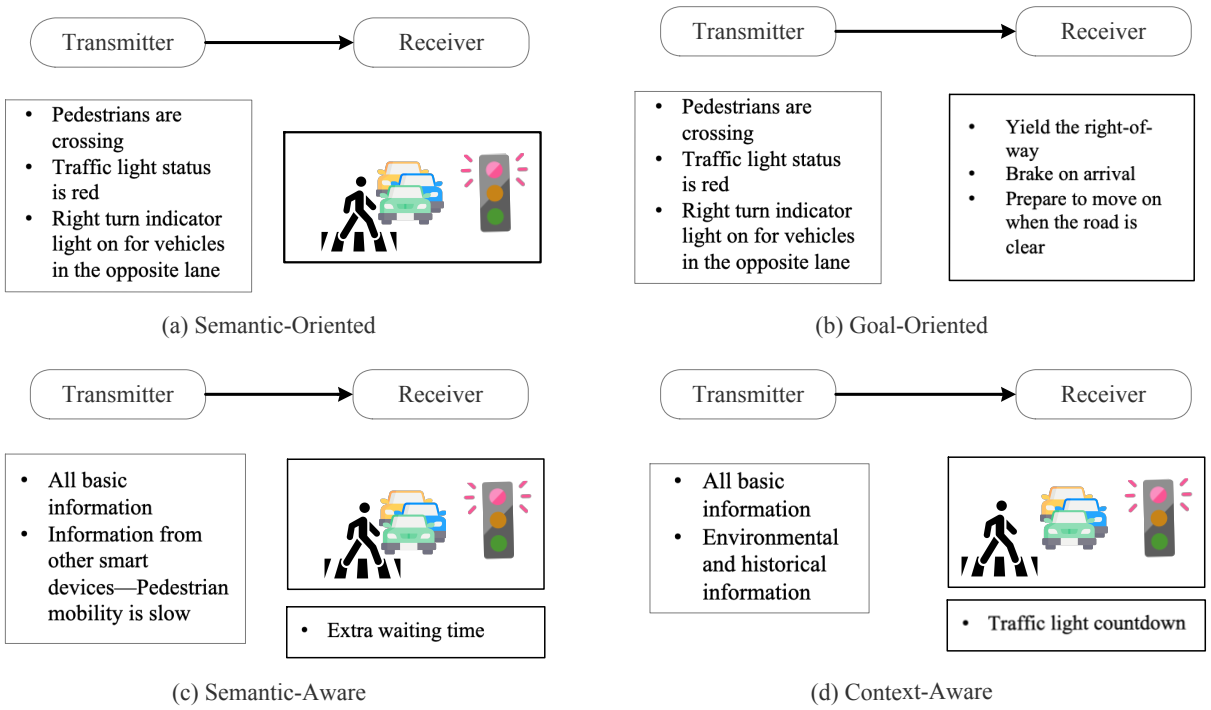


Fig. 1: Illustration of data handling in different SEM-COM systems during the same traffic scenario

of source data recovery, can lead to data redundancy and an increase in network load, which could be more practical for the bandwidth constraints of V2X applications. The 'Goal-Oriented' and 'Semantic-Aware' types, despite their focus on task relevance and agent cooperation, require constant adaptation and extensive customization that can pose real-time processing challenges in the dynamic vehicular context [7]. The effectiveness of Context-Aware's communication depends significantly on the quality and accuracy of the data it receives. Poor data quality can lead to incorrect interpretations and decisions [8].

Based on the challenges inherent in these SEM-COMs, it becomes evident that their respective efficacies are markedly scenario-dependent within the V2X communication framework. The 'Semantic-Oriented' is especially effective in emergency response systems, where the precision of source data recovery is paramount. Conversely, the 'Goal-Oriented' is particularly suited to traffic management systems, where it integrates semantic accuracy with specific operational objectives. In collaborative settings like autonomous vehicle fleets, the 'Semantic-Aware' excels by augmenting the collective intelligence among vehicles, enhancing overall communication efficacy. Lastly, the 'Context-Aware' is optimally deployed in smart city applications, leveraging its adaptive communication capabilities to respond to dynamic environmental data. This contextual application of each SEM-COM type underscores the criticality of aligning the right technology with the specific requirements of diverse V2X scenarios.

III. Semantic V2X Communications

This section discusses the integration of semantic communication technologies within V2X systems. A layered overview of the SEM-COM V2X communication system is provided, followed by a detailed exploration of the key metrics crucial for effectively implementing and assessing semantic communications in vehicular environments.

A. Network Architecture and Design

Despite the varying focuses and data utilization strategies of the four SEM-COM types previously discussed, they operate within a similarly structured network layering architecture, ensuring their foundational functionalities are aligned, as shown in Fig. 2. The Device Layer anchors this architecture, managing primary V2X communication streams such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I), among others, to maintain reliable and consistent operational data. Progressing to the Network Layer, the system's backbone emerges, equipped with multi-access edge computing (MEC) and roadside units (RSUs) designed for rapid and high-capacity data transmission, essential for real-time responsiveness in vehicular communications. Above this, the Semantic Layer processes semantic information and context-aware data,

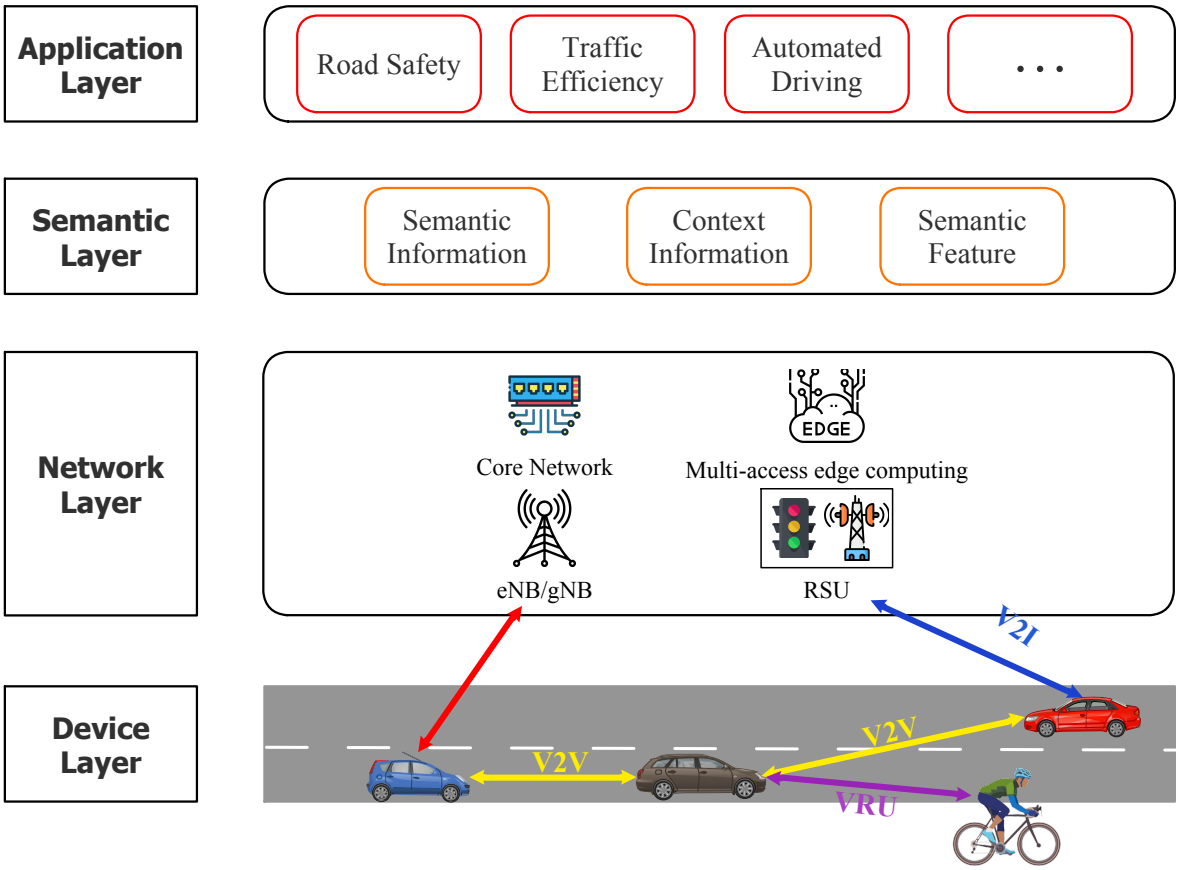


Fig. 2: Layered Overview of SEM-COM V2X System

transforming raw inputs into actionable insights that enhance communication efficiency, as confirmed by the studies in [11]. The architecture culminates with the Application Layer, which capitalizes on the semantically rich data to fuel various vehicular applications, enhancing road safety, improving traffic flow, and supporting autonomous driving initiatives. This topmost layer demonstrates the practical application of semantic processing, where complex data interpretations are effectively translated into tangible outcomes for the transportation ecosystem.

In exploring SEM-COM V2X, the research underscores a cooperative, semantic-aware architecture (Co-SC) that effectively conveys essential semantics from users to servers, significantly reducing data traffic while enhancing system performance in vehicular transportation systems. Studies offer a comprehensive survey of the evolution of V2X technologies, including early developments like dedicated short-range communications and the impact of big data and cloud-edge computing, highlighting the challenges and opportunities these technologies present for the Internet of Vehicles (IoV) [12]. Big data's role within IoV is critically examined, emphasizing its importance in efficient processing, decision-making, and urban development while providing a taxonomy of big data usage in IoV and discussing the challenges and opportunities that arise [13]. The integration of SEM-COM with V2X requires a careful and complex network architecture design for the IoV [9], [12], [13], imposes the following requirements:

1) There is a need for high-speed data transmission to support real-time decision-making, dynamic context awareness to accommodate a variety of vehicle scenarios, and the scalability necessary to manage an expanding IoT network.
2) The most important thing is to ensure that stable and reliable performance is provided in all environments and that efficient data management strategies are employed.
3) Implement stringent security and privacy measures to protect the connected in-vehicle network.

B. Key Metrics

Key performance metrics crucial to the efficacy of information exchange within intelligent transportation systems.

1) Age of Information: The AoI measures the time that has elapsed since the generation of data at the source, representing the freshness of information in real-time communication systems [14], [15].

2) Age of Incorrect Information: The AoII quantifies the time since the last accurate and relevant update was received, indicating the prevalence of misinformation in the network [16].

3) Age of Outdated Information: The Ao2I gauges the duration since information at the destination became outdated relative to its source [16].

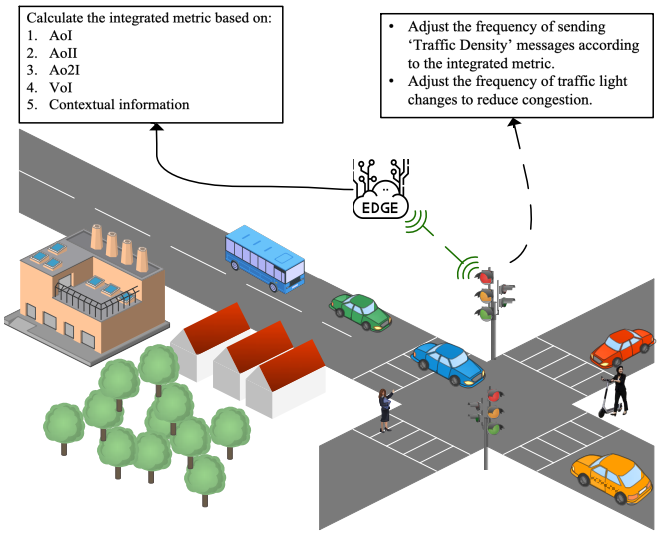


Fig. 3: Adaptive Traffic Management Using SEM-COM

4) Value of Information: The VoI assesses data's significance and decisional impact, playing a crucial role in optimizing system responses within vehicular communication networks [14], [17].

Scenario Description:: As shown in Fig. 3, an intelligent traffic light system powered by a semantic sensor measures the level of congestion at an intersection. The system employs edge computing to process this data along with one metric. Commands are then formulated based on this composite data, prompting the traffic light to dynamically adjust the color and duration of the lights to manage traffic flow efficiently. Moreover, the intelligent traffic light system adapts the frequency of congestion level reporting back to the edge computing system, depending on the real-time traffic conditions and the associated performance metric. The results of the above-mentioned metrics in adjusting the frequency of 'congestion level' sending in the face of this scenario are as shown in Table I.

In Semantic V2X communications, the synthesis of critical metrics attains a heightened level of sophistication when contextual information is intricately woven into the evaluation framework. The triadic relationship between the Age of Information (AoI), the Age of Incorrect Information (AoII), and the Age of Outdated Information (Ao2I) is augmented by the contextual relevance of updates, yielding a nuanced understanding of the data's currency and its pertinence to specific vehicular scenarios. Alongside the Value of Information (VoI), which appraises the data's decisional impact, these metrics collectively establish a multi-dimensional lattice for assessing communication efficacy. By integrating contextual information, this lattice transcends mere temporal metrics, encapsulating contemporary vehicular networks' dynamism and complex exigencies. This integration ensures a sophisticated orchestration of data flow, optimally tuned to the exigencies of safety, operational efficiency, and the overarching demands of SEM-COM V2X communications.

IV. Vehicular Use-cases

This section examines four different vehicular use cases, each of which exemplifies the transformative impact of SEM-COM in addressing contemporary automotive challenges. These four use cases provide a comprehensive overview of the capabilities and benefits of SEM-COM in the automotive environment, highlighting its potential to redefine vehicular communication and contribute to the advancement of intelligent mobility solutions.

A. Collaborative Driving

Scenario: This scenario occurs when a vehicle's view is obstructed by another vehicle in front, necessitating insight into the road ahead beyond the immediate line of sight.

Traditional V2X Approach: Traditional V2X would transmit a real-time image from the front vehicle to the rear vehicle to provide visual information about the road ahead.

SEM-COM Solution: SEM-COM would transmit key semantic features (like distance to the next vehicle, speed, and traffic light status) from the front vehicle, enabling the rear vehicle to understand and react based on these specific, concise semantic cues.

Comparison: SEM-COM offers a more bandwidth-efficient and focused approach by transmitting only pertinent semantic features rather than entire images. This results in faster processing, less data transmission, and potentially quicker response times, which are crucial for safety in collaborative driving scenarios.

B. VRU Awareness

Scenario: This situation arises when a vehicle encounters pedestrians, necessitating either an alert to the pedestrians or an appropriate reaction from the vehicle to ensure safety.

Traditional V2X Approach: Traditionally, automated emergency braking (AEB) systems are employed in vehicles to prevent collisions with pedestrians. Audible beeps can be used to alert pedestrians in the vicinity of the vehicles.

SEM-COM Solution: SEM-COM can enhance pedestrian safety by transmitting detailed contextual information about the pedestrian's location, speed, and direction to the vehicle. The vehicle can then calculate the potential risk and either alert the pedestrian more effectively or adjust its own behavior (like slowing down or rerouting) based on a deeper understanding of the pedestrian's movements and intentions.

Comparison: While traditional systems rely on basic alerts or automatic braking, SEM-COM introduces a more proactive and nuanced approach. By understanding the context and predicting pedestrian behavior, SEM-COM can facilitate more tailored and potentially more effective responses, enhancing pedestrian safety and reducing the likelihood of accidents.

C. UAV-assisted V2X

Scenario: In this scenario, a cluster of UAVs captures high-definition images or videos from an overhead perspective to assist vehicles on the ground, e.g., in a crash or emergency situation.

TABLE I: Congestion Level Information Reporting by the Traffic Light in Relation to Metrics [14], [15], [17], [16]

Metric	Congestion Level Information Reporting	Relevance and Utility in V2X (Out of 5)
AoI	The traffic system regularly updates the 'congestion level' to provide current data for ongoing applications.	★ ★ ☆ ☆ ☆
AoII	The system verifies and corrects 'congestion level' data accuracy to minimize misinformation and network traffic.	★ ★ ★ ☆ ☆
Ao2I	Congestion updates are triggered based on data age to support timely decision-making in traffic management.	★ ★ ☆ ☆ ☆
VoI	Update frequency for 'congestion level' is adjusted based on critical need, enhancing V2X communication during peak times.	★ ★ ★ ★ ☆

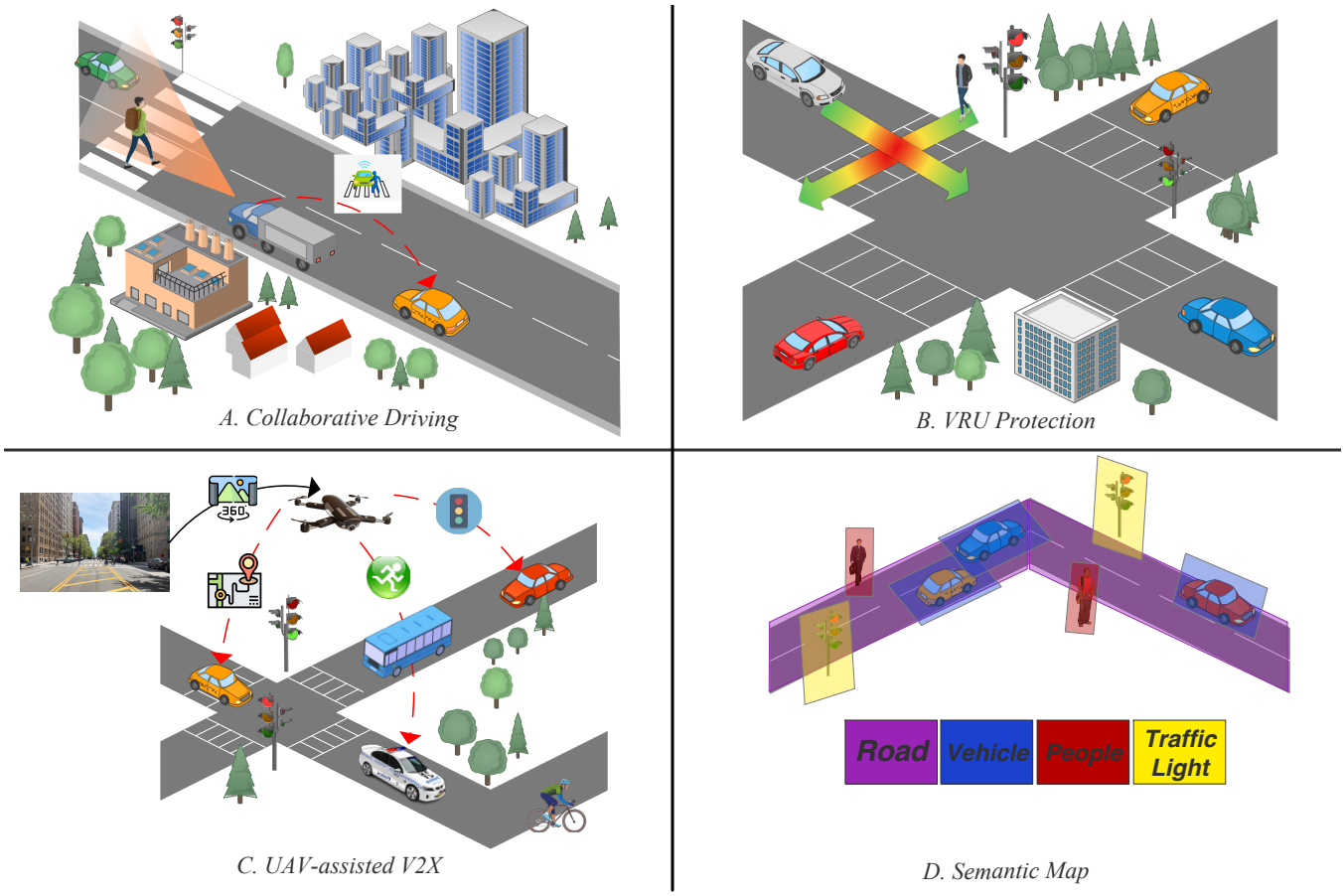


Fig. 4: V2X communication use cases demonstrates the applications of SEM- COM in Intelligent Transport System.

Traditional V2X Approach: Traditionally, UAVs closest to the vehicle transmit these pictures or real-time videos directly to the vehicle, providing an aerial view of the surroundings.

SEM-COM Solution: In the SEM-COM approach, the UAVs would process these images or videos to extract meaningful contextual information. They would then send tailored semantic messages to the vehicle based on its specific context and requirements. This could include highlighting potential hazards, traffic conditions, or environmental changes that are relevant to the vehicle's journey. Furthermore, it is customized to send different relevant information to vehicles with different goals.

Comparison: Traditional methods provide a direct but potentially bandwidth-prohibitive stream of visual data, which the vehicle must then process. SEM-COM, on the other hand, offers a more efficient and focused approach by pre-processing this data into meaningful and actionable insights. This not only reduces the data processing load on the vehicle but also ensures that the vehicle receives the most relevant information in a timely manner, enhancing decision-making and situational awareness.

D. Semantic Map

Scenario: When a vehicle enters an unfamiliar road section, prompting a need to acquire a map to navigate the area securely and efficiently.

Traditional V2X Approach: Conventionally, vehicles would request high-precision maps from the cloud or roadside units to gain detailed information about the current road section's layout.

SEM-COM Solution: The SEM-COM approach leverages cooperative efforts with other vehicles and roadside units, such as cameras, to construct semantic maps that encapsulate es-

sential navigational data, optimizing travel through unfamiliar road sections.

Comparison: The SEM-COM methodology offers a bandwidth-efficient solution that dynamically updates semantic maps through real-time collaboration and information fusion. This enables vehicles to react promptly to real-time road conditions, ensuring safer and more informed navigation, particularly in areas where traditional mapping data may be insufficient or outdated.

V. Challenges and Open Research Challenges

A. Background Knowledge

Background knowledge is indispensable for accurately interpreting and transmitting context-rich information in vehicular environments. This knowledge base is primarily constructed through advanced artificial intelligence techniques bolstered by extensive datasets that inform and refine the training process [18]. Addressing the gap in semantic entropy akin to Shannon's concept of information entropy, yet without a validated formula for semantic entropy, is crucial for enhancing the predictability and optimization of vehicular communication systems. A direct correlation exists between the training model's expansiveness and the SEM-COM system's accuracy, necessitating larger models for more precise outcomes. However, integrating these sophisticated models into vehicle systems poses a challenge, especially in maintaining system responsiveness and computational efficiency. Furthermore, the dynamic nature of vehicular environments demands that SEM-COM systems exhibit a high degree of adaptability and be capable of contextual understanding and real-time communication adjustments in response to diverse environmental factors. Future research will aim to develop more sophisticated AI models that can dynamically adapt to the ever-changing contexts of vehicular environments while maintaining computational efficiency.

B. Edge-based Computing

Edge-based computing is pivotal for SEM-COM V2X communications, offering reduced latency and localized data processing critical for real-time vehicular decision-making [19]. The implementation of edge computing in SEM-COM involves a seamless integration of vehicular networks with edge nodes, which must be robust and ubiquitous to ensure consistent performance. However, this integration introduces complexities in network architecture, requiring sophisticated coordination between vehicles and edge nodes. A significant challenge lies in balancing computational load distribution and maintaining rapid communication channels [18]. Moreover, vehicles' dynamic and mobile nature necessitates an edge computing infrastructure that can adapt to varying densities and speeds, ensuring uninterrupted and efficient communication flow. Further research is directed towards creating more resilient and adaptable network architectures. These should ensure uninterrupted communication and consistent performance across devices and conditions in vehicular networks.

C. Resource Management

Effective resource management is crucial in SEM-COM V2X communications, ensuring optimal utilization of computational and communication resources in vehicular networks [20]. This involves strategically allocating bandwidth and processing power, which is challenging given the fluctuating demands in a vehicular environment [21]. Prioritizing data transmission based on urgency and relevance, particularly in SEM-COM, is a complex task requiring advanced algorithms. The challenge is further compounded by the need to balance resource distribution among a large number of vehicles and infrastructure elements. Additionally, ensuring energy efficiency in resource management while maintaining high performance is essential, especially in electric and hybrid vehicles where energy consumption impacts overall efficiency. Future investigations will center on devising advanced algorithms for real-time, adaptive resource allocation, ensuring optimal bandwidth and processing power distribution in the highly variable vehicular network environment.

D. Security and Privacy

In SEM-COM V2X communications, balancing enhanced semantic performance and robust security and privacy measures presents a significant challenge. Enhanced semantic capabilities often require the processing and transmitting of detailed and context-rich information, which can inadvertently expose sensitive data, raising privacy concerns [18], [22]. Conversely, stringent security protocols may impede the fluidity and richness of semantic communication, potentially diminishing its effectiveness. Developing SEM-COM systems that maintain high semantic performance while ensuring data security and user privacy is a complex endeavor, necessitating innovative approaches to encryption, data handling, and user consent mechanisms. This delicate balance is pivotal in fostering user trust and broad acceptance of SEM-COM V2X technologies. Future studies will explore innovative encryption methods and data handling protocols that enhance security and privacy in SEM-COM V2X communications without compromising semantic performance.

E. Standardization

Establishing comprehensive standards and protocols is paramount for ensuring interoperability among diverse systems and devices within the SEM-COM V2X ecosystem. The seamless integration and functioning of various components in this ecosystem hinge on universally accepted guidelines that facilitate communication and data exchange. However, the development of such standards for SEM-COM V2X is challenged by the evolving nature of semantic communication technologies and the need to accommodate a wide range of vehicular and infrastructural systems. Crafting these standards requires a concerted effort among industry stakeholders, regulatory bodies, and technology developers to create a unified framework that supports the diverse functionalities of SEM-COM V2X while fostering innovation and technological advancement. The absence of such standardization could lead

to fragmentation and inefficiencies, impeding the widespread adoption and effectiveness of SEM-COM V2X communications. The forthcoming research effort will be directed toward developing unified standards and protocols that accommodate the evolving nature of SEM-COM technologies, ensuring interoperability and efficiency across diverse vehicular and infrastructural systems.

VI. Conclusion

SEM-COM is poised to be a formative technology in the growth of 6G networks and can address the bandwidth challenges posed by emerging vehicular applications. This article has outlined SEM-COM's key components, performance metrics, and network-layered architecture in the context of vehicular networks. Through real-world use cases, we have demonstrated SEM-COM's practical applications, showcasing significant advancements in intelligent mobility. Finally, we have pinpointed open research questions that signal a promising direction for future exploration, underlining SEM-COM's critical role in evolving intelligent and interconnected vehicular communications.

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