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Cooperative Vehicular Networking: A Survey

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Abstract

With the remarkable progress of cooperative communication technology in recent years, its transformation to vehicular networking is gaining momentum. Such a transformation has brought a new research challenge in facing the realization of cooperative vehicular networking (CVN). This paper presents a comprehensive survey of recent advances in the field of CVN. We cover important aspects of CVN research, including physical, medium access control, and routing protocols, as well as link scheduling and security. We also classify these research efforts in a taxonomy of cooperative vehicular networks. A set of key requirements for realizing the vision of cooperative vehicular networks is then identified and discussed. We also discuss open research challenges in enabling CVN. Lastly, the paper concludes by highlighting key points of research and future directions in the domain of CVN.

Index Terms

Vehicular ad-hoc network; vehicular communication; cooperative networking; cooperative vehicular networks

I. Introduction

With the convergence of computers, vehicular infrastructure, communication, and automobiles technologies, research in the area of vehicular networks has reached new horizons in its development. These remarkable advancements have enabled researchers and engineers to predict the future of driverless cars that will be based not only on in-car sensors, but also on communication between vehicles. The experts at the Institute of Electrical and Electronic Engineers (IEEE) predict that autonomous cars will comprise 75% of total traffic on the road by the year 2040.[1] The emergence of such vehicles and their networks will impose new requirements for applications and services, such as safety messaging [1], traffic monitoring [2], lane changing [3], and intersection management [4]. Some of the important challenges facing vehicular networking are due to the high-mobility nature of vehicular commutations, randomness in channel dynamics, and link interferences. In this context, researchers have shown interest in employing cooperative communications within vehicular

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[1] http://www.ieee.org/about/news/2012/5september_2_2012.html

networks to alleviate the impact of these challenges and improve reliability by enabling nodes to cooperate with each other.

In cooperative networking, neighboring nodes can cooperate with each other by transmitting the overheard messages to achieve better communication. This paradigm of communications where other vehicles are involved in helping transmission is referred to as cooperative vehicular networking (CVN). Indeed, over the past few decades, researchers have extensively investigated the potential of cooperative communication in designing protocols that involve the physical (PHY), medium access control (MAC) and network layers. For example, PHY protocols employ different strategies for cooperation, such as amplify-and-forward [5], compress-and-forward [6], store-and-forward [7], and decode-and-forward [8]. The cooperation at the PHY layer imposes complex and manual requirements for operators and end-users [9]. This sparks a need to design intelligent cooperation functionality at the MAC layer to enable nodes to automatically manage the physical layer cooperation [10]. For instance, when a relay node is required to assist communication between transmitter and receiver, an exchange of extra control messages may be required for relay selection at the MAC layer [11]–[13]. In addition, routing protocols can further benefit from cooperation between the MAC and PHY layers in selecting a suitable path from source to destination [14]–[16]. Also, a great deal of research has been carried out with respect to power allocation [17], [18], link scheduling [19]–[22], and security [23]–[25]. These cooperative strategies highlight a few examples of the wide ranging research activities covering routing protocols, MAC protocols, traffic management, beaconing protocols, and mobility models, which are built upon a few decades of research progress in the general area of vehicular communications and cooperative networking.

While this is first survey paper of its kind that primarily focuses on the cooperativeness in vehicular networks, there do exist a number of survey papers that cover cooperative networking [10], [26]–[28] or vehicular communication [29]–[40] in general. Figure 1 shows the related surveys classification and highlights the research gaps with respect to this survey. In addition, there are other survey papers that are mainly concerned with the physical layer aspects of cooperative communications. Interested readers are referred to [9] and [41]–[46] where physical layer cooperative communications are reviewed in detail. Considering the theme of our survey paper, we have selected a set of research articles, which address issues specific to cooperation among nodes in vehicular networks.

The remainder of the survey is organized into six sections. Section II briefly discusses vehicular networks, cooperative communication in traditional wireless networks, and the concept of CVN. Section III presents recent advances in cooperative vehicular networks; and section further investigates the similarities and differences in recent research works in the domain of CVN. A taxonomy of cooperative vehicular networks is derived from the literature and presented in Section IV. Section V discusses the key requirements that should be fulfilled to enable CVN. Section VI highlights the open research challenges in realizing the vision of CVN. Section VII concludes the paper.

II. Background

This section first provides an introduction to vehicular networks and cooperative communication before describing various aspects of cooperative vehicular networking. For ease of reading, we list commonly used acronyms in Table I.

A. Vehicular Networks

Vehicular networks have emerged as a result of advancements in wireless technologies, ad-hoc networking, and the automobile industry. These networks are formed among moving vehicles, road side units (RSUs), and pedestrians that carry communication devices. Vehicular networks can be deployed in rural, urban, and highway environments. There are three main scenarios for vehicular communication: vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P) [47]. The commonly used technologies are dedicated short-range communications (DSRC) [48]/IEEE 802.11p [49], IEEE 1609 family of standards [50], and Long Term Evolution (LTE) [51]. Some of the key technologies that shape the modern automobile industry and vehicular networks are described in [52] and [53] respectively.

With the advancements in communication technologies, a number of promising applications are emerging for vehicular networks. These are mainly related to infotainment, active road safety, and traffic management. These applications impose different service requirements in terms of latency, throughput, and reliability on the network.

B. Cooperative Communication

Cooperative communication is an emerging technology that is capable of enabling efficient spectrum use by exploiting the wireless broadcast advantage of overhearing the signal transmitted from a source to a destination. According to the definition presented in [54] “cooperative communication refers to the processing of over-heard information at the surrounding nodes and retransmission towards the destination to create spatial diversity.” More precisely, cooperative communication can assist in achieving a higher spatial diversity [55], lower transmission delay [56], higher throughput [57], adaptability to network conditions [58], and reduced interference [59]. Considering these features, cooperative communication technology can play an important role in improving the overall performance of vehicular networks.

C. Cooperative Vehicular Networking (CVN)

Similar to other wireless networks, cooperative communication in vehicular networks has also been leveraged to offer various improvements; namely, spectral efficiency, increased transmission reliability, and reduced transmission delay [60], [61]. CVN enables neighboring vehicles to cooperate with each other by sharing information at different layers of the network so that it has multiple transmission alternatives for robust communication. Vehicles can cooperate with each other either directly or through a roadside infrastructure. Usually, the vehicular node which helps the sender node to transmit its data is called a helper node or relay node.

Please note that, for the sake of consistency, we use the term "relay node" instead of "helper node" throughout this paper. The relay node can operate in different transmission modes such as amplify-and-forward, decode-and-forward, compress-and-forward, and store-carry-and-forward. A summary of various strategies for cooperative communication in vehicular networks is presented in [62].

Figure 2 shows a simple illustration of CVN where cooperation is performed in different ways. For example, a vehicle can provide assistance to other vehicles with failed direct transmissions, as illustrated in Figure 2a. Similarly, a vehicle can assist a RSU in relaying its packets to other vehicles, which are out of the RSU transmission range (Figure 2b). Figure 2c shows a scenario where both RSU and vehicle node, are involved in relaying failed packet transmission. For instance, when a source RSU fails to successfully transmit a packet to the targeted destination, it forwards the failed packet to the next RSU along the path using the backhaul wired connection. The new RSU relays the received packet to a vehicle, moving towards the targeted destination, that carries and transmits the relayed packet when it is in transmission range of the targeted destination.

III. Recent Advances in CVN

Much of the recent innovation that spawned today's CVN research progress can be classified into eight main categories: physical layer cooperation, MAC protocols, routing/forwarding mechanisms, link scheduling, performance analysis, power/resource allocation, cooperative group communication, and secure cooperative communication. Tables II and III present a comparative summary of studied literature.

A. Physical Layer Cooperation in CVN

In wireless networks, exploiting spatial diversity is one of the mechanisms for enhancing the reliability of a message by transmitting it through two or more different communication channels. Spatial diversity is achieved by using multiple antennas of both transmitter and receiver. Conventional MIMO systems are an example of achieving the spatial diversity using multiple antennas [63]. In some cases, it is infeasible or costly to achieve spatial diversity by employing multiple antennas. In such scenarios, spatial diversity is achieved by enabling cooperation among multiple nodes to obtain similar benefits as achieved by conventional MIMO systems. Such spatial diversity is called cooperative diversity.

Figure 3 provides an illustration of cooperative diversity. One example of cooperative diversity is a cooperative MIMO (also known as distributed [65] or virtual MIMO [66]). The performance of cooperative vehicular relaying is analyzed by Feteiha and Hassanein [67] in LTE-Advanced MIMO downlink channels for coded transmission. The data transmission considered in the analysis is involved into two main phases: broadcasting phase and relaying phase. Each phase is further divided into two levels. During first level of broadcasting phase, source node sends two precoded blocks from two different antennas. Another version of precoded blocks is transmitted during the second level of broadcasting phase from previously used antennas. Similarly, the relaying phase is also divided into levels. In each level, the relay first amplifies the received signal and then transmits the resultant signal to the destination. To investigate the achievable diversity gain in these phases pairwise error probability expressions are derived. The investigation reveals that the significant diversity gain is achieved through MIMO deployment and encoded transmission. In another work, Nguyen *et al.* [68] proposed cooperative strategies to enable the energy-efficient transmission in I2V and I2I communication scenarios. These cooperative strategies rely on cooperative relay, multihop, and cooperative MIMO techniques. The cooperative relay and cooperative MIMO techniques are more energy efficient than the multihop techniques. Further, for a given transmission distance, an optimal cooperative MIMO scheme selection is proposed to select the optimal antenna configurations.

B. MAC Protocols for CVN

Similar to traditional wireless networks, the design of the MAC layer protocols in vehicular networks is also vital for improving network performance. Generally, MAC layer protocols can be divided into three major categories: contention-free, contention-based, and hybrid. Contention-free MAC approaches utilize Time Division Multiple Access (TDMA) and synchronization, whereas contention-based approaches rely on backoff mechanisms. Hybrid MAC protocols combine the advantages of both contention-free and contention-based MAC protocols. We discuss research works that focus on cooperativeness at MAC layer of CVN.

1) Contention-Free Cooperative MAC Protocols—Contention-free MAC protocols rely on a scheduler to regulate participants by defining which nodes may use the channel and at what time. TDMA is a contention-free channel access mechanism that divides time into multiple slots. These time slots are assigned to vehicular nodes for communication. The number of time slots assigned to a node depends on the data volume. Here, we discuss the contention-free cooperative MAC protocols proposed for vehicular networks.

A cooperative ad-hoc MAC (CAH-MAC) for VANET is proposed by Bharati and Zhuang [69] that is based on distributed TDMA. Cooperation is offered by a relay node only if the following conditions are satisfied: a) the direct transmission fails, b) the relay node receives the packet, c) the destination is reachable from the relay, and d) a time slot is available. If there are multiple potential relay nodes, the one that first announces to relay the packet will become the relay, while the remaining nodes will not participate. Bear in mind that cooperation is performed by a relay node during an unused time slot to relay the packet for which direct transmission failed. Therefore, the cooperation does not affect regular communication. The use of unused time slots for cooperative transmission by the relay ameliorates throughput the VANET. However, CAH-MAC is suitable for a scenario where the relative mobility is negligible; otherwise, the protocol faces slot reservation collision. Even in the case of no collision, relay nodes consume available unreserved time slots for cooperative transmission, which lessens the opportunities of other nodes to find an unreserved time slot. The impact of time slot reservation for cooperative transmission on the performance of the CAH-MAC is investigated by Bharati *et al.* [70]. They observed that reservation of a time slot leads to cooperation collisions that degrade network performance.

To deal with the issue of reservation slot collision, the authors further extend the CAH-MAC protocol and propose an enhanced version, the eCAH-MAC protocol [71]. In eCAH-MAC, a relay node suspends cooperative transmission to avoid reservation slot collisions if any of the one-hop neighbors of the relay node and/or destination node attempts to transmit. The relay node performs cooperative transmission if no possible communication is detected in its one-hop neighborhood and that of the destination. Although the proposed collision avoidance scheme in eCAH-MAC enhances unreserved slot utilization, switching between the sending and receiving mode on both nodes (relay and destination) is required within a time slot that intensifies system complexity.

A cooperative clustering-based MAC (CCB-MAC) protocol is proposed in [72] to improve safety broadcast message reliability in VANETs. In CCB-MAC, cluster formation is mainly involved in the joining process, cluster-head election process, leaving process, and cluster merging process. The entire process of cooperation includes three key tasks; transmission failure identification, appropriate relay selection, and collision avoidance with other potential relays and packet retransmissions. To offer a reliable broadcast service, CCB-MAC introduces an ACK message that cluster members (destination nodes) send back to the cluster head on successful reception of a broadcast message. If the ACK message is not received by the neighboring nodes of a destination, they will consider it an unsuccessful transmission for the destination, and themselves as potential relays. To avoid possible collision, the cluster head assigns a time slot to each potential relay node for transmission. When one relay transmits the failed packet to the destination node, other relay nodes suspend transmission of the packet after overhearing the transmission. Although the proposed MAC enhances the successful reception rate of the safety messages, the exchange of ACK message against each broadcast message puts significant communication overhead on the CCB-MAC protocol and increases the interference. The CCB-MAC also does not consider node mobility which is a critical parameter for vehicular networks. This causes huge overhead as a result of frequent cluster head selection.

The above-mentioned TDMA-MAC protocols require idle slots to offer cooperative communication; however, in the dense VANETs, a sufficient number of idle slots may not be available for cooperation. A vehicular cooperative TDMA-based (VC-TDMA) MAC protocol is proposed by Zhang and Zhu [73], which opportunistically exploits the reserved time slots of a cooperative node to improve throughput. Usually, VANET communication has to rely on multi-hop relays if the distance between the source and destination is larger than a one hop transmission range. However, selection of a relay node is critical because of the vehicles mobility. If the selected relay node has a longer buffer of packets ahead of the packet that needs to be relayed, then the destination may go out of the relay node transmission range, while waiting for transmission. In this case, the authors suggested to use a neighbor of the relay node as a cooperative node to forward the packet if its own buffer is empty. When the relay node receives a packet from the cooperative neighbor, it deletes the packet from its buffer. The cooperative node offers cooperation to a relay only considering its own empty buffer without considering channel conditions. The VC-TDMA MAC may not provide a significant advantage in cooperation with varying channel conditions and node speed.

Although contention-free MAC protocols provide deterministic delay, time synchronization is required for each participant. The time slots are reserved for the nodes and channel can be accessed without any contention. However, the scheme usually suffers from dynamic transmission delay in dense networks and topology changes. Scalability, non-periodic data, and assigning time slots to nodes with diverse data rates are some of the others main concerns in implementing contention-free MAC protocols.

2) Contention-Based Cooperative MAC Protocols—In the case of contention-based cooperative MAC protocols, a node has to contend with other neighboring nodes that are also interested in getting access to the channel for transmission. Carrier-sense multiple access (CSMA) is a contention-based mechanism that is used to access shared medium for transmission. CSMA/CA is an amendment of CSMA that facilitates avoiding packet collision caused by concurrent transmissions. In the following, we discuss contention-based cooperative MAC protocols for vehicular networks.

A vehicular cooperative MAC protocol (VC-MAC) that takes advantage of spatial reusability is proposed by Zhang *et al.* [11]. The VC-MAC protocol consists of four components: a) gateway's broadcast period, b) information exchange period, c) relay set selection period, and d) data forwarding period. During the gateway's broadcast period, the gateway node broadcasts packets to vehicles within its transmission range. During the information exchange period, nodes that are within range reveal their existence to the other nodes, channel state and topology information that are required in the later stages of the protocol. During relay-set selection, an optimal relay set is chosen among potential relay vehicular nodes. Finally, in the data forwarding period, the selected relay nodes broadcast packets received from the gateway. Although VC-MAC aims to maximize system throughput, the protocol faces higher channel access delay in non-uniform relay distribution scenarios and severe exposed node problem in a dense vehicular networks. Figure 4 illustrates both the non-uniform relay distribution problem and the exposed node problem. In the non-uniform relay distribution, some of the destination nodes are far from the relay nodes. The required two-hop forwarding of data slows delivery of the necessary information. In the exposed node scenario, when D3, the second relay's destination, is out of transmission range of R1, the first relay, the second relay, R2, in order to avoid conflicting signals, refrains from transmitting after hearing the R1's transmission. The exposed node problem causes extra delay in the transmission by the second relay.

To alleviate the channel access delay and mitigate the exposed node problem in VC-MAC, Chen and Hung [74] proposed a VC^2-MAC. The main improvement of minimizing the channel access delay is made in VC-MAC by merging four phases of its information exchange period (two T_R and two T_D) of two different cycles into VC^2-MAC three phases (T_R, T_D, and T_{SD}) of a single cycle as illustrated in Figure 5. T_R, T_D, and T_{SD} denote the information exchange time of relay, first level destination, and second level destination, respectively. VC^2-MAC significantly reduces the data forwarding time of two hop transmission of VC-MAC. The exposed node problem is resolved by letting the two relay nodes to exchange their neighbors information in a single cycle. Therefore, before data forwarding period, each relay node knows about the other relay node's neighbors so both relay nodes can forward data concurrently if their destinations are not in each other's transmission range.

An adaptive distributed cooperative MAC (ADC-MAC) protocol for vehicular networks is presented in [12]. The nodes implement a cooperative relay activity coordination by leveraging new handshake messages, namely, Helper-Request-To-Send (HRTS) and Helper-Clear-To-Send (HCTS). This forms a triangular handshake with the exchange of RTS-CTS-HRTS/HCTS messages, which is used to choose the most appropriate relay node for cooperative transmission. After successful end of the handshake process, the sender starts transmitting the data. Unlike VC-MAC, the ADC-MAC does not rely on a time synchronization mechanism and employs a self-learning mechanism for the relay topology information. This reduces complexity of network operation. However, the triangular handshake contributes additional delay in the actual transmission delay of the data.

A concurrent transmission enabled cooperative MAC protocol (referred to as Mizar), for VANETs is proposed by Zhang *et al.* in [13]. Mizar operation is comprised of three phases: a) relay selection, b) RSU transmission, and c) relay forwarding. The RSU disseminates an RTS packet along with the size of the packet to be transmitted and the concurrent data rate at maximum transmission power level. After receiving the RTS packet, the neighboring node ‘n’ finds the SNR ratio and computes the maximal available link rate from the RSU to node ‘n’, as illustrated in Figure 6. Similarly, the destination node ‘d’ also computes the maximum data rate for a link between source and destination considering the measured channel quality, and then sends back a CTS message. After successful reception of the CTS packet, node ‘n’ can then make the decision to participate in relay competition, considering the mentioned data rate in CTS. If cooperative transmission through the node ‘n’ can be advantageous for a link between the source and destination nodes, then node ‘n’ participates in the optimal relay selection process. After reception of data from the RSU, the optimal relay finds the concurrent data rate and determines the tolerable power for concurrent transmission. Although Mizar significantly increases the throughput and minimizes the transmission delay as compared to basic relay-based cooperation mechanism, the packet level cooperation may incur a significant overhead particularly in continuously varying channel conditions.

Unlike contention-free cooperative MAC protocols, the absence of a schedule for transmission induces packet loss and variable latency due to randomness. Another drawback of contention-based cooperative MAC protocols is packet collision caused by hidden terminals and increased network density.

3) Hybrid Cooperative MAC Protocol—Hybrid MAC protocol combines the advantages of TDMA and CSMA/CA MAC protocols while offsetting their weaknesses. Like TDMA, hybrid MAC protocols experience less collisions among two-hop neighbors and attain high channel utilization under extreme contention conditions. Similar to CSMA/CA, hybrid MAC protocols incur low latency and elevates channel utilization under low contention conditions. In vehicular networks, this class of MAC protocols implement both TDMA and CSMA/CA mechanisms to support critical traffic, as well as non-critical.

A Cooperative-Efficient-Reliable MAC (CER-MAC) protocol [75] is designed for efficient transmission of non-safety messages and reliable broadcast of safety messages in VANETs. CER-MAC is designed for the multi-channel networks and can work in both TDMA and

CSMA modes. The time is split into sync intervals that have Control Channel Intervals and Service Channel Intervals. Control Channel Intervals are further divided into a reservation period (RP) and a contention period (CP). The RP is comprised of several emergency slots used for collision-free safety message transmission, whereas CP is used for service slot selection or to reserve emergency slots of the RP. The CER-MAC enables nodes to use their own reserved time slots or time slots allowed by neighbors for transmission of safety messages. Service channel resources are used for non-safety message transmissions during the control channel interval.

CER-MAC achieves reliability by broadcasting each safety message twice. In order to retransmit, the safety messages need to be buffered. In case of high packet arrival rate, the number of safety messages stored in the buffer becomes higher. Also, there is a limit on number of safety messages that can be broadcasted in a sync interval. Therefore, some of the buffered safety messages cannot be re-broadcasted before time-out. That is why CER-MAC has lower safety message average broadcast efficiency than its counterpart.

C. Routing/Forwarding Mechanisms for CVN

Unlike achieving space diversity by employing multiple antennas (on both transmitter and receiver) to improve the wireless link quality, the space diversity can also be achieved by enabling the cooperation among nodes [76]. Such cooperation among nodes along the route can be enabled by designing and employing cooperative routing protocols. The cooperative routes are usually the concatenation of direct-transmission links and cooperative-transmission links [27]. The cooperative-transmission links are formed by utilizing the services of relay node for forwarding of the packet between transmitter-receiver pair. As illustrated in Figure 7, the cooperative-transmission link is formed between nodes ‘i’ and ‘j’ using a relay node ‘k’. Similar to other wireless networks, there has been a growing interest in designing cooperative routing protocols for vehicular networks. These routing protocols incorporate the available node diversity along the path while finding the route between a source and a destination.

1) Routing Protocols—As we have discussed above, the routing protocols in CVN have a special requirement of finding the paths which can fully exploit the available forwarding relay options at each hop to enhance the transmission performance. To meet this requirement, researchers are investigating different methods of designing cross layer routing protocols that can share and use physical layer information.

A two phase-based generous cooperative (GEC) routing protocol is proposed by Li and Wang [14]. The objective is to monitor and identify misbehaving vehicles. A cooperative watchdog model is employed to minimize the number of false alarms and ameliorate misbehavior detection probability. The GEC routing protocol is comprised of numerous components that are involved in discovering cooperative paths and distributing the traffic over these paths. The GEC architecture has two key phases; route discovery and route maintenance. Route discovery involves three sub-phases, namely, neighbor discovery, learning relay metric, and cooperative relay selection. Whenever a node receives a route error message, the node initiates the route recovery process. If the link fails, then the route is erased from the routing table. The proposed solution isolates the uncooperative vehicles, thereby reducing the end-to-end delay. However, the proposed solution has not incorporated the service differentiation that can be vital to consider for effectively fulfilling the requirements of various kind of traffic.

Ding and Leung [15] propose a cross-layer routing that exploits cooperative transmission in VANETs. A new approach to path selection is presented to optimize the trade-off between end-to-end reliability and transmission power consumption. Two optimization problems are formulated and investigated to meet the different requirements. The first objective function is to maximize end-to-end reliability subject to given constraints on each link's transmission power. The second objective function is to minimize total power consumption subject to given constraints on end-to-end reliability. The optimized solutions for both functions provide criteria to find the best route among the available options. Though the proposed routing selection criteria find the efficient route in terms of transmission power and end-to-end reliability, the proposed solution assumes only one route in the network. The co-channel interference caused by multiple active source destination pairs is not considered in the solution. Hence, performance of the protocol may degrade if the multiple routes in the network become active.

A cross-layer routing protocol for VANET with the objective of maximizing the throughput and overwhelming the wireless channel unreliability is discussed in [16]. The route discovery and management are performed by the AODV-like protocol. Then, a new relay selection algorithm is proposed with the objective of maximizing the throughput. The selection criteria (cost) uses estimated connection time and the physical layer information, such as SNR. The relay with the highest cost is selected among those available. When a relay node receives a frame from a sender, it decodes the frame. If the frame is decoded successfully, the relay forwards the frame in its reserved slot. Otherwise, it discards the frame and remain silent during its reserved slot. To further improve the stability and reliability of the routing path, a MAC protocol is proposed to extend the route duration. Though the proposed routing protocol maximizes the throughput, the research work assumes that every vehicle is directly associated with RSU. This requires a large number of RSUs, resulting into a high deployment cost.

2) Forwarding Mechanisms—In cooperative routing, the main focus is on finding the paths between source and destination that can exploit the physical layer diversity. However, cooperative forwarding involves in finding an alternate node on each individual hop for transmitting a packet. Herein, we discuss the research works, which consider the cooperativeness in forwarding mechanism.

Cooperative positive orthogonal code (POC)-based forwarding mechanism for vehicular networks is discussed in [77]. "A POC is a fixed length binary code where the cross correlation between any pair of codewords is no more than the maximum cross correlation [94]." The proposed solution extends functionality of the POC-based MAC protocol. Time slot selection is based on a POC codeword, as in POC-MAC. POC-based forwarding exploits the wireless broadcast characteristic and spatial diversity by employing multiple forwarding nodes at each hop. To minimize the number of collisions, a set of relays is selected that uses a POC codeword to define the nodes transmission pattern. A set of cooperating relays that shares the POC codeword forms a virtual relay. Each virtual relay node shares its transmission opportunities among its cooperating relay member nodes. The proposed cooperative forwarding mechanism has three phases, namely, relay selection, POC codeword selection for the next hop's virtual relay, and time slot assignment. Though the proposed solution improves the transmission success ratio, the channel condition has not been considered while forwarding the message. With the restriction of fixed number of messages transmitted within a frame, the node may send either too few or too many packets. Too few packets may increase unreliability and too many packets may lead to significant overhead.

One of the goals of implementing cooperativeness in forwarding is to minimize the number of retransmissions. This can be further improved if the forwarding mechanism employs network coding. Network coding is a well-established technique known for its capability to minimize the number of retransmissions [95]. A network coding-based cooperative forwarding mechanism is investigated by Celimuge *et al.* [78]. The proposed solution is based on the concept of master/slave topology. The master node selects the forwarding slave nodes according to the direction, stability, and closeness to the master node. The source and forwarding nodes encode the packet using linear network coding with fixed coding vectors. In both reactive and proactive routing protocols, the slave address is inserted in the route reply message and periodic update messages, respectively. Therefore, the source node can find the master and slave forwarding nodes using any of the routing protocols. Despite the proposed scheme significantly improves the packet delivery ratio, the network coding may introduce additional delay on each hop which can significantly increase end-to-end latency for each packet.

Lee *et al.* [81] discuss a cooperative vehicular video streaming protocol, which addresses four key concerns; relay selection, video packetizing, streaming task assignment, and packet forwarding. Huang *et al.* [96] provided a more detailed discussion on relay node selection. The relay node is selected based on information such as hop-count distance, neighboring nodes and their hop-count distances, and available bandwidth. Video encoding and packetizing that is composed of multiple network abstract layer units is discussed in [97]. The streaming task assignment method assigns streaming tasks to relay nodes, and the packet forwarding strategy defines the forwarding sequence of the stored video data in a relay node. The base layer of the streaming video is downloaded by the requester, whereas the enhancement layers are transmitted through relays and forwarders. The proposed protocol can adapt to the dynamic characteristics of the network and smoothly transmit video hop by hop.

A cooperative store-carry-forward (CSCF)-based transmission scheme is proposed by Wang *et al.* in [7] to minimize the outage time of vehicle transmissions. The CSCF scheme considers bi-directional vehicular traffic flow and chooses two relay vehicles in both directions. The relay selection criteria takes into consideration transmission outage time while moving between two RSUs. Initially, the data is forwarded to the first relay by the first RSU. Next, the residual data is forwarded by the first RSU to the second RSU via the backhaul. Then, the data is forwarded to the second relay by the second RSU. The relay vehicle node stores the data and then transmit it as soon as a communication link with the target vehicle is established. Evaluation of the proposed solution demonstrates that the CSC-based transmission scheme minimizes transmission outage time.

Liu *et al.* [80] investigate cooperative data dissemination system characteristics by proposing a network coding assisted scheduling algorithm. RSUs can share the data to passing vehicles using a V2I communication channel, whereas vehicles can also deliver cached data to their neighbors using a V2V communication channel. The proposed solution works in three phases. During the first phase, each vehicle advertises its presence and collects information about neighboring nodes by exchanging and receiving heartbeat messages. During the second phase, all the vehicle nodes communicate the updated information about their own and their neighbors' presence, as well as the identifiers of the stored data items with the RSU. During the third phase, each vehicle changes its operational mode according to the scheduling decision made by the RSU. Further, a cache strategy is proposed to maximize the network coding impact. Although the proposed network coding-assisted data dissemination improves the service performance, the network coding may induce additional delay on each hop, thereby increasing end-to-end latency for each packet.

Mehar *et al.* [82] propose a dissemination protocol for heterogeneous cooperative vehicular networks (DHVN) that aims to optimize bandwidth usage. The DHVN selects a farthest away node in each direction as a relay node to enable fast dissemination of data. Furthermore, DHVN has the capability to adapt itself according to road architecture and vehicular environment. The proposed protocol utilizes an algorithm that optimizes packet retransmission, especially at intersections. Further, a store and forward mechanism is added to mitigate the effect of disconnections in a partitioned vehicular network. DHVN offers a high delivery ratio, low end-to-end delay, and minimum bandwidth.

Bharati and Zhuang [83] propose a cooperative relay broadcasting (CRB) scheme to rebroadcast neighboring source node packets to increase the reliability of broadcast transmission. Furthermore, an optimization framework and a channel prediction scheme based on a two-state Markov chain is proposed. The optimization framework gives an upper bound on the performance of CRB, whereas the channel prediction scheme helps in choosing the best relay node. CRB also supports proactive cooperation decisions that helps in delivering the packets before they expire.

Unlike cooperative forwarding schemes that exchange a huge amount of information to coordinate, Zhang *et al.* [79] discuss an uncoordinated cooperative scheme which use forwarding probability based on the node location to make the next hop transmission decision. The use of location information enables the node to take forwarding decision without any prior coordination with its neighbors. Though the proposed scheme reduces the coordination overhead, the location-based forwarding rely on global positioning system information that may not be available in tunnels.

D. Cooperative Link Scheduling

Cooperative link scheduling is the process of selecting a subset of links such that the nodes can concurrently utilize the cooperative links while transmitting simultaneously without interfering with the receptions of each other. Figure 8 illustrates the concurrent scheduled link in vehicular networks where links corresponding to same color edges can be active simultaneously.

Link scheduling and resource allocation as a joint optimization problem is proposed by Zheng *et al.* [20]. They present a two-dimensional-multi-choice knapsack problem (2D-MCKP)-based scheduling scheme for 2-hop vehicular networks. The scheduling scheme selects coordinator vehicles for each sink vehicle and also assigns radio resources to V2V and V2I links to address the maximum sum utility optimization problem. The proposed scheduling scheme enhances the average utility with justifiable computational complexity. However, the scheme does not consider the requirements of multiple services and dynamic process of data packets arrival.

Pan *et al.* [19] investigate a throughput maximization problem in cognitive vehicular networks under various constraints. A cooperative communication-aware link scheduling is proposed to address the problem. The network is modelled in the form of a graph where normal links are extended by introducing a dummy cooperative relay node. This is to make sure that the direct link communication representation is compatible with that of the relay-based cooperative communication. In the graph, each vertex is considered as a resource point for scheduling and represented by an extended link channel pair. Then a 3-D cooperative conflict graph is established to represent interference among cooperative extended links. From the conflict graph, independent sets and conflict cliques are defined to demonstrate which extended links can be active simultaneously and which cannot. Using a 3-D cooperative conflict graph, the problem is formulated as a throughput maximization problem subject to various constraints (i.e., transmission mode, licensed spectrum availability, and link scheduling). The problem is near-optimally solved by linear programming and provides feasible results using a simple heuristic algorithm.

Zheng *et al.* [22] propose a bipartite graph-based link scheduling scheme for vehicular networks. The scheme consists of three phases: a) formation of a weighted bipartite graph, b) solving the maximum weighted matching, and c) optimizing the number of relaying vehicles. The vertices in the weighted bipartite graph represent the vehicles. These vertices are divided into two groups: one group consists of the *1*-hop vehicles and the other comprises *2*-hop vehicles. The weights on the edges are based on the capacity of the communication links between vehicles. Next, a maximum weighted matching problem of bipartite graph is solved by the Kuhn–Munkres algorithm. Finally, in the third phase, a search algorithm is employed to determine the optimal separation. The bipartite graph-based link scheduling algorithm has lower complexity than the exhaustive search, hence providing better fairness. However, the proposed scheduling scheme does not incorporate the user arrival and departure process that is critical factor in vehicular environment.

Zhang *et al.* [84] analyze the performance of multi-hop cognitive vehicular networks focusing mainly on energy consumption. The energy efficiency in cognitive vehicular networks is formulated as an optimization problem, which is solved by using the recursion method. Based on an optimization model, a cooperation relay scheduling scheme is proposed that aims at enhancing the performance of the network in terms of energy consumption. The relay selection is based on the distance of the candidate node from the source node. The proposed relay scheduling scheme improves the network performance in terms of energy consumption.

E. Performance Analysis

There have been a number of interesting studies that aim at investigating the impact of various cooperative strategies on the performance of vehicular networks. In the following, we present research efforts that are mainly concerned with analytical models in the context of cooperativeness in vehicular networks.

For instance, V2V and V2I communications and the effect of node mobility to optimize the throughput performance has been investigated by Chen *et al.* [85]. The authors propose a strategy that enables the vehicle of interest (VoI) to receive data from an infrastructure (e.g., RSU) using V2I communications when the vehicle is in coverage of the infrastructure. When the VoI leaves the transmission range of infrastructure, it relies on V2V communications to continue reception of the data via relay nodes. Moreover, an analytical framework is proposed for investigating the data transmission process under cooperative communication strategies.

Shirkhani *et al.* [86] investigate the performance of bidirectional cooperative V2V communication in two scenarios: vehicle-assisted communication and RSU-assisted communication. The proposed scheme relies on the location of relay nodes without incorporating channel state information. A closed-form expression is derived for the symbol error rate. The effect of rate and transmission range on cooperative vehicle safety systems is examined by Fallah *et al.* [87]. Based on their investigations, a model is proposed that quantifies the performance of a network using a channel busy ratio as feedback. Initially, a node behavior is modeled, then the effect of a hidden node on channel busy time ratio and collision probability is investigated. An analysis of the joint effect of three key elements of CVN: cooperation, interference, and channel fading has been carried out in [88]. To conduct the analysis, a Nakagami fading channel model is considered with independent and identically distributed (i.i.d) and independent non-identically distributed (non-i.i.d.) interference. A closed-form expression of the connectivity probability is derived and a lower bound on the cooperative ratio is determined. The connectivity probability for both i.i.d. and non-i.i.d. is also investigated.

Feteiha *et al.* [89] propose to jointly use a pre-coded cooperative transmission along with opportunistic best-relay selection to get the multipath-Doppler-spatial diversity gain. Closed-form error rates expression is derived for the analysis. Numerical analysis shows that a significant coverage improvement is achieved by extending transmission distance with the same transmitting power. Nguyen *et al.* [68] analyze the energy consumption and performance of cooperative MIMO and cooperative relays. The performance of these cooperative techniques is compared with that of a traditional multihop technique. The relay techniques outperform the single-input-single-output (SISO) techniques, but are less efficient than the cooperative multiple-input-single-output (MISO) techniques in terms of energy consumption. However, cooperative MISO techniques perform better than relay techniques with the same SNR. The relay techniques also out-perform cooperative MISO in the case of high transmission synchronization error that results in better energy efficiency.

Chen *et al.* [90] propose a cooperative communication strategy that leverages V2V and V2I communication, mobility, infrastructure and cooperation among vehicles to maximize the achievable throughput. An analytical framework is designed to investigate the data dissemination process under proposed cooperative communication strategy. A close-form expressions are also determined for achievable throughput that shows the relationship between key performance-impacting parameters (e.g., distance between adjacent infrastructure points and data rates and transmission range of vehicles and infrastructure) and achievable throughput.

F. Power/Resource Allocation

There have been a number of interesting studies focusing on power/resource allocation in CVN. Here, we discuss those research works that consider cooperativeness while allocating power and resources.

Xiao *et al.* [17] develop a joint power allocation and relay selection mechanism for hybrid decode-amplify-forward (HDAF) networks. The proposed solution takes advantage of the ranking value computed for channel characteristics at relay nodes. Further, the relaying method optimizes transmission power to minimize outage probability and relay nodes can change modulation levels to enhance spectral efficiency. Numerical simulation and theoretical analysis show that the outage probability of the proposed HDAF is less than the incremental HDAF.

Ilhan *et al.* [18] analyze cooperative diversity in a vehicular network environment considering two distinct scenarios: vehicle-assisted cooperation and AP-assisted cooperation. The communication channels are modeled as cascaded Nakagami fading. A diversity order for these scenarios is obtained by deriving the pairwise error probability. Then, a power-allocation problem is formulated to find the share of the transmit power between the relaying and broadcasting phases for optimization of performance.

Real-time video streaming for vehicular networks is studied by Yaacoub *et al.* [91]. The authors propose a cluster-based cooperative communication technique for real-time video streaming where moving vehicles are grouped into cooperative clusters. An LTE based system transmits the video data over cellular links to a selected cluster head that uses IEEE 802.11p links to multicast the received video within the cluster. Error concealment techniques, along with efficient resource allocation mechanisms are used to improve the quality of the received video. The proposed methods have significantly improved Quality of Experience (QoE) and Quality of Service (QoS) compared to the non-cooperative vehicular networking scenarios.

G. Cooperative Group Communication

Group communication is a critical concern when the objective is common among vehicles. Herein, we discuss the research works, which consider cooperativeness in group communication scenarios.

Kim and Seo [92] highlight spatially secure group communication (SSGC) as a key issue in enabling secure cooperative multiple unmanned autonomous vehicle (UAV) control [98]. An analytical framework is developed to model the dynamics of multiple UAVs and SSGC. Further, a distributed solution for a UAV formation method is proposed that aims at minimizing spatial group size under multiple constraints, including network congestion control, spatial group radius, spatial group communication radius, and thickness of insecure area. The simulation results demonstrate that the proposed solution asymptotically meets the SSGC constraint when the transmission power is correctly assigned.

Saad *et al.* [93] propose a cooperative protocol for RSUs in vehicular networks to optimize revenues generated from data dissemination. The problem of revenue optimization is formulated as a coalition game among RSUs. In a coalition game, multiple players form a group to participate in a game instead of participating individually. Then, a distributed algorithm for coalition formation is proposed that enables RSUs to distributively join and leave a coalition while optimizing their utility. The utility considers the gain from cooperation and cost incurred on coordination. Simulation results demonstrate that the proposed algorithm enables RSUs to self-organize while enhancing the payoff between 20.5% and 33.2% as compared to the non-cooperative case.

H. Secure Cooperative Communication

Similar to other wireless networks, security is also an important issue in vehicular networks. Luo and Liu [99] have highlighted a number of threats and solutions for wireless telematics systems in intelligent and connected vehicles. The security concerns may further be intensified when a vehicular network allows the cooperation among the nodes because of the likelihood of malicious behavior in cooperating nodes.

Zhu *et al.* [23] investigated the trade-offs between security and QoS in vehicular ad-hoc networks. Both parameters performance is optimized using cooperative communication. Also, a prevention-based security scheme is proposed that offers both hop-by-hop and end-to-end integrity protection and authentication. An outage capacity, bit error rate and a closed-form effective secure throughput are derived by incorporating both security and QoS provisioning in VANETs. The proposed scheme has significantly enhanced secure throughput of VANETs by exploiting cooperative communications.

Lai *et al.* [24] proposed, SIRC, a secure incentive scheme for reliable cooperative downloading in VANETs. SIRC motivates the vehicle users to support each other in securely downloading-and-forwarding packets. The proposed scheme is comprised of two phases: cooperative downloading and cooperative forwarding. The cooperative downloading uses virtual checks that are associated with the nominated verifier's signature to guarantee secure and fair cooperation. Further, a reputation system is implemented to motivate cooperation and penalize the malicious vehicles. An enhanced SIRC is proposed that utilizes reputation system to encourage the packet forwarding and achieve reliability. During the cooperative forwarding phase, an aggregating Camenisch-Lysyanskaya (CL) signature is utilized to ensure security of the proposed incentive mechanism.

Javed and Hamida [25] analyzed an interrelation among QoS, security, and safety awareness of vehicles in cooperative intelligent transport system. A vehicle and infrastructure centric metrics have been proposed to accurately measure the vehicle safety awareness. The vehicle nodes employ the vehicle heading based filtration mechanism to incorporate the critical neighbors for awareness calculation. The vehicle heading based filtration mechanism finds critical vehicles, which are potential accident threat, among the neighborhood. The infrastructure nodes also incorporate the position error of each neighbor vehicle while calculating the awareness. The metrics are comprised of a number of received cooperative awareness messages (CAMs), their safety importance, accuracy, and vehicle heading. Prior to each CAM transmission, Elliptic Curve Digital Signature Algorithm (ECDSA) based signature is added to incorporate the security procedure. On the receiver, the CAM waits in a security FIFO queue for verification at its turn. The authors claim that the proposed metrics outperform other contemporary metrics used in measuring VANETs safety awareness.

IV. Taxonomy of Cooperative Vehicular Networks

Figure 9 shows the thematic taxonomy of cooperative vehicular networks. The existing literature is categorized based on the following characteristics: (a) objectives, (b) cooperative transmission modes, (c) cooperation-based network functions, (d) cooperating devices types, and (e) communication technologies.

A. Objectives

This category of research work refers to the main goal of integrating cooperativeness in CVN. Current research efforts in cooperative vehicular networking aim to attain a number of objectives, such as throughput maximization, power allocation optimization, transmission outage minimization, reliability improvement, utilization maximization, and reservation slot collision minimization.

Similar to other wireless networks, exploiting available resources to maximize the overall network throughput is the primary challenge in CVN. Throughput maximization in CVN has been studied in various ways, such as designing a cooperative MAC [11]–[13], [69], [73], [85], cooperative routing [16], and cooperative link scheduling [19]. The optimization of transmission power allocation is another objective targeted by some of the research works [15], [86]. For instance, the main focus of the work presented in [15] is to minimize transmission power consumption while considering the constraints of reliability and performance, whereas the works proposed in [86] optimize the power allocation to relaying and broadcasting phases.

Transmission outage time minimization-based approaches aim to reduce the no-coverage period between vehicles or V2I during the transmission session. The transmission outage can be along highways where the RSUs are deployed sparsely and intermittent connectivity is available. In the case of larger uncovered areas, transmission outage can be intolerable to delay-sensitive applications. To minimize the impact of transmission outage on delay-sensitive applications, Wang *et al.* [7] propose a cooperative store-carry-forward (SCF) scheme. The SCF scheme enables a vehicle in the transmission coverage area to store the received data, carry, and forward it to the targeted vehicle in an uncovered area.

Transmission reliability refers to a percentage of correctly transmitted packets between the nodes in a vehicular network. The main purpose of enabling the cooperativeness in vehicular networks is to improve transmission reliability. A number of research efforts [15], [72], [75], [100] aim at improving transmission reliability in vehicular networks. The solutions presented in [72] and [75] focus on designing a MAC protocol to improve transmission reliability, whereas the solutions proposed in [15] and [100] leverage routing strategies to improve transmission reliability. Efficient resource utilization is an important objective for network operators to obtain a good return on their investments. The protocol presented in [71] aims to maximize the utilization of an unreserved time slot.

The work reported in [20] maximizes sum utility of vehicular networks by incorporating a two-dimensional multi-choice knapsack problem- based scheduling in cooperative vehicular networks. In order to cooperatively transmit failed packets of neighboring nodes, the relay nodes have to reserve time slots to transmit failed packets. Cooperative transmission can be performed only if the destination vehicle node does not notice the attempt to reserve the slot from another relay among its 1-hop neighbors. C-ACK is introduced by Bharati *et al.* in [70] to deter reservation collision avoidance. By minimizing the reservation slot collision, the throughput of the network can be increased.

B. Cooperative Transmission Mode

The cooperative transmission mode defines the necessary set of actions performed by the cooperating nodes for a particular cooperative transmission. These transmission modes can be divided into four classes, namely, amplify-and-forward, decode-and-forward, compressed-and-forward, and store-carry-and-forward.

The amplify-and-forward transmission mode enables the relay node to amplify the received signal before forwarding it to the destination node. The decode-and-forward transmission mode enables the relay node to decode the overheard transmission and forward it after correctly decoding the packets. In the case of unrecoverable errors, the relay node will not be able to participate in the cooperative transmission. The compress-and-forward transmission mode enables the relay node to compress the received signal before forwarding it to the destination. The store-carry-and-forward transmission mode enables the relay node to store the received packet temporarily and carry it until the relay node reaches into coverage of the destination node to forward it.

C. Cooperation-Based Network Functions

Cooperation-based network functions refer to networking related functions that implement cooperativeness to optimize the performance of a vehicular network. The key functions, which implement cooperativeness, are routing, MAC, and link scheduling.

Cooperative routing involves in finding the routes between source and destination which can exploit the available forwarding relay options at each hop to improve the transmission performance. Cooperative routing enables multiple relays at each hop to cooperate either at the symbol-level or packet-level to forward the message. Cooperative routing reduces the number of times a route has to be rediscovered, thereby minimizing the network overhead and delay.

Cooperative MAC protocols leverage medium access contextual information and available resources to improve link-level data reliability. In the majority of TDMA-based cooperative MAC protocols, the sender's neighboring nodes leverage the available unused slots to transmit the sender's data frame.

Cooperative link scheduling refers to the problem of coordinating interfering links among cooperating nodes so that network performance can be optimized. Most cooperative link scheduling research work is aimed at maximizing the throughput and enhancing the average utility of the network.

D. Cooperative Devices Types

Cooperative device types refer to the type of nodes in the vehicular network which assist other vehicular nodes in making their transmission successful. Usually, relaying vehicles, non-relaying vehicles, and RSUs are the cooperating devices in a vehicular network. The relaying vehicles cooperate with the sender node by re-transmitting failed packets to the destination in an available time slot. Non-relaying vehicles cooperate with the relay nodes by transmitting a packet of the relay node for which they can minimize the delay. An RSU cooperates with other RSUs by transmitting their overheard packets in the available time slots that have failed; thereby minimizing the transmission overhead.

E. Communication Technologies

The main communication technologies that are used in cooperative vehicular networks are IEEE 802.11p and 3GPP LTE. IEEE 802.11p is a modification to the IEEE 802.11 standard. The standards main objective is to support wireless access in vehicular environments. It defines the amendments to IEEE 802.11 needed to enable various applications for intelligent transportation systems (ITS). IEEE 802.11p supports the exchange of data for high-speed vehicles using V2V and V2I communication. The data rates range from 3 to 27 Mbit/s based on puncturing and modulation schemes.

LTE was introduced by 3GPP in data terminals and mobile phones for high-speed wireless communication using the UMTS/HSPA and GSM/EDGE technologies. The peak download and upload data rates supported by LTE are up to 299.6 Mbit/s and up to 75.4 Mbit/s respectively. The standard supports both TDD and FDD communication systems. With the support of a wide range of cell radii from 10 km to 100 km, the standard is suitable for vehicular networks [51]. A. Vinel investigates the suitability of IEEE802.11p and 3GPP LTE for cooperative vehicular safety applications [101].

To meet the requirements of emerging delay sensitive applications, researchers are investigating the fifth generation (5G) mobile communication systems to integrate it into the future vehicular networks. Though the standard is not fully defined yet, 5G systems will possess a number of characteristics that assist in realizing the vision of several intelligent transport systems application. These characteristics are a large number of antenna arrays, high bandwidth, network densification, use of millimeter wave (mmWave), and direct device-to-device communication. With these unique characteristics, the performance of several applications including vehicle navigation and critical safety applications can be significantly improved. Considering the capabilities of 5G, researchers in the domain of vehicular networking are taking initiatives to exploit the technology for improving the performance of vehicular applications. Dong *et al.* [102] proposed a 5G-enabled smart collaborative vehicular network architecture, referred as SCVN, to fulfill the requirements of reliability, handover and throughput of future vehicular networks. Huang *et al.* [103] proposed a 5G enabled software defined vehicular networks, named 5G-SDVN, which exploits the software defined networking technology to dynamically manage vehicular neighbor groups in 5G-based vehicular environment. Wymeersch *et al.* [104] discussed the key characteristics of 5G mmWave positioning for vehicular networking. Va *et al.* [105] presented an overview of mmWave vehicular communication by mainly focusing on summarizing the key findings in the area of MAC layer, physical layer, and channel measurements. In their another work [106], the authors proposed an optimal design of mmWave beam to maximize the data rate for V2I communication. Tassi *et al.* [107] modeled a mmWave-based highway communication network and defined its link budget metrics. Figure 10 illustrates the mm-wave-based cooperative communication in vehicular networks.

Similar to some other emerging technologies, researchers are also investigating mmWave-based IEEE Wi-Fi standard IEEE 802.11ad for vehicular communication. The Wi-Fi standard is developed for short range communication using the millimeter range frequency of 60GHz ISM band. The standard aims at offering a data rate of up to 7 Gbps. Kumari *et al.* [108] investigated the feasibility of IEEE 802.11ad standard for designing of mmWave automotive radar. Kumari *et al.* [109] also proposed an IEEE 802.11ad-based radar which forms a joint waveform for a potential mmWave vehicular communication system based on IEEE802.11ad and automotive radar.

V. Requirements for Cooperative Vehicular Networks

CVN possesses the unique characteristic of enabling cooperation among vehicular nodes. The unique feature imposes several new requirements on vehicular networks that should be fulfilled to realize the vision of CVN. Herein, we are discussing some of the key requirements.

A. Adaptive Transmission Power Control

The quality of V2V and V2I communication links varies with space and time [110]. Further, the speed of moving vehicles also intensifies the issue. Therefore, there is a need to design adaptive transmission power control protocols for cooperative vehicular networks. Existing static transmission protocols are not effective for dynamic run-time varying conditions caused by cooperation among moving vehicles. Further, the adaptive transmission protocol needs a learning mechanism to become aware of the changes in surrounding vehicular environments, especially because of the cooperation among vehicles. These adaptive transmission control protocols will have a significant practical impact in the context of cooperative vehicular networking.

B. Optimal Cooperative Relay Selection

Recently, cooperative vehicular networking has gained much attention because of its ability to improve the reliability of transmission and throughput in highly dynamic wireless environments. In the majority of cooperative vehicular networks scenarios, the relay node cooperates with the sender nodes to re-transmit failed packets to the destination node. There can be multiple relay nodes which are eligible for this task. However, re-transmission of the same packet from multiple relay nodes can increase data redundancy and maximize the probability of data collision at the destination node; thereby causing inefficient utilization of resources. Therefore, there is always a need to select the one optimal cooperative relay node that can maximize the reliability and throughput of the network by utilizing the resources in an efficient manner. The criterion to select the optimal cooperative relay node is mainly based on the direction of the moving vehicle, speed, traffic load on the relay node, and channel quality.

C. Minimal Coordination Overhead

The nodes in CVN have to exchange information about their own and neighbors conditions. This information is used by the vehicle nodes in relay selection, slot selection, resource allocation, and forwarding decision. These phases of cooperation are critical for enabling cooperation among vehicular nodes and bringing a positive impact on the network performance. Usually, during an information-sharing period, the nodes exchange messages to share channel states and to collect topology information required for selection of the relay nodes. This information is exchanged by the destination node and the potential relay nodes. The destination node shares its channel state and topology information with potential relays in the destination access period and potential relay nodes share their channel state and topology information in the relay access period. There may be multiple potential relay nodes among which an optimal relay node needs to be selected in order to minimize the redundant transmission. Therefore, the overall amount of information exchanged can be significantly high and should be minimized to reduce the coordination overhead involved in the CVN. Minimal coordination overhead enables efficient utilization of resources that are available for a short period of time in the case of moving vehicles.

D. Friendly Cooperative Transmission

CVN aim to improve performance of the network in terms of throughput and reliability of packet transmission. However, cooperation mechanisms can affect the cooperating node and neighboring nodes. The cooperating node should also consider its own transmissions and resource constraints while cooperating with any other node. Similarly, the cooperating node should also take care of transmissions of the neighboring nodes. In short, the phases involved in cooperation among nodes should be designed in such a way that the performance of the cooperating node and its neighboring nodes should not be affected because of the cooperative transmissions.

E. Fair Resource Allocation

Although the main focus of CVN is to increase transmission reliability, fair resource allocation is equally important. Fairness should be considered while allocating resources (e.g., time slots, frequency) to cooperative nodes in order to improve the overall performance of the vehicular network. Fairness has been widely studied in different aspects of wireless networks including bandwidth allocation [111], channel assignment [112], and power control [113]. Fair resource allocation is the critical metric where each node expects to get an equal amount of bandwidth and power consumption. An unfair resource allocation may lead to resource starvation, therefore fair allocation of resources is also vital for the CVN.

F. Effective Incentive Mechanisms

As discussed in Section IV, CVN aim at increasing reliability and throughput by introducing cooperation among nodes. However, because of the limited availability of resources (e.g., time slots, frequency), nodes in CVN may be unwilling to offer relay services without any incentive. The throughput of the network will be decreased if majority of the nodes do not offer their relay service and show a selfish behavior. Therefore there is a need to develop effective incentive mechanisms for persuading the nodes to cooperate with each other. These incentive mechanisms should be dynamic to adjust them for each node based on its behavior.

VI. Open Research Challenges

The following discussion highlights research challenges in realizing the vision of cooperative vehicular networks.

A. High Speed Mobility

High speed mobility is a unique characteristic of vehicular networks and distinguishes it from other wireless ad-hoc networks. The high-speed induces temporal variability that can severely impact the reliability of vehicular communications. There have been several research efforts to address the issue of multiple path fading using MIMO under high-speed mobility conditions. For example, cooperative relay and cooperative MIMO techniques to exploit the spatial and temporal diversity still remain challenging issues. However, as mentioned before, covering physical layer research issues, including MIMO and channel modeling, is beyond the scope of this paper.

As far as layers above the physical are concerned, the topology of vehicular network varies frequently because of the high-speed mobility that causes frequent link breakage and fragmentation in V2V and V2I communication-based networks. Moreover, relay node selection becomes a challenging task in highly dynamic scenarios where the relay node may quickly go out of the coverage of the sender/receiver. In such conditions, relative mobility speed-based agile relay selection mechanisms are required to reduce the delay involved before the actual communication and to minimize the frequency of the relay selection process. Hence, there is a need to design optimal cooperative networking protocols, which consider the high-speed mobility of vehicles while making a cooperative decision. Nonetheless, the frequently changing topology and fast fading caused by vehicle mobility still remain a challenging task.

B. Multi-Objective Protocols

The majority of existing research solutions designed for CVN consider only a single objective where network performance is optimized with respect to only one parameter. The performance optimization of a single objective protocol does not consider varying aspects of the vehicular network. However, in a practical real environment, a trade-off may exist between multiple metrics, such as delay and throughput [114], fairness and spectrum spatial reuse [115], energy and throughput [116], to name a few. Hence, there is a need to design CVN protocols, which considers these trade-offs to fulfill the requirements of a practical real environment. However, designing multi-objective cooperative protocols is a challenging task because of the need to balance conflicting trade-offs between these metrics.

C. Channel State Information Estimation

In wireless networks, channel state information refers to the current values of channel properties that characterize the effects of fading, power decay, and scattering. The estimation of channel state information is vital for taking real-time cooperative networking decisions in order to adapt the transmissions according to the current conditions of a channel. However, fast changing channel conditions and the high-speed mobility of vehicles make it a challenging task to estimate channel state information in real-time. Researchers can use guidelines from work in similar domains, such as the one reported in [117], to design estimation algorithms for channel state information.

D. Optimal Cooperative Relay Selection

As discussed in the previous section, there is a need for selecting one optimal relay among the multiple available nodes to reduce the data collision probability and minimize the transmission redundancy. However, the selection process of an optimal relay node should incorporate the vehicle speed, varying channel quality, and traffic load on the relay node which are diverse and dynamically changing. Consequently, the objective functions and constraints on these time-varying parameters make the optimal cooperative relay selection a challenging problem. The research work reported in [118] can be helpful for researchers while designing optimal cooperative relay selection solutions.

E. Security

Security is an important concern in wireless networks that needs further attention due to the likelihood of exhibiting malicious behavior in cooperating nodes. The malicious behavior of cooperating nodes may degrade network performance and reduce the cooperation benefit. For example, a relay node with false information should be identified in the relay selection process. There is a need for security measures to enable secure cooperative communication among vehicular nodes. However, it is impotent to establish trust before actual transmission under high mobility conditions where the network topology, as well as relay selection, change more frequently. Researchers can design an authentication mechanism for vehicular networks similar to the work presented in [119], which minimizes authentication computation cost and provides a lightweight mechanism to aggregate the trust scores, respectively.

VII. Conclusions

The key design objectives in CVN are to improve performance of the network in terms of transmission reliability, throughput, and interference by introducing cooperation among vehicular nodes. However, designing and deploying efficient and adaptive cooperative algorithms/protocols for vehicular networks is a challenging research perspective due to high-speed mobility, conflicting trade-offs among various parameters, and runtime optimal cooperative node selection.

In this paper, we classify existing state-of-the-art literature on CVN by focusing on areas which involve network cooperation. Cooperativeness in vehicular networks has been studied in different perspectives, including MAC, routing, scheduling, analysis, power/resource allocation, and group communication. The key requirements related to designing CVN have also been covered in this paper. These requirements are adaptive transmission power control, optimal cooperative relay selection, minimal coordination overhead, friendly cooperative transmission, and fair resource allocation. Future research directions are also provided by highlighting open research challenges, such as high-speed mobility, designing of multi-objective protocols, channel state information estimation, and security.

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Biographies

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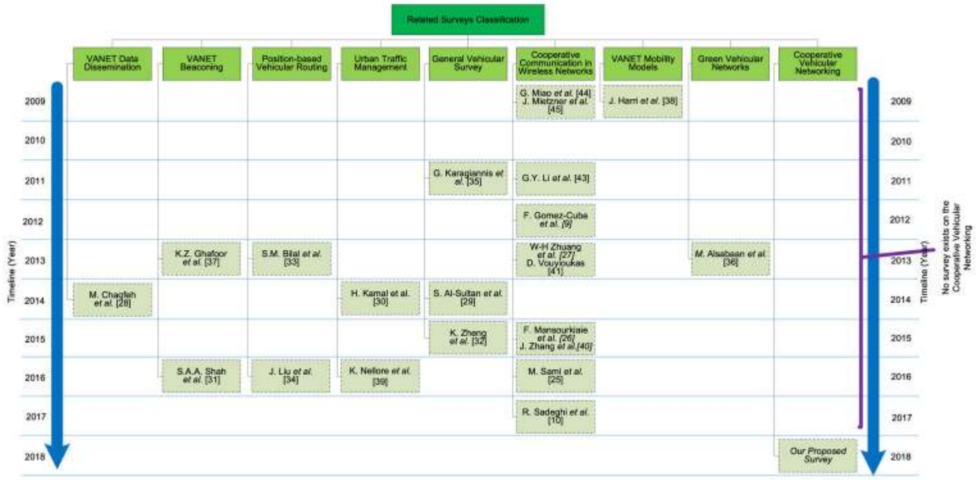
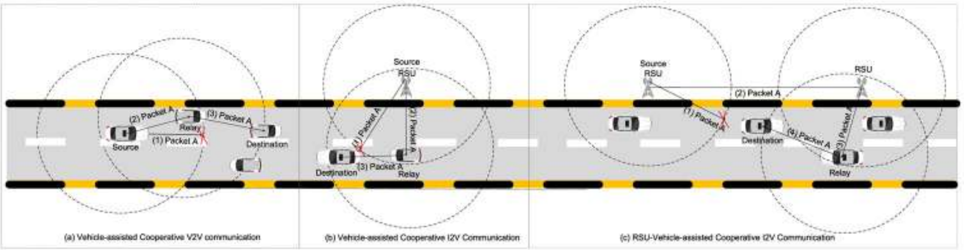


Fig. 1.

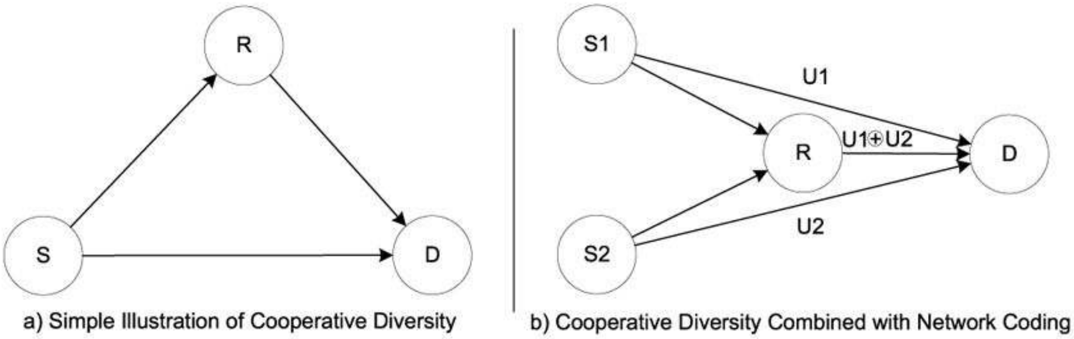
Classification of related surveys.



(a) Vehicle-assisted Cooperative V2V communication (b) Vehicle-assisted Cooperative I2V Communication (c) RSU-Vehicle-assisted Cooperative I2V Communication

Fig. 2.

Simple illustrations of CVN.



a) Simple Illustration of Cooperative Diversity

b) Cooperative Diversity Combined with Network Coding

Fig. 3.

Illustrations of cooperative diversity [64].

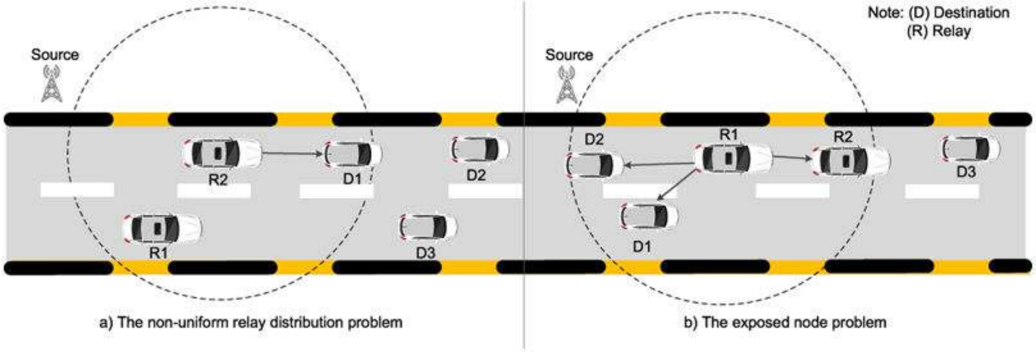
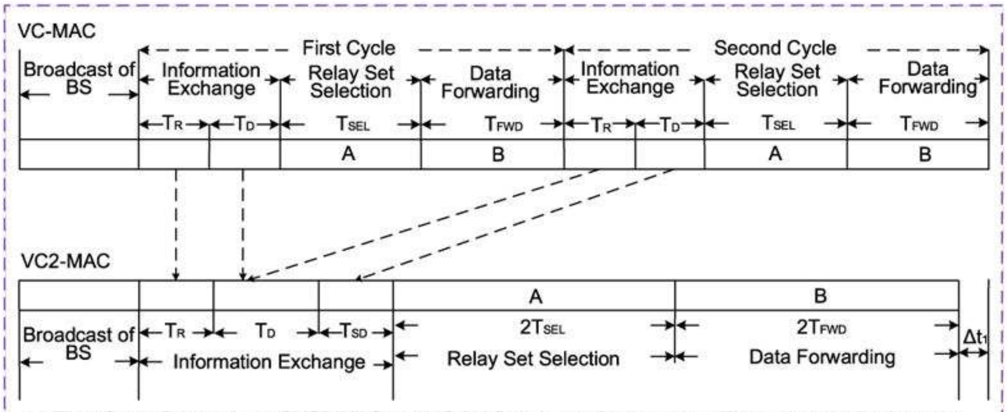
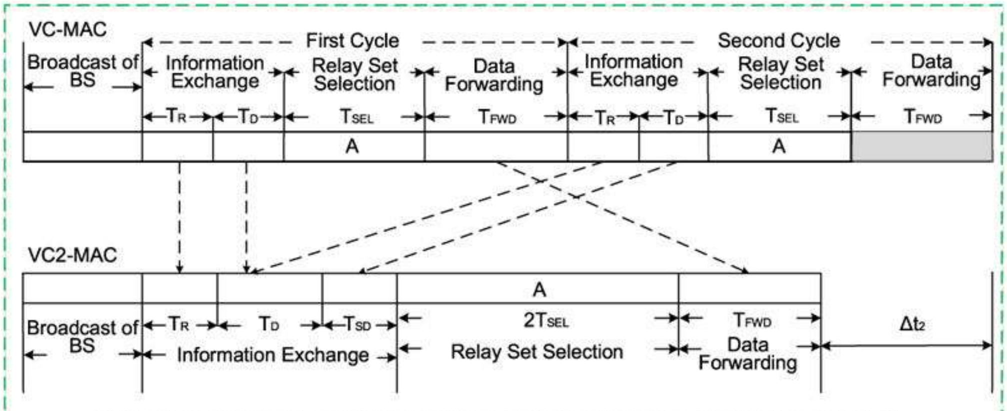


Fig. 4.

Illustration of the non-uniform relay distribution problem and the exposed node problem.



a) Time Costs Comparison of VC2-MAC and VC-MAC protocols for the non-uniform relay distribution case



b) Time Costs Comparison of VC2-MAC and VC-MAC protocols for the exposed node case

Fig. 5.

Time costs comparison of VC2-MAC and VC-MAC protocols.

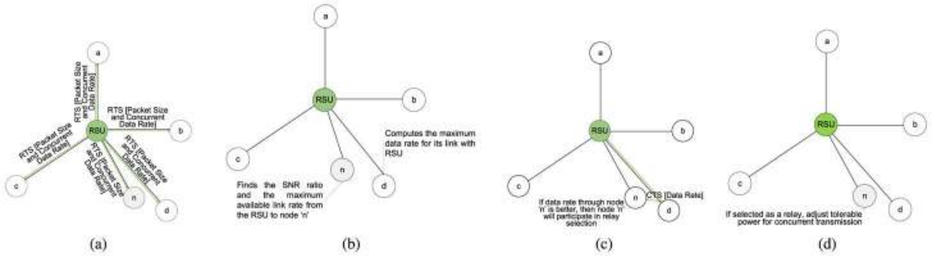


Fig. 6.

Mizar relay selection and power adjustment. (a) RTS transmission by RSU. (b) Neighbor node 'n' and destination 'd' compute the maximum link rate. (c) CTS transmission from destination node. (d) Adjust tolerable power for concurrent transmissions.

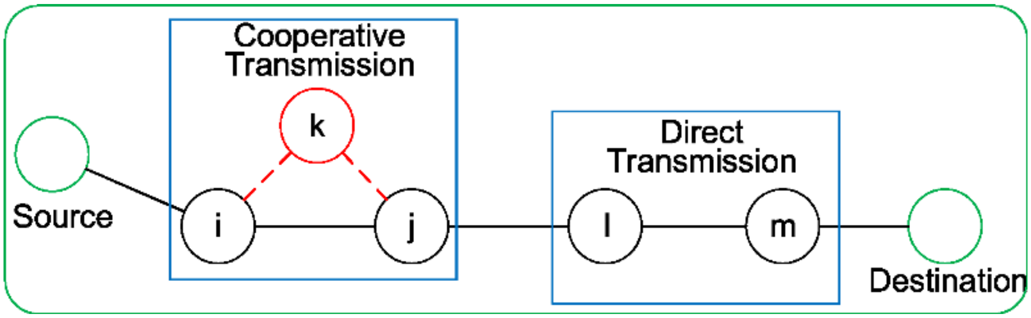


Fig. 7.
A sample cooperative route.

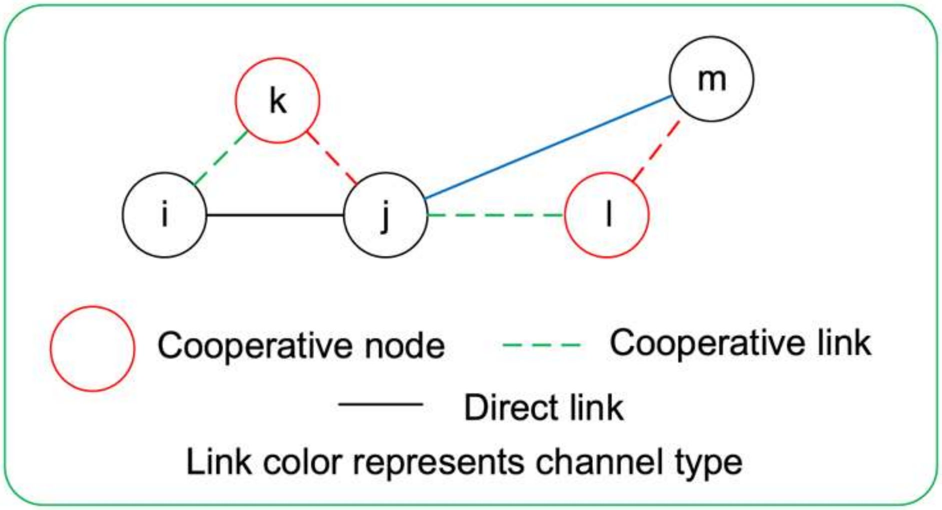


Fig. 8.
Illustration of cooperative link scheduling.

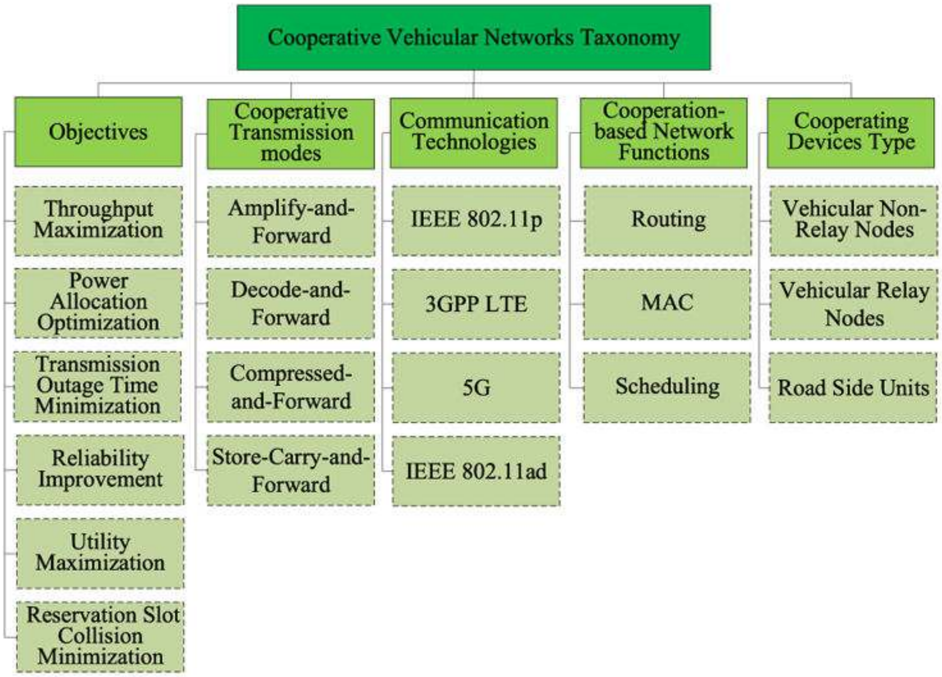


Fig. 9.

Taxonomy of cooperative vehicular networks.

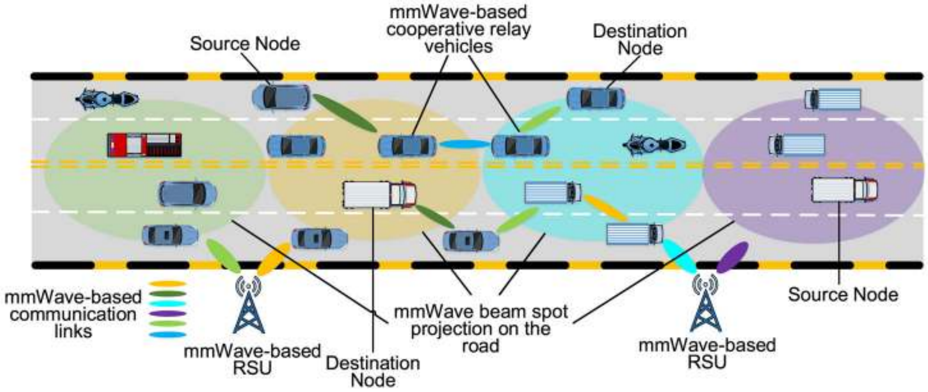


Fig. 10.

Illustration of a scenario for mmWave-based Cooperative communication in vehicular networks.

TABLE I

List of Acronyms and Corresponding Definitions

Symbols	Description
AODV	Ad hoc On-Demand Distance Vector
CP	Contention Period
CTS	Clear to Send
CVN	Cooperative Vehicular Networking
CSMA	Carrier Sense Multiple Access
DSRC	Dedicated Short Range Communications
EDGE	Enhanced Data GSM Environment
FDD	Frequency Division Duplex
3GPP	3rd Generation Partnership Project
GEC	Generous Cooperative Routing
GSM	Global System for Mobile communication
HSPA	High-Speed Packet Access
i.i.d	Independent and Identically Distributed
ITS	Intelligent Transportation Systems
I2I	Infrastructure to Infrastructure
I2V	Infrastructure to Vehicle
LTE	Long Term Evolution
MAC	Medium Access Control
POC	Positive, Orthogonal Code
RSU	Road Side Unit
RTS	Request to Send
VANETs	Vehicular Ad hoc Networks
V2I	Vehicle to Infrastructure
RP	Reservation Period
SCF	Store, Carry and Forward
SNR	Signal To Noise Ratio
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications Service
VoI	Vehicle of Interest
V2V	Vehicle to Vehicle
WLAN	Wireless Local Area Network

TABLE II

Comparison of Cooperative Vehicular Networking Solutions-Based on Objective

Research work	Del.R. Max.	Thr.Gp Max.	T.O./ S.O. Min.	Rel. Imp.	Util. Max.	R.S.C. Min.	D.R. Min.	Delay Min.	Itfr. Min.	NoBR Max.	Sec. Coop.	Pow./E. Opt.	PSNR Max.	R. Max.
T. Zhang *et al.* [73]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
S. Bharati *et al.* [69]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
S. Bharati *et al.* [71]	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗
J. Zhang *et al.* [11]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
T. Zhou *et al.* [12]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
D.N.M. Dang *et al.* [75]	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
F. Yang *et al.* [72]	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
L. Zhang *et al.* [13]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
L. Zhang *et al.* [77]	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗
X. Li *et al.* [14]	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗
Z. Ding *et al.* [15]	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
W-H Chen *et al.* [16]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
WU Celimuge *et al.* [78]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
X. Zhang *et al.* [79]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Y. Wang *et al.* [7]	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
K. Liu *et al.* [80]	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
C-H Lee *et al.* [81]	✗	✓ (Gp)	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
S. Mehar *et al.* [82]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗
S. Bharati *et al* [83]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗
Q. Zheng *et al.* [20]	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
M. Pan *et al* [19]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
K. Zheng *et al.* [22]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
L. Zhang *et al.* [84]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
J. Chen *et al.* [85]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
M. Shirkhani *et al.* [86]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
Y.P. Fallah *et al.* [87]	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Research work	**Del.R. Max.**	**Thr.Gp Max.**	**T.O./ S.O. Min.**	**Rel. Imp.**	**Util. Max.**	**R.S.C. Min.**	**D.R. Min.**	**Delay Min.**	**Itfr. Min.**	**NoBR Max.**	**Sec. Coop.**	**Pow./E. Opt.**	**PSNR Max.**	**R. Max.**
R. Chen *et al.* [88]	-	-	-	-	-	-	-	-	-	-	-	-	-	-
M.F. Feteiha *et al.* [89]	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
J. Chen *et al.* [90]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
H. Xiao *et al.* [17]	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
H. Ilhan *et al.* [18]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
E. Yaacoub *et al.* [91]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗
S-W Kim *et al.* [92]	-	-	-	-	-	-	-	-	-	-	-	-	-	-
W. Saad *et al.* [93]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓
L. Zhu *et al.* [23]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
C. Lai *et al.* [24]	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗

Del.R. Max.: Delivery Ratio Maximization, Thr./Gp Max.: Throughput/Goodput Maximization, T.O./S.O. Min.: Transmission Outage/Secrecy Outage Minimization, Rel. Imp.: Reliability Improvement, Util. Max.: Utility Maximization, R.S.C. Min.: Reservation Slot Collision Minimization, D.R. Min.: Data Redundancy Minimization, Itfr. Min.; Interference Minimization, NoBR Max.: Number of Broadcast Receivers Maximization, Sec. Coop.: Secure Cooperation, Pow./E. Opt.: Power/Energy Optimization, PSNR Max.: Peak Signal to Noise Ratio Maximization, R. Max.: Revenue Maximization, (-): Not mentioned

TABLE III

Comparison of Cooperative Vehicular Networking Solutions

Research work	**Cooperation Strategy**	**Helper Selection**	**Transmission Mode**	**Simulator**
T. Zhang *et al.* [73]	Reactive	Node stability	Store-&-Forward	-
S. Bharati *et al.* [69]	Reactive	A common *1*-hop node between source and destination, successful reception of the failed transmission	-	MATLAB
S. Bharati *et al.* [71]	Reactive	=		MATLAB
J. Zhang *et al.* [11]	Reactive	a) Successful reception of broadcast packet, b) no collision at destination node, and c) system capacity should be maximized.	Store-&-Forward	ns-2
T. Zhou *et al.* [12]	Proactive	SNR values of successfully received RTS and CTS are greater than the given threshold at potential relay candidate	Store-&-Forward	ns3
D.N.M. Dang *et al.* [75]	Proactive	If a *1*-hop node of requesting node is idle	-	MATLAB
F. Yang *et al.* [72]	Reactive	a) Successful reception and decoding of the packet, b) the destination node should be in transmission range, and c) channel conditions are good.	Store-&-Forward	MATLAB
L. Zhang *et al.* [13]	Proactive	Channel state information	Decode-&-Forward	EstiNet
L. Zhang *et al.* [77]	Proactive	a) *1*-hop neighbors of the send closer to the destination and b) link quality is good	Decode-&-Forward	ns-2
X. Li *et al.* [14]	Proactive	Reputation index that is calculated to capture the selfish behavior	-	ns-2
Z. Ding *et al.* [15]	Proactive	Random	Decode-&-Forward	-
W-H Chen *et al.* [16]	Reactive	Relay cost is defined in terms of SNR and connection time	-	ns-2
WU Celimuge *et al.* [78]	Proactive	Stable and nearest node	Decode-&-Forward	ns-2
X. Zhang *et al.* [79]	Reactive	Each node uses its own location to take forwarding decision	Store-&-Forward	MATLAB
Y. Wang *et al.* [7]	Proactive	Direction of movement and effective communication time	Store-Carry-Forward	MATLAB
K. Liu *et al.* [80]	Proactive	-	Store-&-Forward	CSIM 19
C-H Lee *et al.* [81]	Reactive	a) the available bandwidth of DSRC and 3G/3.5G, b) hop-count distance, and c) the neighbors and their hop-count distances	Store-&-Forward	ns-2
S. Mehar *et al.* [82]	-	Road structure and node’s heterogeneity	Store-&-Forward	ns-3
S. Bharati *et al.* [83]	Proactive	Number of destination nodes covered and channel condition	-	MATLAB
Q. Zheng *et al.* [20]	Proactive	Nodes with higher data rates	Decode-&-Forward	OPNET
M. Pan *et al.* [19]	Proactive	-	Amplify-&-Forward, Decode-&-Forward	-
K. Zheng *et al.* [22]	Proactive	Radio link quality	-	-
L. Zhang *et al.* [84]	Proactive	Position of the vehicle on the road	Decode-&-Forward	-
J. Chen *et al.* [85]	Reactive	Direction of movement	Store-&-Forward	MATLAB

Research work	**Cooperation Strategy**	**Helper Selection**	**Transmission Mode**	**Simulator**
M. Shirkhani *et al.* [86]	-	Distance from the source and destination	Amplify-&-Forward	Monte Carlo
Y.P. Fallah *et al.* [87]	-	-	-	OPNET
R. Chen *et al.* [88]	-	-	-	Monte Carlo
M.F. Feteiha *et al.* [89]	Proactive	Average SNRs of associated links	Decode-&-Forward	MATLAB
J. Chen *et al.* [90]	Proactive	a) Movement direction of the node is same as that of the VoI and b) The node is in the transmission coverage of RSUs	-	MATLAB
H. Xiao *et al.* [17]	Proactive	The ranking of channel statistical features.	Decode-Amplify-Forward	
H. Ilhan *et al.* [18] E. Yaacoub *et al.* [91]	- Reactive	Distance from the source and destination -	Amplify-&-Forward -	Monte Carlo MATLAB
S-W Kim *et al.* [92]	-	-	-	MATLAB
W. Saad *et al.* [93]	Proactive	RSU revenues and the costs for coalition coordination	-	MATLAB

[2] (-) : Not mentioned, (=) : Same value as above