C-V2X Resource Deployment Architecture Based on Moving Network Convoys

Venkatnarayanan Lakshminarasimhan*, Alois Knoll†
Chair of Robotics, Artificial Intelligence and Real-time Systems
Department of Informatics, Technical University of Munich
Munich, Germany
Email: *venkat.lakshmi@tum.de, †knoll@in.tum.de

***Abstract*—A reliable and all-pervading information-sharing mechanism between traffic participants and infrastructure systems, widely termed V2X communication, is crucial to realize the goals of future cooperative intelligent transportation systems - that of improving traffic safety and efficiency. The need to maintain high reliability and availability amidst a permanently-changing network topology caused by the moving vehicles translate into an increased demand for network management infrastructure and radio resources. Such capital-intensive demands can act as significant deterrents in the quest for a rapid large-scale deployment of V2X technologies. With the goal to reduce the demand for fixed infrastructure and radio resources, we propose an alternate network deployment architecture based on the concept of moving network convoys, deploy it in a distributed C-ITS simulation environment, and provide a quantitative assessment of the potential benefits in comparison to conventional network deployment architectures.**

***Index Terms*—C-V2X, C-ITS, Resource Allocation, Spatial Reuse, Moving Cells, Network Zones**

I. Introduction

Cooperative Intelligent Transportation Systems (C-ITS), within the context of road transportation, deals with the deployment of interconnected applications and services among traffic participants, and related roadside infrastructure with the goal of enhancing traffic safety and efficiency. Such a C-ITS is realized by implementing applications in a distributed manner amidst the vehicles and the stationary infrastructure, and by establishing an information-sharing mechanism between them, so as to enable interaction and cooperation. A secure and reliable information-sharing mechanism, widely known as V2X communication, is therefore a crucial requirement for the distributed ITS applications to fulfill their purposes in a secure and reliable manner.

A. Conventional C-V2X Deployment Architecture

Scheduled cellular communication networks - LTE, 5G NR and their extensions, with their inherent capabilities to provide service quality assurances, have received wide attention from V2X researchers, and are expected to cater to the next generation ITS application demands [1] [2]. V2X communication links in such cellular networks, hereafter referred to as C-V2X, are established by selecting portions of the sub-carrier time-frequency slots from the available carrier bandwidth, also called radio resources or resource blocks, and by allocating them to the sender nodes ready with information to be transmitted to the receiver nodes. A conventional C-V2X deployment architecture in an ITS environment is illustrated in figure 1, where in a base station establishes a static cell and manages the allocation of network resources between the participating V2X-nodes - vehicles and stationary road side infrastructure, thereby establishing the communication links for the transfer of information.

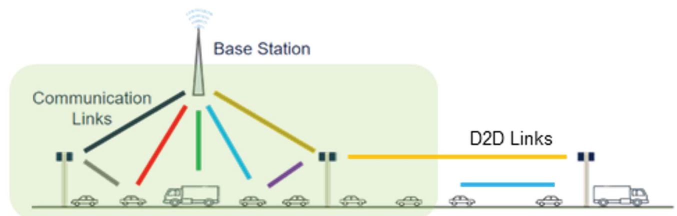

Fig. 1: Conventional C-V2X resource deployment architecture showing the allocation of communication links and transmission resources for the participating nodes.

B. Resource Demand and its Implications

The demand for V2X radio resources is governed on the one side by the C-ITS application requirements, and on the other side by the technological limits in serving these requirements using the available C-V2X radio resources. Considering the wide range of C-ITS applications envisaged for the future [4] - ranging from basic information dissemination to full fledged cooperative automation, the emerging concurrent need for higher data rates, lower latencies, stricter service guarantees and increased penetration of V2X technology calls for an increased deployment of radio resources and corresponding network management infrastructure. V2X for C-ITS also finds itself competing for radio resources with a wider range of data-intensive application domains. Further, the costs involved in acquiring radio resources and setting up the cellular communication infrastructure have also been shown to influence the availability of seamless communication services through extensive cell coverage, and the pace at which such infrastructure get deployed [5]. An efficient utilization of V2X radio resources can therefore play an important part in accelerating and widening the adoption of V2X technologies, and for this reason becomes the focus of our work in this paper.

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Contributions - Towards the goals stated above, the authors propose a new resource deployment architecture by exploiting the spatial proximity of sender and receiver nodes, and by utilizing positional information made available by C-ITS infrastructure. Furthermore, the authors evaluate the potential benefits offered by their scheme, present quantitative results for various situations based on implementations in a simulation environment, and point out the opportunities and challenges involved in deploying such a scheme.

Paper organization - The upcoming sections in this paper are structured in the following manner. The C-ITS system and the related V2X applications are first introduced in section II. Section III addresses the existing resource deployment architectures and points out the scope for improvements. The proposed moving network convoy scheme along with related literature is described in section IV, and assessed for its benefits and challenges in section V. The contributions in this paper and the potential future work are summarized and concluded in section VI.

II. Providentia C-ITS

This section describes the specific C-ITS applications, for which the resource deployment investigations are carried out.

A. Application Description

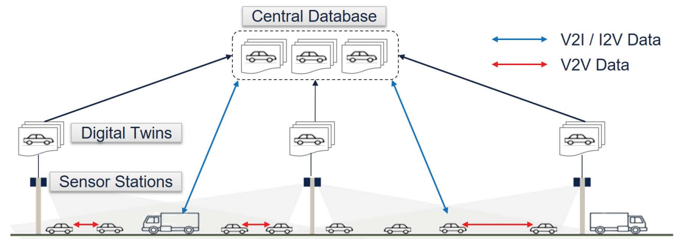
The Providentia C-ITS [6] [7] aims to enhance road-safety and comfort by providing conventional and autonomous vehicles with reliable and real time information about traffic objects over an extended geographical region, far beyond the limited immediate neighbourhood covered by the on-board vehicular sensors. This is achieved by equipping the highway with sensor stations and interlinking them along with traffic objects over a reliable C-V2X communication network. While the stationary sensors in combination with the on-board sensors generate the positional information for the traffic objects, the vehicles in turn utilize this information - referred to henceforth as the digital twin - for a variety of applications including improved trajectory planning and cooperative maneuvering.

Figure 2 illustrates the Providentia C-ITS in two possible variants depending on the manner in which the digital twin information is hosted. While the centralized option calls for a bundling of information into a single database, the distributed option allows for the digital twin information generated at the sensors stations to be locally hosted. While a central database provides the advantage of being a single repository of information capable of resolving data duplication in adjacent sensor stations with overlapping detection zones, the distributed option offers a realistically scalable solution. For this reason the resource deployment investigations in this paper are conducted considering the distributed digital twin scenario.

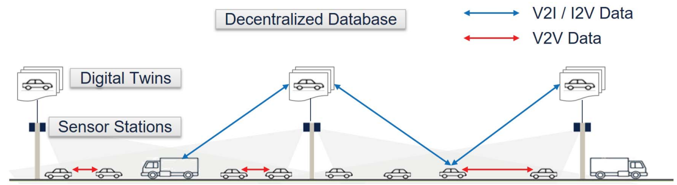
B. V2X Communication Links and Traffic Characteristics

The Providentia C-ITS V2X communication network serves two classes of applications. The first - a digital twin application involving the creation and distribution of real time information about the traffic objects present in the extended vicinity, and second - a cooperative maneuvering application involving trajectory planning and driving maneuver control between vehicles in the immediate vicinity based on mutual exchange of information. Vehicles identify their potential partner candidates for cooperative maneuvering based on the digital twin information received from the Providentia C-ITS infrastructure. As shown in figure 3, the two applications call for the following communication links.

The Vehicle-to-Infrastructure (V2I) link involves the transmission of information about traffic objects detected by the vehicles equipped with on-board sensors. The vehicular sensors are expected to detect objects present within a certain radius. The information is transferred to the next immediate sensor stations that are present ahead and behind the current vehicle. The payload length varies with the number of objects being detected and is transmitted periodically. The V2I link also enables periodic digital twin subscription requests from the vehicles to the sensor stations.

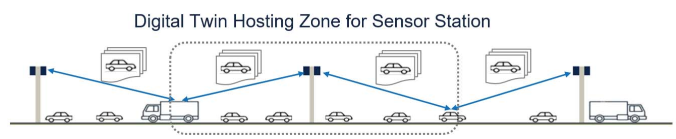


(a) Centralized Digital Twin

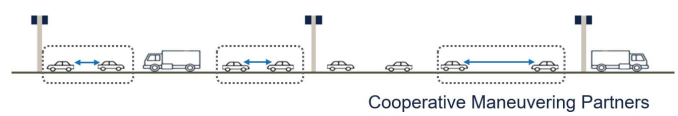


(b) Decentralized Digital Twin

Fig. 2: Providentia C-ITS concept showing the creation of real-time digital twin of the traffic using fixed sensor stations and their distribution to the vehicles from either centralized or decentralized data stores.



(a) V2I and I2V communication links

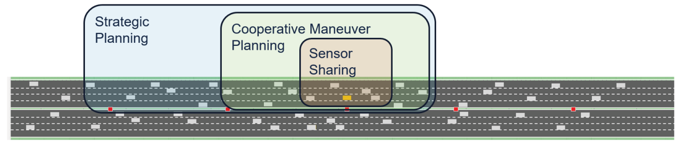


(b) V2V communication link

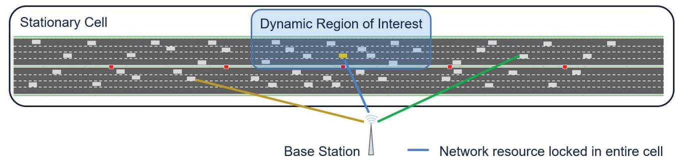
Fig. 3: Various communication links required for the distributed digital twin and cooperative maneuvering applications.

The Infrastructure-to-Vehicle (I2V) link involves the transmission of the digital twin information by the sensor stations to the subscribing traffic objects. Each sensor station hosts the digital twin information for all the traffic objects which are within its allocated hosting boundary. The digital twin information payload can also be variable in length depending on the number of objects present within the sensor station's hosting region, and is transmitted to the subscribing nodes periodically.

Upon receipt of the digital twin information, individual traffic nodes form Vehicle-to-Vehicle (V2V) links with the next immediate partners within a certain proximity range and exchange information necessary for cooperative maneuvering. The V2V payload is fixed in size and is also exchanged periodically as long as the proximity conditions are met. All the three links use UDP/IP based unicast addressing and transport mechanisms.



(a) Spatial relevance for various cooperative V2X applications



(b) Stationary cell serving mobile nodes and regions of data demand

Fig. 4: Demand for V2X data being largely limited spatially around the receiver nodes, stationary cells limit the possibility of resource reuse within the cell and increase handover efforts.

III. State of the Art and Scope for Improvements

This section describes the current state of the art C-V2X deployment architectures and points out the scope for improvements when applied to the Providentia C-ITS system described in the previous section.

The current state of art C-V2X deployment architecture [1], [3] is characterized by the following features

- Message transport support for the various V2X communication links
- Message routing through the network link over the base station or through the Device-to-Device (D2D) side link
- Transmission resource allocation by the base station for communication over the network link or over the side link in mode 3 operation
- Autonomous resource selection by the transmitting nodes for communication over the side link in mode 4 operation

One of the unresolved challenges with the current deployment architecture is the dependence on network management infrastructure in the form of base stations to coordinate and allocate network resources to the transmitting nodes. While the nodes may select their transmission resources independent of the base stations in mode 4 operation, the risk of transmission collisions nevertheless exist and become more pronounced as the nodes travel longer in an out-of-coverage zone and when the transmitted packet sizes do not remain constant, as shown by Molina-Masegosa and Gozalvez in [8].

A second aspect with potential scope for improvement is that of resource reuse through better exploitation of V2X data traffic characteristics - that of spatial relevance in particular. As shown in figure 4, most ITS applications depend on transport of V2X data within a localized region of relevance around the sender and receiver nodes. While some real time C-ITS applications may for example require accurate environment information within a few hundred metres, cooperative inter-vehicular applications like sensor sharing or maneuver exchanges may have a much lower region of relevance around the receiver nodes. With all the nodes being highly mobile, this spatial region of interest also remains closely coupled with the nodes and thereby are themselves non-stationary. A conventional C-V2X network enabled by static base stations in this scenario would imply serving a mobile region of data generators and consumers from stationary cells, thereby leading to the following effects.

- Locked radio resource blocks over the entire stationary cell even if the spatial region of interest is much smaller than the cell, in order to avoid interference.
- Permanent reconfiguration and handover of nodes from one stationary cell to the other, and the associated traffic duplication required at the cell edges during handover.

To compensate for these limitations while continuing to deploy the same architecture would require increasing either the base station infrastructure or the amount of radio resources for communication, thereby resulting in increased cost of C-V2X deployment.

IV. Proposed Improvements to the Deployment Architecture and Related Work

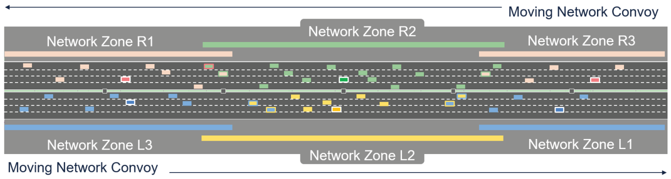
This section proposes an alternate resource deployment architecture - the Moving Network Convoy - to address the limitations explained in the earlier section and briefly discusses the related work.

A. *The Moving Network Convoy Architecture*

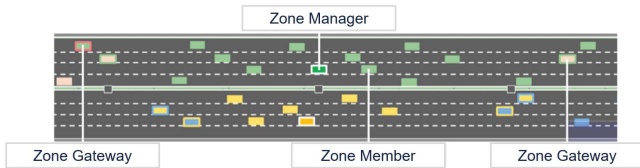
The salient features of the proposed scheme, an illustration of which is presented in figure 5 are as follows.

- Smaller network zones to aid in increased resource reuse
- Network zone mobility to reduce node reconfiguration and handover actions
- Elastic zone boundaries allowing node entries and exits
- Dynamic selection of cell master nodes and gateway nodes for inter-zone communication
- Coordinated spatial reuse of network resources along the network convoy

The moving network convoy consists of a limited number of distinct network zones each allocated with its own distinct



(a) The overall scheme for convoy formation



(b) Network zone membership and management

Fig. 5: Moving network convoy deployment and membership. Network zones, allocated with unique resources, are associated with the zone managers and interconnected through gateways.

resource pool set. An example can be seen in figure 5 wherein two convoys are setup - one for each driving direction. Each convoy is formed by deploying two distinct network zones in an alternating manner along the length of the highway - network zones L1 and L2 in one direction, R1 and R2 in the other direction. The nodes are allocated radio resources corresponding to the network zone within which they are present. While the use of distinct radio resources between adjacent network zones removes the need for managing interference, their redeployment down the line increases their effective utilization.

Each of the traffic nodes can take up one of three different roles as a member of any particular network zone - zone manager, zone member and zone gateway. The zone manager has the task of allocating resources within the zone, managing the zone boundaries and the inter-zonal data traffic. The zone gateways act as interconnecting units for data transfer beyond the immediate zone. Zone members are not assigned network management responsibility.

B. Convoy Zone Formation and Membership Allocation

Considering the dynamic nature of network topology and varying data demands for such mobile scenarios, the mechanisms for the establishment of the zone boundaries and the allocation of roles to the traffic nodes can themselves pose challenging optimization problems requiring detailed studies and are beyond the scope of this paper. A simplified mechanism with the following characteristics has been chosen for the assessments in this paper.

- Zone managers are chosen in each of the driving directions from the slowest lane, and do not change their role for the complete stretch.
- Vehicles upon entry into the test field first configure themselves as members of the network zone immediately ahead and start receiving the digital twin information for a certain initial time period.
- Upon expiry of this window, the first vehicle from the slowest lane configures itself as the next zone manager if it is at least a certain distance away from the zone manager ahead.
- Zonal members moving at different speeds reconfigure their membership based on the nearest zonal managers available.
- Vehicles equipped with multiple user-equipments (UE devices) which are at the edge of the network zones act as gateways for multi-zone data traffic.

C. Related Work

The problem of spatial reuse of radio spectrum has received wide attention from network researchers, mostly from the domains of stationary personal devices and commercial cellular communication involving non-critical data transfer, and increasingly from the more demanding V2X domains. This section briefly describes the most relevant work from recent literature.

Campolo et al [9] propose an LTE-based D2D communication strategy to realize vehicle platooning, in which network access and spatial reuse are coordinated by the base station. An in-band underlay mode of communication allocates the same radio resources for both cellular and D2D communication. Low power transmissions between adjacent members of a platoon enable spatial reuse beyond the immediate platoon. Evaluations considering a TDD mode of transmission over a limited channel bandwidth of 5MHz, with up to 300 bytes of data for platoon communication, indicate that it would be possible to use the same network resources in another platoon, which is at least 20m apart, without the risk of interference. The authors also demonstrate that spatial reuse reduces message latencies significantly, in the case of a limited channel bandwidth of 5MHz. Spatial reuse and latency performances look promising, however the scheme still involves the presence of base station infrastructure, and the mechanisms and performance expectations for a scaled up solution are unclear.

Moving cells as an option for mobile vehicular users has been investigated by Sui et al [10] and Shin et al [11], wherein moving relay nodes serve on-board users, for example within a moving bus, by forming local moving cells and a backhaul link to the external base station. The authors report performance improvements primarily on the account of the relay node solving the problem of higher signal attenuation within moving vehicles. While being applicable for Vehicle-to-Network (V2N) traffic in environments like buses and trains, the condition that the end users within the moving cell need to be relatively stationary makes the approach less suitable for V2I and V2V communication.

In summary, while spatial reuse and moving cells have received isolated attention from researchers for certain application groups, a generic architecture for V2X in C-ITS, and a quantitative assessment of benefits and challenges have however, to the knowledge of the authors, not yet been addressed. This paper attempts to address this gap.

V. Implementation and Evaluation

This section describes the implementation of the V2X applications and the resource deployment architectures in a simulation environment and presents comparative results for the various deployment architectures.

A. Simulation Setup

The evaluations are carried out with the help of the VeinsLTE simulator [12] integrated with the SimuLTE framework [13] for the cellular network simulation. The traffic scenario involves a stretch of 5km representing the Providentia C-ITS test-field [6] on the German A9 highway. The highways are equipped with sensor stations placed every 300m. Traffic throughput has been set based on measurements made through the Providentia C-ITS and using statistics made available by the German Federal Highway Research Institute [14].

B. Evaluation Scenarios

The simulation runs have been executed for three different evaluation scenarios. The first scenario involves a large stationary cell architecture, and forms the baseline for comparison. The length of the highway is covered by multiple cells with 5 base stations placed parallel to the highway at an approximate distance of 200m from the edge of the highway. The sensor stations are equipped with UE devices and are statically associated to the nearest base stations. The vehicles, also equipped with UE devices, enter the test field with an initial association to the next immediate base station, but dynamically change their association through a handover procedure as they move ahead.

The second scenario implements small stationary convoys of network zones as an intermediate possibility between the conventional large stationary cell and the moving convoy. The coordination of the zones is handled by the stationary sensor stations. The available network resources are divided into three unique sets which are then allocated in an alternating 1-2-3-1 manner to the successive network zones formed by the sensor stations. The vehicles enter the test field with an initial association to the nearest sensor station and dynamically change their association similar to the previous scenario.

The final scenario involves the moving network convoy architecture explained in section IV. The parameters used in the simulation runs are summarized in table I.

C. Results and Discussions

The three scenarios are evaluated by comparing the number of unique resource blocks deployed over the 100ms message interval time for a total test duration of 5s. Histograms of this metric are shown in figure 6 for different penetration rates for cooperative vehicles (CV).

The results for a low CV rate of 20% show that the stationary architectures demand at least up to 8% lower resources than a moving architecture. This can be attributed to the dominance of V2I traffic to and from stationary nodes in comparison to the V2V traffic. Furthermore the stationary network convoy also uses up to 18% lower resources than the large static cells which can be attributed to the localized demand for V2I data between sensor stations and vehicles in the vicinity.

As the density of cooperative vehicles increases it can be seen that the resource demands made by the moving network convoy are progressively lower in comparison to the stationary architectures. The shift can be attributed to the increasing levels of V2V traffic in comparison to the V2I traffic. For CV rates of 80% the moving network convoy uses up to around 10% lower resources. The improved performance is

TABLE I: Simulation parameters and network convoy setup

Parameter	Value
Traffic throughput	4700 vehicles per hour
Cooperative vehicles (CV)	20%, 50% and 80% penetration rates
Sensor station field of view	300m in each direction
Digital twin subscription from	Sensor station ahead and behind
Digital twin message size	20 bytes per traffic object
Digital twin message periodicity	100 ms
Vehicular sensors field of view	50m in each direction
V2V cooperative maneuvering	Partners with 100m radius
V2V message size	100 bytes
V2V message periodicity	100 ms
Message addressing mechanism	Unicast
LTE carrier frequency	2.4 GHz
Operational mode	Network link FDD mode
Channel model	Rural Macro Model
Bandwidth and resource blocks	20 MHz, 100 resource blocks
Scheduling policy	Maximum carrier over interference
Resource allocation	60% Uplink (UL), 40% Downlink (DL)
Stationary network convoy	3 zones, equal bandwidth distribution
Moving network convoy	4 zones, equal bandwidth distribution
Zone manager selection	Candidate from slowest lane
Network zone spacing	Min. 300m at test field entry

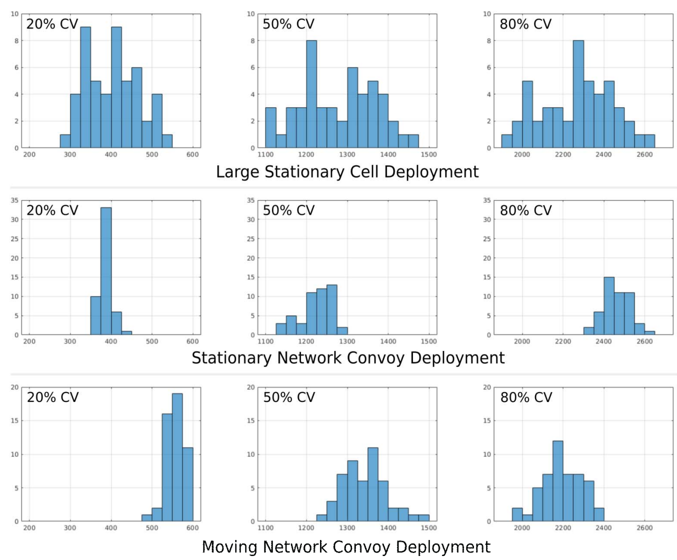


Fig. 6: Histogram of the number of unique resource blocks deployed over the 100ms message interval time for a total test duration of 5s. The proposed moving network convoy architecture becomes more suitable as the density of cooperative vehicles with V2V traffic increases.

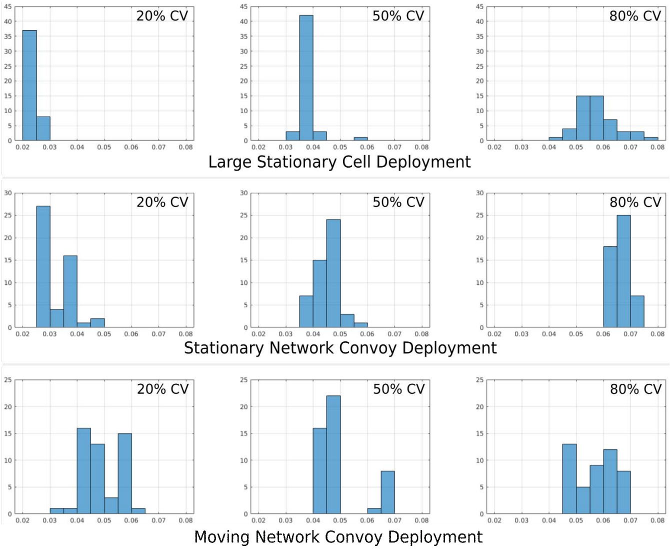


Fig. 7: Histogram of the maximum V2V transfer delay observed over the 100ms message interval time for a total test duration of 5s. The moving network convoy again ensures lower maximum delays as the density of cooperative vehicles with V2V traffic increases.

also reflected with lower maximum message transfer delays for V2V traffic, as shown in figure 7.

The lower resource demands shown above for the network convoys in comparison to the large static cells are conservative estimates. A further reduction can be expected if factors such as loss of resource blocks due to inter-cell overlap, multicast geo-addressing and improved situation-adaptive network convoy formation algorithms are incorporated.

D. Challenges and Future Work

Apart from the opportunities for better resource reuse, the network convoy based architecture also brings with it certain dependencies and challenges requiring further investigation. Primary among the dependencies is that of positional information being made available as part of a C-ITS. However, since reliable environmental models form a critical prerequirement for cooperative autonomous driving, it would be reasonable to expect availability of such information either from the cooperative vehicles or from sensor stations. Among the primary challenges introduced is that of increased computational needs within cooperative autonomous vehicles. The extent to which available resources can be made available for network management requires to be investigated in detail. Another aspect restricting the selection of zone managers would be that of channel conditions and power consumption limitations. Finally, the challenge of selecting zone managers and establishing zone boundaries in an optimal manner by using minimal computational resources and signalling information deserves attention as part of future work.

VI. Conclusion

An alternate resource deployment architecture for C-V2X communication based on moving network convoys has been proposed with the goal of reducing the demand for radio resources and network management infrastructure. The authors have demonstrated the potential for saving resources with their approach through simulation runs, pointed out viable situations for implementation, and summarized the challenges to be resolved in order to make the network convoy based deployment approach a full-fledged alternative for V2X communication.

Acknowledgement

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