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A moving cluster architecture and an intelligent resource reuse protocol for vehicular networks

Hrishikesh Venkataraman · Romain Delcelier · Gabriel-Miro Muntean

Abstract Real-time data transmission, especially video delivery over high-speed networks have very stringent constraints in terms of network connectivity and offered data rate. However, in high-speed vehicular networks, direct communication between vehicles and road side units (RSU) often breaks down, resulting in loss of information. On the other hand, a peer-to-peer based multihop network topology is not sufficient for efficient data communication due to large packet loss and delay. In this paper, a novel 'moving cluster multiple forward' (MCMF) architecture is proposed and investigated for efficient real-time data communication in high speed vehicular networks. MCMF involves novel aspects in relation to the formation of clusters and managing the communication between groups of vehicles and introduction of a hierarchical multiple forwarding mechanism which enables communication between any vehicle and RSU via other vehicles. Additionally, a novel protocol called 'alternate cluster resource reuse' (ACRR) is proposed and its detailed communication mechanism is presented. Simulation tests show how the use of MCMF and the ACRR protocol results in superior bit-rate performance—around three times that obtained in peer-to-peer multihop communications and twice that of MCMF with no ACRR protocol. Further, the average delay in MCMF-based transmissions from vehicle to RSU is around 50 % that of a peer-to-peer multihop communication mechanism. MCMF/ACRR has the potential to support multimedia traffic according to the IEEE 802.11p standard, even with a sparse investment in the infrastructure.

Keywords Clustering · Multihop communication · Road-side-unit · Resource reuse · TDD · Vehicular networks

1 Introduction

A vehicular communication infrastructure is being researched extensively in the automotive and intelligent transportation system domains. Particularly, sensors and new on-board wireless radio technologies are being developed in order to have both monitoring and communication with roadside infrastructure (vehicle to infrastructure—V2I) and other vehicles (vehicle to vehicle—V2V) in order to support public safety applications, traffic management and delivery/sharing of multimedia content [1]. In a motorway environment, a typical road side unit (RSU)/access point would be located only once every tens of kilometers. Hence, it is very difficult to have a continuous connection between a high-speed vehicle and a service provider's server (the Internet world), which is especially required for real-time multimedia communication [2]. Further, current protocols that enable communication between the vehicles (peer-to-peer/multihop) are quite poor for real-time high-rate information transfer between the vehicles and the service provider's server. This is a major bottleneck in providing real-time multimedia and other infotainment

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services in the next generation vehicular communication networks [3, 4].

A motorway usually consists of two to six lanes on either side. In order to have high data-rate communication between the fast moving vehicles and RSU, there needs to be either a significant investment in setting up the infrastructure (not desirable) or an efficient multihop-based communication mechanism (preferred). In this context, a dedicated short range communication (DSRC) mechanism has been proposed and standardized as IEEE 802.11p under the wireless in vehicular environment (WAVE) initiative. DSRC/IEEE 802.11p stipulates a specific spectrum band (75 MHz in 5.9 GHz band) [5]. In 2001, ASTM E 17.51 sub-committee confirmed IEEE 802.11a/RA as the Physical and MAC (medium access control) layer standard for this purpose. However, 802.11a R/A has been mainly designed for indoor, low-mobility, single-hop, non-real-time use. Hence, it cannot be directly used for high-speed vehicular networks. Its applicability to vehicular environment requires that the MAC layer of the current 802.11p be significantly re-engineered for outdoor, multihop, mobile usage with critical constraints on delay/delay jitter for real-time applications (e.g., emergency broadcast messaging).

The fundamental challenges in using IEEE 802.11p MAC for DSRC applications rest in the premises underlying the basic 802.11 protocol design. The base access mechanism of IEEE 802.11 namely, "distributed coordination function (DCF)", is contention-based and does not provide quality of service (QoS) support [6]. Further, DCF mainly operates in the infrastructure mode, implying that messages from all client vehicles will be relayed via an RSU. The maximum communication distance between the RSU and a vehicle would depend on the transmit power and the receiver sensitivity. Irrespective of that, a high-speed vehicle would be in the range of a stationary RSU for a very brief period. For example, if it is considered that a RSU can communicate with the vehicles over a range of 1 km, then a vehicle moving at a speed of 100 km/h would be in the RSU's range for 36 s only. This further reduces to less than 36 s, often at edges, where the communication is very poor. Also, if the vehicle moves faster, the vehicle loses connectivity with that particular RSU. Hence, a direct communication of the vehicles with the RSU is not efficient. An alternative solution [7] is a peer-to-peer (p2p) multihop vehicular transmission over a flat wireless network. However, it is quite inefficient in terms of the connectivity and the system throughput [8, 9]. This is especially because, in case of higher number of multiple hops, the total amount of overhead signal required significantly increases which in-turn increases the delay. This not only reduces the system capacity, but importantly, renders real-time high data-rate communication (like video and multimedia transmission), ineffective in the high-speed vehicular environment.

The main contribution of this paper is two-fold. The paper proposes a novel "moving cluster multiple forward" (MCMF) architecture based on clustering of vehicles, cluster movement and continuous transmission of messages in a multihop manner. A novel data delivery protocol for vehicular wireless communications called "alternate cluster resource reuse" (ACRR) is also proposed and its detailed communication mechanism is presented in the context of MCMF. MCMF along with ACRR ensures that the communication between the vehicles and the Internet takes place uninterrupted, with a considerably high throughput and with the lowest possible delay, even when the vehicles are not directly connected to the network.

The organization of the paper is as follows. Section 1 describes the related works of real-time communication in high-speed vehicular networks. Section 3 presents the MCMF architecture in details for the high-speed vehicular network. Section 4 presents the ACRR protocol along with its detailed algorithm in the context of high-speed vehicular networks. Section 5 describes the test set-up and presents a detailed mathematical analysis of multimedia data transmission. Section 6 discusses the simulation results and Sect. 7 concludes the paper.

2 Related works

The enthusiasm for vehicular networking is not only due to the potential benefits to different applications, but also mainly due to the scalability of the solutions and the challenges in achieving them. The vehicle infrastructure integration proof of concept [10] identified many shortcomings in the DSRC standard mainly in the dynamic nature of the users and the road environment. In this regard, the primary motivation for deploying DSRC is to enable collision prevention applications. These applications depend on frequent data exchanges among vehicles and between vehicles and roadside infrastructure. The US Department of Transportation has estimated that vehicle-to-vehicle (V2V) communication based on DSRC can address up to 82 % of all crashes [11].

DSRC can be used for many other applications beyond collision avoidance. Most of these involve communication to and from RSUs. For example, DSRC can be used to assist navigation, make electronic payments (e.g., tolls, parking, etc.), improve fuel efficiency, gather traffic probes and disseminate traffic updates. It can also be used for more general entertainment and commercial purposes. In a landmark paper, the authors in [12] classify the vehicular network application into four classes:

1. *General information services* These are the services for which the delayed or lost information does not compromise safety and/or render application useless. These include weather reports, web browsing, core business services, etc. Notably, vehicles with GPS and wireless transceiver could use an historical database to record encounters with other vehicles [13].
2. *Information services for vehicle safety* This mainly includes context-specific safety alerts related to potential dangers such as abnormal vehicle behavior or surface conditions [13]. Notably, the CarTALK2000 project proposed a similar information and warning function as part of driver assistance system [14, 15]. In this scheme, emergency messages are broadcasted through a multihop system to warn others of breakdowns, traffic anomalies and dangerous surface conditions. Further, a time critical diffusion model for Vehicular Ad Hoc Network (VANET) was presented in [16].
3. *Individual motion control using inter-vehicular communication (IVC)* This involves applications that issue operator warnings or regulate local vehicle actuators to ensure safe and/or efficient operation. They require the use of IVC broadcasts to exchange position, velocity, acceleration and bearing and actuator state [17, 18]. Further, under the proposed mechanism [17, 18], the vehicles communicate different information so that the drivers receive an audio warning if the vehicle's estimated time to an intersection is close and little time reaction time remains.
4. *Group motion control using inter-vehicular communication* This includes motion and actuator state broadcasts, as well as motion-related control messages for centralized or distributed applications. This could be further classified into two categories: In the first application, the vehicles are organized into groups to facilitate complimentary trajectory planning and couple the motion of one vehicle with another [12]. The second category is the leader based regulation, where one vehicle broadcasts motion reference and other vehicles combines this leader's information from other nearby vehicles to determine its own course of action [19]. A group motion system has several advantages as it enables efficient and rapid transmission of information from one vehicle to another, thereby paving way for high-rate communication. However, in reality, the leadership and motion control are extremely complex and challenging.

The real-time multimedia information could be classified into class 1 or class 4. However, each class of application has some drawbacks. The class 1 applications may tolerate best effort service with intermittent communication failures, such as loss of query response or dropped media data frames while class 4 applications require the additional ability to synchronize the communication. However, given the stringent requirements in terms of group-motion of the vehicles, it is extremely challenging to develop a general protocol for carrying real-time multimedia information by controlling the group motion of vehicles.

DSRC is a wireless communication technology used in high-speed environment such as VANET. DSRC is especially useful for driving safety applications or real-time traffic information delivery [20]. The vehicles can communicate with infrastructure and download traffic information or multimedia files from infrastructure [21]. The application of DSRC technology, the technical characteristics and communication mechanism is discussed in [22]. Notably, DSRC is based on IEEE 802.11 protocols, especially at the MAC layer. In this regard, the MAC protocols for vehicular networks can be classified into two categories: *contention-based* protocols and *scheduling-based* protocols. The *contention based* protocol is a communication protocol for operating wireless equipments that allow many users to use the same radio channel without pre-coordination. The IEEE 802.11 is a well-known standard that is based on the contention based protocol. It is mainly based on carrier sense multiple access (CSMA), wherein a node verifies the absence of other traffic before transmitting in a shared medium. However, contention based protocol often results in unbounded delay and rapid collisions, which greatly hinders real-time communication. The unwanted collisions have been avoided through the Channel Reservation MAC (CR-MAC) protocol [23]. The CR-MAC protocol takes advantage of the overhearing feature of the shared wireless channel to exchange channel reservation information with little extra overhead. Further, another CSMA based MAC protocol—the Batch Mode Multicast MAC protocol has been proposed [24], which uses control frames for broadcast transmissions. However, the problem of unbounded delay still holds significance in the contention-based networks. On the other hand, the *scheduling-based* protocol has been designed for supporting multi-class services in wireless networks. It is based on time division multiple access (TDMA) technique, wherein, the time slots (TSs) are selected based on the traffic and the network topology. The advantage of TDMA based protocol is that the energy inefficiency caused by the idle-listening problem and high collision probability can be avoided [25]. TDMA based protocols outperform CSMA based protocols in all areas except the protocol adaptability to changes in network topology. Further, TDMA based protocols need a good synchronization scheme which is difficult to implement in a dynamic environment like a vehicular network [25].

Over the recent years, there have been several efforts on proposing new TDMA based protocols. The authors in [26] proposed and implemented Soft-TDMAC, a software TDMA based MAC protocol, running over commodity 802.11 hardware. Soft-TDMAC has a synchronization mechanism, which synchronizes all pairs of network clocks to within microseconds of each other. Building on pair-wise synchronization, Soft-TDMAC achieves network wide synchronization. Similarly, a distributed TDMA slot allocation mechanism is realized by DRAND [27] that uses an out-of-band handshake signaling. DRAND does not require any time synchronization and is shown to be effective in adapting to local topology changes without incurring global overhead in the scheduling. Further, a hybrid solution ZMAC [28] had been proposed in which each node is allocated a dedicated TDMA slot, but at the same time, the nodes are allowed to contend for bandwidth using CSMA with a goal to improve the bandwidth usage. However, ZMAC mainly suffers from high slot reallocation latency after a network topology change.

A multihop design for an infrastructure-less wireless communication system significantly increases the system capacity of the network [29]. Keeping this in mind, the multihop concept was extended to vehicular networks in [30]. However, it was observed that the existing protocols performed poorly when multimedia information was transmitted in high speed vehicular networks. Tarik et al. proposed a scalable routing protocol wherein the vehicles are grouped according to their velocity [31, 32]. This guarantees a highly stable communication mechanism in VANETs. Going further, Little and Agrawal [33] first proposed the idea of forming and utilizing clusters for effective information transmission in infrastructure-less vehicular networks. In a significant effort, Tarik et al. extended this idea and proposed a cluster-based mechanism for risk-aware cooperative collision avoidance in a vehicular network [34]. However, its focus was on collision avoidance and not on high-rate data transfer; that is required for video and multimedia content transmission. Further, in the model described [33], there is only one cluster-head node. This hinders continuous connectivity in high-speed vehicular environment, especially with sparse infrastructure. Hence, it is essential to enhance the existing communication mechanism by developing a more stable architecture and subsequently designing a customized TDMA based protocol that would be less dependent on the mobility of the network. In the next section, new system architecture is proposed and described in detail.

3 System architecture

3.1 Multihop vehicular network

Consider a national motorway network (single/multi-lane) wherein the vehicles are moving in the same direction. The vehicles move at a speed of 80–200 km/h. All the vehicles move in the same direction, with the distance between the junctions ranging from 2 to 50 km, depending on the scenario. The vehicles could communicate with the RSU either directly or in multihop fashion. In order to have real-time communication and real-time connectivity with the Internet, it is essential that the vehicles be connected with the RSU/service provider's server. However, given the large distance between the RSUs, the vehicles in the high-speed network are not always connected to the RSUs. A novel architecture, called MCMF is developed wherein the highway lane is divided into multiple moving clusters and a communication is established with the RSU based on vehicular delay tolerant network principles.

3.2 Moving cluster architecture

The cluster-based architecture comprises of multiple clusters. The vehicles moving in the same direction and in the vicinity of each other (up to a certain distance; approximately 1 km) come under a single cluster, as shown in

Fig. 1 Multiple cluster multiple forward architecture (instance when RSU is in communication range of CC)

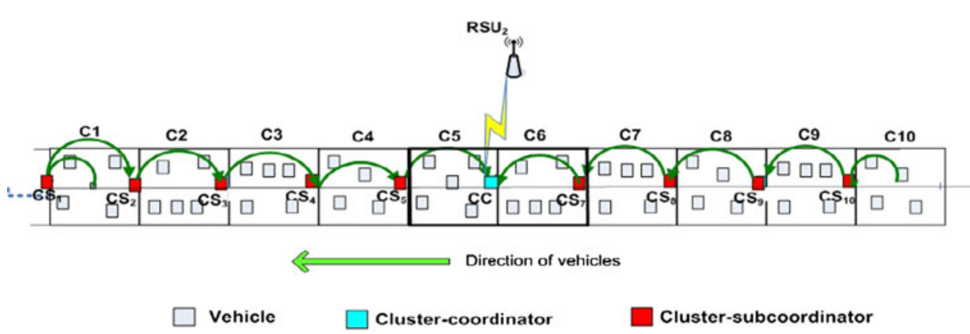

Fig. 1. The cluster spans across two to four lanes, depending on the number of lanes in a particular direction of the road. The clusters are rectangular in shape, with the major side denoted by r_c and the minor side, denoted by q_c, respectively. In the vehicular network, the length of the cluster is much more significant and much bigger than the width of the lane, (i.e., $r_c \gg q_c$). A vehicle entering a freeway/national highway would first search for any available cluster by broadcasting a message or by communicating with a RSU when it in its communicating range. If there is no cluster of vehicles, then the RSU directs the particular vehicle to form a cluster of length $r_c = A$ km; and be the local head of the cluster. This local head is called as *cluster-sub-coordinator* (CS). The CS node then forms a network with all other vehicles coming behind, within a communication range of A km. Subsequently, after a distance of A km, when the next vehicle arrives in the range of RSU, the RSU identifies whether it belongs to any pre-defined cluster. If not, then the RSU dictates the vehicle to act as CS node (say, CS2) which in-turn then takes over the responsibility of the next set of vehicles. In this way, the RSU determines the CS nodes and delegates the formation of clusters to different CS nodes. Further, for every certain number (B) of CS nodes, the RSU indicates a CS node to take over the responsibility of the whole set of clusters; and marks it as the overall-head of the set of $2B$ clusters. This overall-head is called as cluster-coordinator (CC); and is responsible for receiving and buffering the packets from all CS nodes in the set of $2B$ clusters.

A set of $2B$ clusters is made so that there are even numbers of clusters per CC node. This is done in order to have an efficient resource reuse, which would be explained later. As shown in Fig. 1, the vehicles in a cluster communicate with the CS. This CS node in-turn sends the data packets to the next CS node which in-turn transmits it again to next CS node. This process is repeated till one of the following events takes place.

1. The CS node that has received the packets is in the communication range of RSU and hence, could transmit these packets directly to the RSU (external network).
2. The data packets reach the CS node that is marked as the CC node. At this stage, the CC node either transmits these packets to RSU if it is in its communication range or stores them in its buffer, till the CC node comes in contact with the RSU; or transmits them to the adjacent CS node if the adjacent CS node is the range of RSU and there are no more packets to be transmitted in the network.

It is well-known that increasing the number of multiple hops beyond 4 or 5 not only increases the delay, but also results in significant packet drop. Hence, in order to reduce the number of multiple hops, the CS nodes could transmit the packets in either forward or reverse direction, depending on which of the closest CS/CC node is in the communicating range of RSU. The vehicles in the rear-side cluster(s) of the CC node transmit the information to the CC node in the forward direction while the vehicles in the front-side cluster(s) of the CC node transmit the information to the CC node in the reverse direction. Notably, the distance between two CS nodes is restricted to around 1 km. Hence, the maximum distance between a vehicle and a CS node is less than that, thereby satisfying the requirement set by the IEEE 802.11p standard. Further, theoretically, the number of multiple hop communication between the CS nodes (i.e., no. of clusters on either side of CC node, B) could be any value. However, higher the value of B, higher is the number of multiple hop communication from the vehicle to CC node. Hence, in order to restrict the number of multiple hops, the value of B is restricted to 6. In Fig. 1, the value of B is 5, i.e.; the maximum number of multiple hops through which a vehicle would transmit its information to the CC node is 6. Further, there are two main differences in the functionalities of CC and CS node:

1. The CC node is the overall head of the *moving cluster* mechanism, i.e., head of $2B$ clusters. On the other hand, each CS node is head of only one cluster.
2. The CC node does not immediately forward information received from other CS nodes to any other CS nodes. It communicates this information with the stationary RSU when the CC node is in RSU's communicating range. If the CC node is not in RSU's range, it either buffers the information till it is in the range of RSU or till the time, when there is no traffic in the networks, during which it transmits the information to the CS node that is in the range of RSU. The CS node, on the other hand, transmits its information immediately (within one time frame), either to the CC node if it within its range or to the next CS node.

The MCMF architecture has the following salient features:

1. The clusters are themselves mobile, moving along with the high-speed vehicles.
2. The vehicles communicate with the RSU in multiple hops, through CS and CC node.
3. The presence of CC/multiple CS nodes enable a hierarchical architecture and thereby an increase in resource reuse.
4. The vehicles could communicate with the RSU that is located several kilometers farther. This is possible

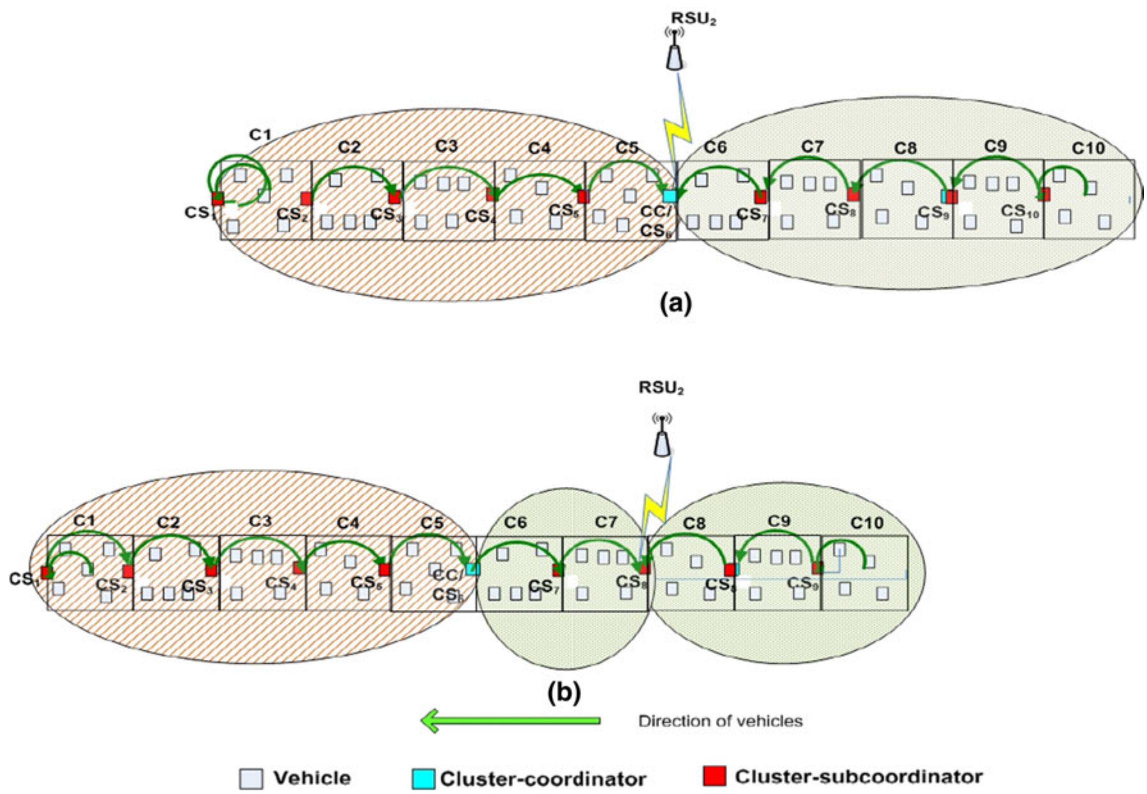

Fig. 2 Communication with RSU when the vehicles and clusters are mobile

through a multihop mechanism. Importantly, the maximum distance between two communicating vehicles is still 1 km or less, thereby satisfying the DSRC standard for vehicular communication.

5. All the CS nodes located on one side of the CC node communicate in one-direction only. As shown in Fig. 1, the vehicles and CS node located in the rear-side of CC transmit its information in the direction of the vehicle; whereas the vehicles/CS node located in the front-side of CC transmit the information in the direction opposite to that of the vehicle. This enables the potential use of a directional antenna at the vehicle which in turn reduces the interference coming from other vehicles that are located ahead of the current vehicle.

Figure 2 shows the effect of the movement of the vehicles on the MCMF architecture with a CC node heading 10 clusters. Figure 2a shows two distinct communication zone, centered around the CC node, which in-turn is in direct communication range of the RSU. Further, as the vehicles move, the CC node loses contact with the RSU while some other CS node (CS3, as shown in Fig. 2b) comes in direct contact with the RSU. The CS3 communicates the information of all the vehicles from clusters C1, C2 and C3 to the RSU; while the vehicles in clusters C4 and C5 communicate with the CC node. Hence, as shown in Fig. 2b, there are three distinct communication zones, depending on CC/CS node that is in direct communication range of RSU. Further, as the vehicles move forward, the CS node that is in contact with RSU changes, resulting in consistently having three communication zones. This returns to two zone mode only when the CC node is in range of next RSU. At this stage, it should be noted that the number of clusters after which a CC node is allotted is not fixed at 10, but could be any value, depending on the number of multiple hops, decided for vehicle-to-RSU communication.

In the MCMF architecture, the exact location of the CC node in the cluster could vary with the movement of the vehicles. As the vehicles move, the node acting as the CC could change; especially when it is moving far away from the cluster. This applies to the CS node as well. In such scenarios, the CC/CS nodes send a request message to other CS/CC, asking it to be relieved and subsequently transfer all the requisite information to another node selected as CC/CS node. A significant advantage of having multiple moving clusters is that even though the clusters are mobile, the vehicles and the CS nodes move along with the cluster and other vehicles in the cluster. This ensures that even with high-speed vehicles, the moving cluster architecture result in relatively stable topology, as long as velocity of the vehicles remains more or less the same. For instance, if the CC node travels at a speed of 120 km/h and its neighboring vehicle, say P, travels at 100 km/h, the vehicle P would still remain in the cluster as long as it does not fall behind by more than half the cluster distance. For a cluster distance of 1 km, the vehicle P would be in the same cluster as the CC node for at least 90 s. Further, if the speed of the vehicle is 110 km/h, then it would remain in the same cluster as the CC node for 3 min. This is significantly greater than the 18–36 s time duration when the vehicles communicate directly with the RSU or when a fixed cluster is considered.

Apart from the network connectivity, it is essential to ensure that the communication between the vehicle and external network take place efficiently with optimum utilization of radio resources. Further, given the high speed nature of the vehicles, it is imperative that the resource allocation is done based on the nature of the vehicular network rather than based on the content [35]. Hence, a novel protocol is proposed for real-time data transfer across the multihop vehicular networks. The next section describes the resource (time slot) allocation mechanism in the MCMF architecture and how the resources are reused intelligently.

4 ACRR protocol—resource allocation for MCMF architecture

The protocol designed for intelligent resource allocation for the MCMF architecture is based on allocating resources simultaneously across alternate clusters. Hence, the protocol is termed as alternate cluster radio resource (ACRR) protocol. The first step in designing a new protocol for the MCMF architecture is to determine a communication model for the vehicles under the MCMF. The communication model could be categorized into two stages. The first stage involves allocating an identification number (ID) whereas the second stage involves broadcasting the control information. According to the proposed ACRR protocol, the radio resources are reused in every alternate cluster. Further, within a single cluster, the available resource is divided dynamically and used sequentially by the vehicles within the same clusters. An illustration is shown in Fig. 3, wherein alternate clusters are marked with the same color. The radio resource used for communication in C1 (e.g., vehicle to CS1) is also

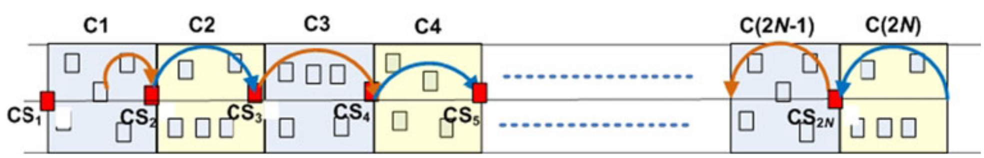

Fig. 3 ACRR protocol for communication in MCMF architecture

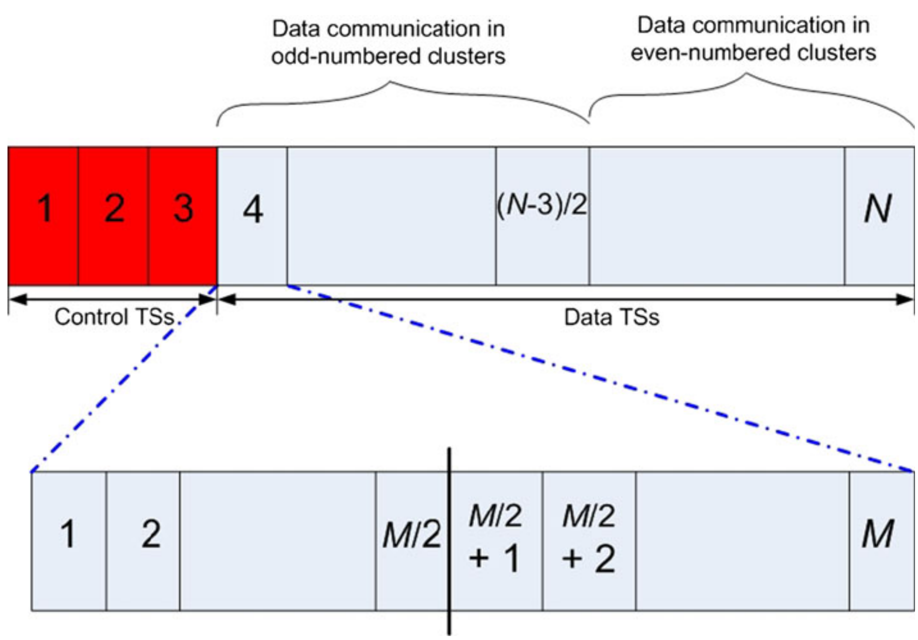

Fig. 4 Time slot/resource allocation under ACRR

used by links from all other alternate clusters, i.e., C3, C5, etc. This is indicated by the same color of the clusters and the communicating links in these clusters. Similarly, the links in even-numbered clusters i.e., C2, C4, etc. communicate using the same resource. Notably, the ACRR protocol is not limited by the value of B, i.e., the number of clusters within one CC node.

The ACRR protocol for multihop hierarchical vehicular networks has been developed based on the *protocol based interference model* proposed by Gupta and Kumar [36]; and the interference analysis investigated in [37, 38]. In this paper, this ACRR protocol is developed for a time division duplexing (TDD) technique, in combination with TDMA, though it could be equally applied to frequency division duplexing technique as well. The major advantage of the TDD based technique is that the vehicle-specific traffic asymmetry can be easily supported in the design, without having any additional interference. Further, this will enable real-time transmission of huge files, as required during video/multimedia communication. In this paper, the ACRR protocol is designed for TDD based LTE (long-term evolution) design. This is done due to the wide-spread use of LTE in wireless networks. However, it should be noted that the time slot allocation in the ACRR protocol could be easily adapted to other wireless network standards. Each TS is divided into several mini slots and one symbol is transmitted in every mini slot. Figure 4 shows the time slot/resource allocation mechanism between the vehicles in the cluster; along with the TSs allotted for control and data communication in the ACRR protocol.

There are two distinct phases in the ACRR protocol. The first is the initialization phase (control phase) where the communication is established between the different vehicles, the CS node and the RSU. The second phase is the transmission phase (data message phase) where the information/data packet is transmitted between the vehicles and the external network. The different parameters in the development of the protocol are described in Table 1 and the pseudo-code for the protocol is shown in Algorithm 1.

In a system with N TSs per frame, the first $i = 3$ TSs is reserved for control messages that need to be sent in order to establish the ACRR protocol and the remaining $N - 3$ TSs are reserved for sending data information. The control information section and the data transmission section are explained as follows:

4.1 Control information

The ACRR protocol requires three TSs for sending control information. To begin with, the first TS is reserved for assigning a particular ID to every vehicle in the cluster.

Table 1 Parameters used in the algorithm and their description

A	Road length of one cluster lane
B	The number of clusters on either side of the cluster with CC node
K	Number of clusters under a single CC node ($K = 2B$)
k	The cluster number at the particular instant
N	Number of time slots per frame
ts	The time slot number at the particular instant
$i = 3$	Number of time slots for control signals
M	Number of mini slots per time slot
ms	The mini slot number at the particular instant
$V_{k,ms}$	The vehicle communicating in cluster k at time instant ms
CS (k)	The local-head of cluster k
CC	The cluster-coordinator node among the set of clusters

During the previous time frames, the CS node in each cluster intercepts information on all the vehicles arriving into its cluster. In the first half of the first TS, the CS nodes in the odd-numbered clusters send a message to each vehicle, indicating its ID. In the second half of the first TS, the CS nodes of the even-numbered clusters communicates and assigns ID to the vehicles within its cluster. If the vehicle already has an ID allotted from the previous time frame and the vehicle has not since changed its cluster, then also, this ID is transmitted, in order to ensure that all the vehicles are synchronized with its allotted cluster. The next two TSs are reserved for setting up the communication between the vehicles and the external networks. The second TS is reserved for the vehicles to send the information on the amount of data it has to transmit to the CS node; whereas in the third TS, the CS node broadcasts the information on the allotted TS resource to the vehicles. Both the second and the third TS are divided into two equal halves; wherein the first half is reserved for communication in odd-numbered clusters (C1, C3, C5, etc.) whereas the second half is reserved for communication in even-numbered clusters (C2, C4, C6, etc.).

As shown in Fig. 4, each of these two TSs is divided into K mini slots whereby, in each of the mini-slot, a vehicle in the cluster broadcasts a signal indicating its presence and the amount of data traffic it has to transmit to the external network. The vehicles transmit this information to the CS node sequentially, based on its ID. A Poisson distribution is considered for the data traffic generated by each vehicle but with different mean values. This amount of traffic for each vehicle is intercepted by the local head, i.e., the CS node; for half the TS period ($M/2$ mini slots). The CS node intercepts the channel conditions from the received information; and importantly, calculates the time slot resource needed for each vehicle to transmit its information back to the CS node. In the $M/2$ mini slots in the third TS, the CS node responds back by broadcasting

```
FOR (ts = 1; ts < N; ts = ts + 1)
/*Start processing control component of the message*/
   If ((ts == 1) || (ts == 2) || (ts == 3))
      /*control message for the odd-numbered clusters in the 1st half of the time slots*/

      For (ms = 1; ms < M/2; ms = ms + 1) do
         For (k = 1; K < K; k = k + 2)
            If (ts == 1)
               CS(k) allocates an ID to vehicle V_{k,ms}. In case the vehicle already has an ID
               from previous clusters, the ID is then re-transmitted
            elseif (ts == 2)
               V_{k,ms} informs CS(k) about the number of packets to be transmitted
            else
               CS(k) broadcasts the amount of resource required for vehicle V_{k,ms}
            end
         end for
      end For
      /*control message for the even-numbered clusters in the 2nd half of the time slots*/
      For (ms = M/2; ms < M; ms = ms + 1) do
         For (k = 2; k < K; k = k + 2) do
            If (ts == 1)
               CS(k) allocates an ID to vehicle V_{k,ms}. In case the vehicle already has an ID
               from previous clusters, the ID is then re-transmitted
            elseif (ts == 2)
               V_{k,ms} informs CS(k) about the number of packets to be transmitted
            else
               CS(k) broadcasts the amount of resource required for vehicle V_{k,ms}
            end
         end for
      end For
else
/ *Start processing data component of the message*/
   if (ts > 3 && ts < (N-3)/2) /* Data message transfer in  the 1st half of time slots */
      for (k = 1; k < K; k = k + 2) do /*simultaneously across all odd numbered clusters*/
         • All vehicles from cluster k transmit their data to CS(k) sequentially
         • Once all vehicles finish their transmission, CS(k) transmits its data to CS(k+1) or CC
         • Once CS-CS transmission is over, the CS/CC node (whichever is in the range of RSU) communicates with RSU
      end for
   elseif (ts > (N-3)/2 && (ts < N)) /* Data message transfer in  the 2nd half of time slots */
      for (k = 2; k < K; k = k + 2) do /*simultaneously across all even-numbered clusters*/

         • All vehicles from cluster k transmit their data to CS(k) sequentially
         • Once all vehicles finish their transmission, CS(k) transmits its data to CS(k+1) or CC
         • Once CS-CS transmission is over, the CS/CC node (whichever is in the range of RSU) communicates with RSU
      end for
   end if
end for /*end of the algorithm*/
```

Algorithm 1 Pseudo code for the ACRR protocol the amount of time slot resource allocated for each vehicle in the cluster. An important point to be noted is that the number of vehicles in the cluster would be limited to $M/2$. For instance, if each TS is divided into 60 mini slots, then the maximum number of vehicles that could communicate with the RSU within the 1 km range would be 30. If the number of vehicles in the cluster is less than the total number of mini-slots, the CS node uses this resource to send other handshake signals with the vehicles, in order not to waste any time slot resource. This aspect is much more significant during data transmission and is explained in detail in the next sub-section.

4.2 Data transmission

As per the ACRR protocol, the remaining $N - i$ (i.e., $N - 3$) TSs are used for actual data transmission between the vehicles and CS/CC node and establishing communication with the RSU. The communication pattern depends on the uplink and downlink traffic and varies accordingly, albeit slightly.

4.2.1 Uplink

The uplink mode is divided into two sections—depending on whether the vehicles are in odd or even clusters. An equal number of TSs are reserved for odd-numbered and even-numbered clusters. The exact number of TSs per set of cluster depends on the standard adopted. For example, in case of a TDD based LTE system, there are 20 TSs per frame; i.e., $N = 20$ which would result in each set of cluster having 8.5 TSs for communication. On the other hand, in case of UMTS, there are 15 TSs per frame; i.e., $N = 15$ which would result in each set of cluster having 6 TSs for communication. However, this does not change the basic communication mechanism of the ACRR protocol.

To begin with, the number of data TSs per frame is divided into two equal haves—for communication across odd-numbered and even-numbered clusters. The different steps in the communication phase of the ACRR protocol are:

1. In the fourth TS, (i.e., $i + 1$ TS), the vehicles in odd-numbered clusters (i.e., C1, C3, C5, etc.) communicate with CS node sequentially. Accordingly, as soon as one vehicle finishes its transmission to the CS node, the next vehicle begins its transmission. Hence, no TS resource is wasted under the ACRR protocol. This is because, in the control section, the CS node broadcasts the TS resource required for each vehicle to all the vehicles in the cluster. This allows each vehicle in the cluster to compute the exact mini slot resource where it could begin its communication. Further details on the functioning of the dynamic time slot partitioning (DTSP) can be found in [37].
2. In the fifth TS (i.e., $i + 2$ TS), the CS node of the current odd-numbered clusters communicate with the CS node of the even-numbered clusters; for instance, CS1 to CS2, CS3 to CS4, etc. as shown in Fig. 3. A schematic view of the communication mechanism in different time slots in uplink mode is shown in Fig. 5. It should be noted that there are several simultaneously communicating pairs, communicating in alternate clusters. This results in certain interference which limits the data rate of the communication.
3. The process described in the $i + 2$ TS is repeated over the next several TSs; until all the data from the CS nodes have been transmitted—either to CC node or to the CS node that is in the range of RSU. This CS to CS/CC data transfer might be completed within the current time frame or might spill over to the next time frame depending on the amount of data to be transmitted from the vehicles and the CS node. This ensures that the overall communication mechanism would work irrespective of the number of clusters and the CS/CC node that is in communication with RSU.
4. Once all the data has reached CC node/CS-in-range-of-RSU, this particular node transmits all its data to the RSU. Notably, there are no notable interferers during this communication with RSU. Hence, this communication takes place over a significantly higher data rate; as compared to vehicle/CS to CS/CC node transmission.
5. Similar to the four steps mentioned above, the communication takes place in the adjacent even-numbered clusters in the second half of the data TS.

4.2.2 Downlink

The DL mechanism is similar to the uplink mode, including the communication mechanism and the reuse of resources between the odd-numbered and even-numbered clusters. There is one notable difference though. In the downlink mode, there are no TS reserved for control

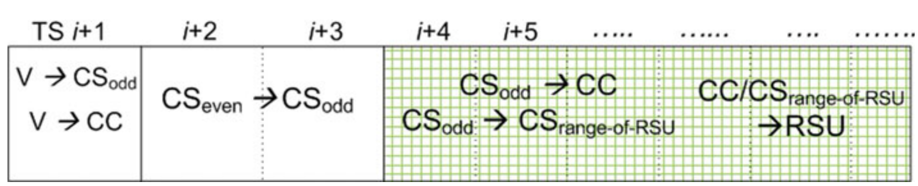

Fig. 5 ACRR protocol for uplink mode in the MCMF architecture

information. This is because, the CS and the CC node already knows how many packets it has to transmit to the vehicles.

5 Setup and theoretical analysis

5.1 Setup for vehicular network

In order to formulate a multiple cluster design in a high-speed vehicular network, a national motorway 50 km long with six lanes is considered, with three lanes reserved for each direction. Further, a medium density vehicular network is considered with 1,000 vehicles in each direction, i.e., 1,000 vehicles across 50 km in 3 lanes; resulting in a total of 2,000 vehicles across 50 km. The average distance between the high-speed vehicles in the same lane is around 200–300 m. The server/Internet communicates with the RSU which in-turn communicates with a well-connected CC node that is in its communication range. The average distance within a single cluster is 1 km. Communication between the vehicles during a single time slot is shown in Fig. 6. As can be observed in Fig. 6, the vehicles in rear-end of the clusters communicate with the CC node sequentially over a single TS. This communication between the vehicles and the CC node takes place sequentially. The proposed ACRR protocol is applied for the MCMF architecture. Further, a 180° directional antenna is considered in the system design. This would ensure that the signals transmitted from the vehicle move forward towards the RSU or other vehicles in front. Notably, there is no signal propagation in the reverse direction.

In order to analyze the ACRR protocol, the length of the cluster is considered to be of length, r_c. Further, as shown in Fig. 6, the farthest distance between a vehicle and its CC/CS node is $r_c/2$. The same radio resource is reused in alternate cells. Moreover, as shown in Fig. 6, the CC node in cluster 3 would experience interference from the transmitting node from cluster 1. However, the CC node in cluster 1 would not receive any interference from cluster 3, as the signals are not propagated in the reverse direction. Hence, the distance of this interfering transmitter in cluster 1, from the desired receiver in cluster 3 would be 1.5–2r_c (i.e., 3–4 times $r_c/2$). Further, the next interfering transmitter would be from the cluster located at a distance of 4r_c from the desired receiver, (i.e., eight times $r_c/2$) and hence, the interference arising from this entity would be negligible. This is a significant benefit of communicating with ACRR protocol in the MCMF architecture. Every receiving node in the cluster experiences interference from only one other node in the network.

In order to assess the performance of the MCMF architecture and the efficiency of ACRR protocol for efficient data delivery, an underlying model for the WAVE is considered in the design [39]. The operating frequency band is 5.9 GHz. A BPSK modulation scheme is considered in the first two TSs in order to send the control-based information. Further, a LTE based time frame structure for the IEEE 802.11p standard is considered, wherein each frame has 20 TSs. The entire procedure is repeated after 20 TSs. Notably, due to several multiple hops, many-a-times, the end-to-end communication is not realized over a single iteration of 20 TSs. The ACRR protocol ensures that the communication continues over the next frame such that the data packets reach its final destination. In this analysis, a 1:1 ratio is considered between the uplink and downlink communication. These result in 20 TSs being utilized to complete one complete cycle of uplink and downlink communication. However, the design is in no way restricted to symmetric traffic and an asymmetric traffic could be easily considered. The complete list of parameters and the values is shown in Table 2.

5.2 Mathematical analysis

If the transmitted power of the vehicle could be written as P_T and the distance from the vehicle to the nearest of the CC/CS node is given by d_c, then, given the transmission over a flat fading channel, the received power P_R could be given by:

$$P_{Rc} = P_T - [k_C + 10\ \log 10(d_c) + \varepsilon_C] \quad (1)$$

wherein, k_C is the propagation constant and ε_C represents the shadowing factor in the desired link. Further, the undesired transmitters interfere with the desired signal. The signal strength of these undesired transmitters is represented as:

$$P_{RI} = P_T - [k_I + 10\ \log 10(d_I) + \varepsilon_I] \quad (2)$$

where P_{RI} is the received signal strength from the interfering signal, d_I is the distance of the interfering entity, k_I is the

Fig. 6 Simultaneous communication across clusters in a particular time instant

Table 2 Values of different parameters

Parameters	Values
Total number of lanes	6
Number of lanes in each direction	3
Vehicular environment	Highway/motorway
Total distance in the highway considered	50 km
Total number of vehicles across 3-lanes	1,000 vehicles
Average length of one cluster lane (*A*)	1 km
Average number of vehicle per cluster (3-lanes)	60
Average distance between 2 vehicles in a single-lane	200–300 m
Carrier frequency	5.9 GHz
Bandwidth	1 MHz
Uplink: downlink traffic ratio	1:1
Time slots per frame (*N*)	20
Number of mini slots per time slot (*K*)	60
Number of time slots for control signals (*i*)	3
Mobility model	Uniform speed model with defined min. and max. speed
Average velocity of vehicle	80–120 km/h
Number of modulations	BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM, 128-QAM and 256-QAM
Average multimedia traffic per vehicle	1 MB/s
Distribution of packet arrival in vehicles	Poisson distribution
Propagation constant of wireless channel (α)	2.5–3.2
Propagation model of vehicles	Small-scale fading, zero mean log-normal shadowing
Log normal shadowing standard deviation	2 dB

propagation constant of the *i*th interfering link and ε_I is the shadowing factor of the *i*th link. Considering only one interfering entity from the simultaneously communicating links of the alternate cluster—the carrier to interference ratio, γ_{dB}, could therefore be given by:

$$\begin{aligned}\gamma_{dB}^{\text{MCMF}} &= P_{Rc} - P_{RI} \\ &= 10\alpha \log 10(d_I) - 10\alpha \log 10(d_c) + (k_I - k_C) \\ &\quad + (\varepsilon_I - \varepsilon_C)\end{aligned} \quad (3)$$

In a road environment, the propagation constant and the shadowing factor could be considered to be of same value for both the desired and the interfering entities. Hence, the carrier-to-interference ratio, *C/I*, could be simplified as:

$$\gamma_{dB}^{\text{MCMF}} = 10\alpha \log 10(d_I) - 10\alpha \log 10(d_c) \quad (4)$$

$$= 10\alpha \log 10(d_I/d_c) \quad (5)$$

In a real world wireless environment, the typical value of path loss exponent would vary from $\alpha = 2.5$ to $\alpha = 3.2$.

The average throughput taking into account the interference, C/I and also the number of RSU over the distance would be could be calculated as

$$\text{C} = B \times \log 2\left(1 + \gamma^{\text{MCMF}}\right) / \log 10(D/N)\ \text{bps} \quad (6)$$

where *B* is the bandwidth, *D* is the total distance considered (50 km in this paper), *N* is the number of RSU over distance *D* and γ^{MCMF} is the *C/I* ratio in absolute scale. It should be noted that the Eq. (6) is calculated using the Shannon equation and is further modified based on the number of RSUs over a particular distance. This is essential in order to take into account the coverage distance covered by each RSU.

5.3 Analytical results

To begin with, the ACRR protocol ensures that the resources are re-used only in alternate clusters. The vehicles are distributed uniformly across each cluster. Hence, in any cluster, the average distance between a vehicle and the CC/CS node would be *r*/4 (between 0 and *r*/2). On the other hand, the average distance of the interfering vehicle (two clusters apart) from the CC/Cs node that uses the same resource would be 1.75*r* (a fixed distance of 1.5*r* plus the average distance of *r*/4). Hence, in case of the ACRR protocol model, the ratio between the average distance of the interfering vehicle and the desired vehicle (d_I/d_c) would be 3.5.

Referring to Eq. (5), for a path loss exponent of $\alpha = 2.5$, the average carrier-to-interference ratio would be given by $\gamma_{\min dB}^{\text{MCMF}} = 13.61$ dB while for a path loss exponent of $\alpha = 3.2$, the average carrier to interference ratio would be $\gamma_{\min dB}^{\text{MCMF}} = 17.04$ dB. Given a bandwidth of 1 MHz, the throughput would be calculated for different RSU units from Eq. (6). The average throughput for $\alpha = 2.5$ and $\alpha = 3.2$ is calculated using Eqs. (5) and (6) and is given in Table 3 as follows. It should be noted from Eq. (6) that as the number of RSU's increases for a particular distance, the average distance covered that needs to be covered by one RSU is less; which in turn would increase the overall throughput for that distance.

Given that the vehicles are considered to be spread out uniformly (uniform distribution), the average throughput obtained through the analytical results could be compared with the actual simulated throughput for the same network conditions.

Notably, the instantaneous values of the throughput would depend on the actual location of both the desired and

Table 3 Analytical results for average throughput using ACRR protocol

Distance between RSUs	10 km (Mbps)	20 km (Mbps)	30 km (Mbps)	40 km (Mbps)	50 km (Mbps)
Avg. throughput ($\alpha = 2.5$)	5.05	3.88	3.418	3.152	2.972
Avg. throughput ($\alpha = 3.2$)	5.83	4.48	3.94	3.63	3.43

the interfering vehicle. Hence, it would be interesting to observe the extreme case scenarios for *C/I*. The first scenario is when the desired transmitter is is at the farthest distance from the CC/CS node (say, $0.5r_c$) and the second scenario is when the desired transmitter is very close to the CC/CS node. Though theoretically, a vehicle could be at an infinitesimal distance from the CC/CS node, in practice, the closest a vehicle could get to the CC/CS node is at a distance of around $0.1r_c$. In this paper, the distance of $0.1r_c$ is considered for the calculation of the bounds. The corresponding throughput for the two cases are calculates as follows:

5.3.1 Lower bound

The lower bound of the throughput is when the desired transmitter is farthest from the CC/CS node ($0.5r_c$) and the interfering transmitters are at the closest possible distance. This implies that the interfering transmitter would be at a distance of $1.5r_c$. This would result in minimum d_I/d_c ratio leading to minimum *C/I* and lower bound on the throughput. In this case, the resulting *C/I* ratio would be: $\gamma^{MCMF}_{lower-bound\,dB} = 11.92$ dB and for $\alpha = 3.2$, it would be $\gamma^{MCMF}_{lower-bound\,dB} = 15.26$ dB. Referring to Eq. (6), the lower bound on the throughput for different distances would be as mentioned in Table 4.

5.3.2 Empirical upper bound

The upper bound of the throughput would arise when the d_I/d_c ratio is the highest. Since this ratio could be theoretically infinite, this paper focuses on computing the empirical upper bound alternatively known as realistic upper bound. This would happen when the desired transmitter is very close to the CC/CS node. Theoretically, the vehicle could be exactly at the CC/CS node. However, in reality, the vehicle would always be at some finite minimum distance from the CC/CS node. Assuming this distance to be $0.1r_c$ and the interfering transmitters to be at a farthest possible distance ($1.9r_c$), this would result in maximum d_I/d_c ratio of 19; leading to maximum *C/I* and thereby upper bound on the throughput. For $\alpha = 2.5$, it would be $\gamma^{MCMF}_{upper-bound\,dB} = 31.96$ dB and 45.33 dB for $\alpha = 3.2$. Referring Eq. (6), the realistic upper bound on the throughput for different distances would be as mentioned in Table 5.

Table 4 Analytical results for the lower bound of throughout using ACRR protocol

Distance between RSUs	10 km (Mbps)	20 km (Mbps)	30 km (Mbps)	40 km (Mbps)	50 km (Mbps)
Lower bound of throughput ($\alpha = 2.5$)	4.05	3.11	3.418	2.74	2.38
Lower bound of throughput ($\alpha = 3.2$)	5.11	3.93	3.45	3.19	3.01

5.4 Other existing communication mechanisms

5.4.1 Single-hop V2I transmission

In case of a single-hop transmission, the vehicles communicate with the RSU directly. Further, in a single-hop vehicular network, in order to have the same radio resource reuse efficiency as in the MCMF mechanism, the resource is reused over every window of vehicles. While the average distance between a desired transmitter (vehicle) and the RSU would be $r/2$, the distance of the interfering vehicle (vehicle using the same resource) would vary depending on its exact location. The minimum distance of the closest interferer is when the vehicle using the same radio resource is located at the edge of the cluster. In this case, the interferer would be at an average distance of $r/2$ from the receiver (RSU). On the other hand, the maximum distance of the interfering vehicle is r while the average distance of the interfering vehicle is $3r/4$. In this scenario, the minimum, average and the maximum distance of the second interferer (vehicle from the second adjacent cluster) would be $3r/2$, $7r/4$ and $2r$ respectively. The vehicles located beyond the second adjacent cluster would be located at a

Table 5 Analytical results for the realistic/empirical upper bound of throughout using ACRR protocol

Distance between RSUs	10 km (Mbps)	20 km (Mbps)	30 km (Mbps)	40 km (Mbps)	50 km (Mbps)
Empirical upper bound of throughput ($\alpha = 2.5$)	10.62	8.17	7.19	6.62	6.25
Empirical upper bound of throughput ($\alpha = 3.2$)	15.05	11.56	10.18	9.39	8.85

minimum distance of more than 2.5r and hence, the resulting interference arising from that could be neglected. Referring Eqs. (5) and (6), the *C/I* and the throughput for different scenarios (minimum, average and maximum) for single-hop design is computed for $\alpha = 2.5$ and $\alpha = 3.2$ and is given in Table 6. It should be noted that in Eq. (6), since the RSUs are located every 10 km, the throughput equation simplifies to $C = B \times \log_2(1 + \gamma)$ which is same as Shannon equation (Fig. 7).

Comparing the throughput results of Table 4 and 6, it can be observed that the lower bound of the throughput obtained from the single-hop design are only 23.2 and 19.7 % of what could be achieved as compared to the MCMF based ACRR protocol (for distance between RSUs of 10 km) for $\alpha = 2.5$ and $\alpha = 3.2$ respectively. Further, when the upper bound is compared, the achievable throughput of the single-hop design are 75.32 and 91.2 % of what could be achieved as compared to the MCMF based ACRR protocol for $\alpha = 2.5$ and $\alpha = 3.2$ respectively. Moreover, comparing the average throughput results from Table 3 and 6, it can be found that the average throughput of the single-hop scenario are 76.3 and 85.7 % as compared to the MCMF based ACRR protocol for $\alpha = 2.5$ and $\alpha = 3.2$ respectively. This analysis clearly shows the superiority of the MCMF based ACRR protocol as compared to the single-hop design when the RSUs are spaced every 10 km. This comparative result between single-hop design and MCMF based ACRR protocol is also shown in Fig. 8. Particularly, it can be observed from Fig. 8 that the lower bound of the throughput obtained from the single-hop design is much lower than that obtained from the MCMF based ACRR protocol. An important point to be noted is that the single-hop design mandates the need of an RSU every 10 km. The single-hop design would not support the communication mechanism if the RSUs are located; say after 40 or 50 km. On the other hand, the MCMF based ACRR protocol would not only support communication even if RSUs are at 50 km, but also provide a reasonable throughput which is not possible in the single-hop design.

5.4.2 AODV+ based multihop communication

AODV+ is based on an on-demand algorithm capable of both unicast and multicast transmissions. There is no routing overhead when there is no data packet to be sent. The reason for its selection for vehicular networks is that, the protocol maintains the route only while needed by sources. When a vehicle wants to send a packet, the route discovery process broadcasts a *Route Request* message to discover the destination node. Further, AODV+ has been proved to result in a better throughput as compared to other state-of-the-art routing mechanisms like destination sequenced distance vector [41]. In this mechanism, the information from the vehicles is forwarded from one vehicle to another, until the information reaches a vehicle/set of vehicles that is in the range of RSU. This vehicle then communicates with the RSU. For instance, as shown in Fig. 7, the vehicle P communicates with vehicle Q which in turn communicates with vehicle R. Since the vehicle R is in the range of RSU, it relays all the information from other vehicles to the RSU. This is based on V2V communication [28, 29]. However, in this mechanism, there is no hierarchical structure and hence, no single node that collects information from all the vehicles before passing onto the RSU. The radio resources among the vehicles are distributed on-the-fly.

Table 6 Analytical results for the realistic/empirical upper bound of C/I and throughput under single-hop model

	Lower bound	Average	Upper bound
C/I			
For $\alpha = 2.5$	0.9241	13.465	255.01
For $\alpha = 3.2$	0.9862	31.08	9,303.8
Throughput			
For $\alpha = 2.5$ (Mbps)	0.9441	3.854	8.00
For $\alpha = 3.2$ (Mbps)	0.99001	5.0036	13.183

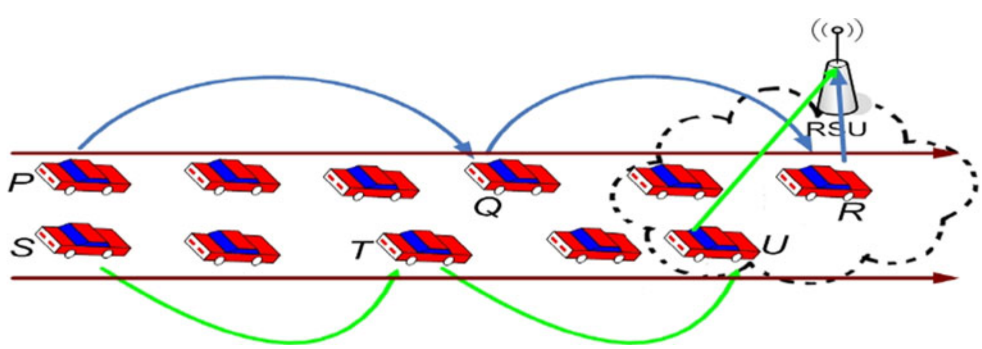

Fig. 7 AODV+ based multihop communication scenario

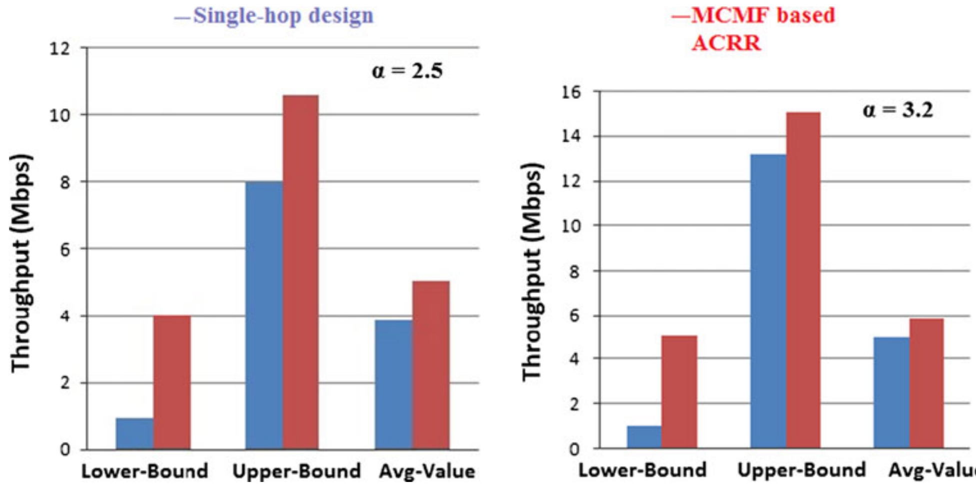

Fig. 8 Comparison of analytical throughput between single-hop and MCMF based ACRR with a RSU every 10 km

6 Simulation scenarios and results

In order to comprehensively evaluate the performance, a set-up is designed based on the parameter values shown in Table 2. A three-lane model is considered across each direction; making it six lanes in total. A distance of 50 km is considered with 1,000 vehicles in total across the six lanes. On an average, each cluster is considered to have 60 vehicles distributed uniformly across the cluster. The 5.9 GHz frequency band is considered in the system design with a bandwidth of 1 MHz. Notably, a symmetric traffic model is considered, i.e., nearly same traffic across both uplink and downlink. A TDD model is considered with 20 TS(s) per frame. Further, each TS is divided up to 60 mini slots. This enables the use of dynamic time slot partitioning mechanism whereby no time resource is wasted in allocating resources. Further, the vehicles are assumed to travel with a speed of 80–120 km/h. Significantly, given the highway nature of the road, a log normal shadowing of zero mean and a standard deviation of 2 dB was considered in the simulations. This shadowing (2 dB) is mainly due to the reflection from the moving vehicles and the road. This is because, in case of a vehicular network, the national roads would be usually free of dense building or other high-reflective environments. Hence, the shadowing factor is quite low. In reality, the exact log-normal shadowing would be different, even slightly higher. However, at this stage, the authors consider 2 dB standard deviation to be a good estimation of the real-world environment. Significantly, the set of clusters as per MCMF architecture spans across 10 km distance, while the RSUs are located 10–50 km apart. Further, it was considered that the vehicles would communicate with the RSU using different data rates, depending on the channel condition. This was achieved using an adaptive modulation technique for transmitting data. In order to evaluate the performance, a medium-to-high multimedia traffic scenario was considered in the vehicular network. Each vehicle in the road has a Poisson based traffic distribution and has a data of 1 MB/s to transmit to the external network.

It should be noted that in order to provide high data-rate to the users in the high speed vehicles, an adaptive modulation technique is considered for data transmission. Under an adaptive modulation scheme, the transmitter selects the modulation technique based on two parameters: the γ experienced at the receiver and the bit error ratio (BER). For multimedia transmission in the wireless vehicular networks, a coded BER of 10^{-6}–10^{-7} is required. The equivalent bit rate in an un-coded system would be 10^{-2} [40] which, when combined with convolutional coding and other techniques like Reed-Solomon codes, would translate the BER of 10^{-2} to around 10^{-6} [41]. The entire system model is simulated using Matlab. The next sub-section demonstrates the obtained results.

6.1 Throughput analysis

Figure 9 shows the average throughput of ACRR protocol for MCMF architecture; along with AODV+ protocol based MCMF architecture, AODV+ based peer-to-peer multihop and single-hop communication scenario; when the distance between RSUs is varied from 10 to 50 km. It can be observed that in all the cases, the average throughput decreases with increasing distance between the RSUs. At the same time, the average throughput in case of ACRR based MCMF is significantly higher than any other architecture + protocol combination. For instance, when the distance between the RSUs is 10 km, the average throughput of MCMF architecture under the ACRR protocol is around 5.2 Mbps, which is 40 % higher than an AODV+ based MCMF architecture (3.8 Mbps) and 70 % higher than AODV+ based peer-to-peer multihop architecture. This improved performance of ACRR/MCMF remains consistent even when the distance between the

RSU is increased from 10 to 50 km. For instance, when the distance between the RSU is 50 km, the average throughput of ACRR based MCMF architecture is 3.5 Mbps, which is again 40 % higher than an AODV+ based MCMF architecture. The reason why ACRR+ based MCMF architecture has higher throughput is because, the radio resources are reused efficiently; taking into account

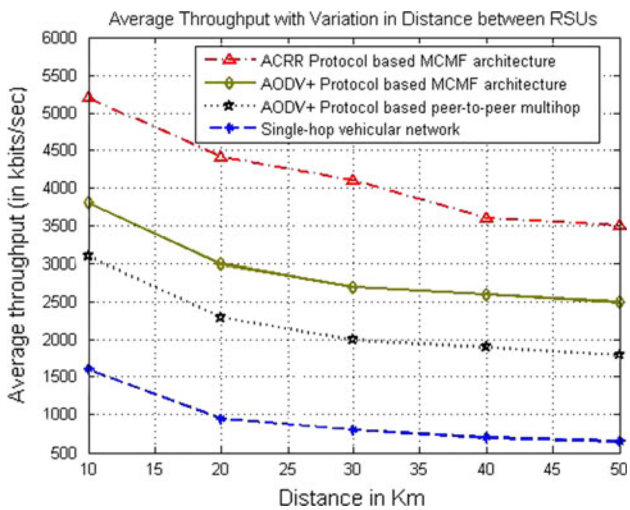

Fig. 9 Average throughout with the distance between the RSUs

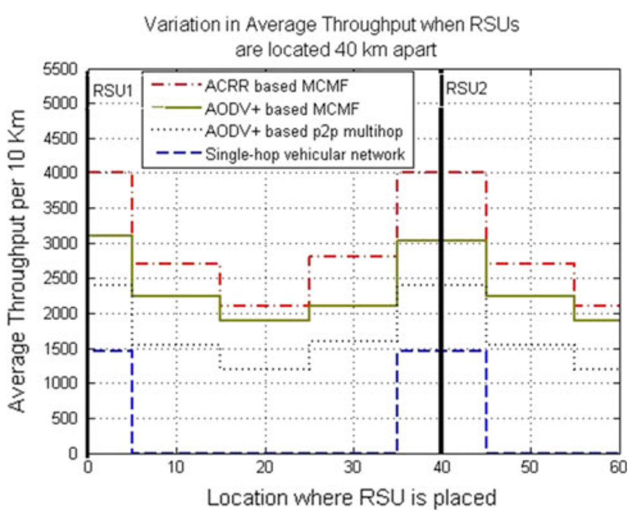

Fig. 10 Average throughput per 10 km when the distance between RSU is 40 km

that the vehicles communicate their packets in one direction only. Further, due to the coordinated hierarchical mechanism in MCMF architecture, the average throughput in case of MCMF is considerably higher than that of simple multihop communication mechanism.

The importance of the MCMF architecture and the ACRR protocol can be understood from a particular scenario, wherein the RSUs are located 40 km apart. Figure 10 shows the average throughput over every 10 km, when the distance between two RSU is 40 km. It can be observed that when the vehicles in the MCMF architecture are in the 10 km range of RSU, the average throughput is significantly higher than other mechanisms. When the vehicles/set-of-clusters in MCMF move away from the RSU, the average throughput reduces drastically. This is because, in case of MCMF, when the clusters are not connected to the RSU directly, the information is forwarded to the next cluster. Hence, the average bit rate during that period does not go to zero, i.e., the vehicles are always connected to the external network, irrespective of whether it is in the range of the RSU or several tens of km away from the range of RSU. As the CC node comes closer to the RSU, it again starts transmitting the packets to RSU. Further, the performance of MCMF with ACRR is notably higher than that of MCMF with AODV+ and considerably higher than peer-to-peer based multihop communication. Importantly, in the absence of the RSU, there is no data transmitted in case of single-hop design due to the absence of any vehicle in the range of RSU. Table 8 shows the improvement obtained through MCMF in terms of average bit rate/vehicle, as compared to AODV+ based multihop communication mechanism and single-hop V2I scheme, for varying distances between RSUs. It can be observed from Table 2 that ACRR based MCMF provides consistently higher average bit rate—*a minimum improvement by a factor of 1.36 as compared to AODV+* based MCMF and *by a factor of at-least 3.35 as compared to single-hop V2I schemes*, even when the distance between RSUs is varied from 10 to 50 km (Table 7).

Significantly, Fig. 11 compares the simulated average throughput results of the MCMF based ACRR protocol with the analytical results derived in Sect. 5.3 for the similar network environment. Particularly, the bandwidth is same as considered in the simulations. The only difference is in that in the analysis, the log-normal shadowing

Table 7 Improvement in bit-rate of MCMF over AODV+ and single-hop V2I communication schemes for different distances between RSUs

Comparison with varying distances of RSU	10 km	20 km	30 km	40 km	50 km
Improvement of ACRR-MCMF over AODV+ MCMF (factor of)	1.36	1.46	1.57	1.41	1.51
Improvement of ACRR-MCMF over AODV+ p2p multihop (factor of)	1.67	1.87	2.05	1.92	2.01
Improvement of ACRR-MCMF over single-hop networks (factor of)	3.35	4.63	5.12	5.14	5.51

factor is not considered. From Fig. 11, it can be observed that the average throughput results of ACRR obtained from the mathematical analysis matches closely with the simulated results. The marginal difference is mainly due to the log-normal shadowing factor (with 2 dB standard deviation) considered in the simulations. Further, Fig. 11 also shows the lower bound and the realistic upper-bound on the obtained throughput. It can be seen that while the achievable upper bound is nearly double that of the average results, the upper bound scenarios arises only when the interfering transmitter is at the farthest possible distance while the desired transmitting vehicle is closest to the CC/CS node (a rare-case scenario). An important observation from Fig. 11 is that the minimum (lower-bound) throughput value obtained through the ACRR protocol (also shown in Table 5 in Sect. 5.1) is significantly higher than the average simulated throughput obtained through the AODV+ based MCMF protocol. This shows the superior performance of the MCMF based ACRR protocol introduced in this work.

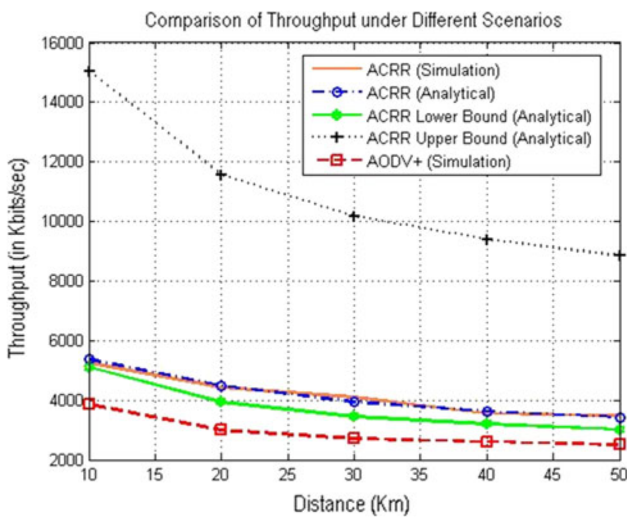

Fig. 11 Comparison of throughout under different scenarios for different distances

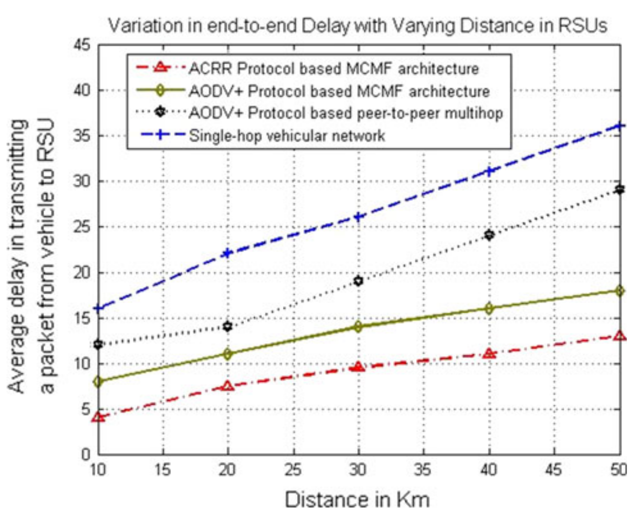

Fig. 12 Delay comparison of MCMF protocol with AODV+ multihop and single-hop V2I network design

6.2 Delay analysis

Figure 12 compares the ACRR based MCMF architecture with AODV+ based MCMF along with a peer-to-peer based multihop communication mechanism and the single-hop network, in terms of *the total end-to-end time taken to transmit the information from all the vehicles in the network to RSU*. It should be noted that this time includes the transmission time plus the time required to wait before resources are allocated for transmission, for all the vehicles. It can be seen from Fig. 12 that as the distance between the RSU's increases, the average delay increases. However, the ACRR based MCMF results in a minimum delay in the transmission of data packets. In particular, when the RSUs are placed 50 km apart, the average delay using ACRR/MCMF is 13 s, which is more than two times less than peer-to-peer multiple forwarding (29 s), and nearly three times less times than that of single-hop V2I network (36 s). Table 8 demonstrates the reduction in time delay obtained in ACRR based MCMF architecture as compared to AODV+ based MCMF, along with AODV+ based multihop communication mechanism and single-hop V2I scheme, for varying distances between RSUs. It can be observed from Table 3 that MCMF (with both ACRR and with AODV+) consistently results in considerably lower delay, *compared to that obtained by AODV+ based multihop and that recorded by the single-hop V2I communication mechanism*—even after variation in the distance between RSUs.

Table 8 Reduction in time for ACRR/MCMF over AODV+/MCMF, AODV+ based peer-to-peer multihop and single-hop V2I communication schemes for different distances between RSUs

Comparison with varying distances of RSU	10 km	20 km	30 km	40 km	50 km
Fraction of time delay for ACRR/MCMF over AODV+/MCMF	0.51	0.694	0.689	0.718	0.722
Fraction of time delay for ACRR/MCMF over P2P multihop	0.34	0.571	0.526	0.469	0.448
Fraction of time delay for ACRR/MCMF over single-hop	0.25	0.3555	0.384	0.365	0.361

7 Conclusions

This paper proposes a novel MCMF architecture for data communication across high-speed vehicular networks. It integrates a moving cluster solution with multi-hop forwarding of information, whereby, real-time high-rate data information is transmitted between the vehicles and the RSU. The multihop forwarding mechanism ensures that the cluster of vehicles not only remain connected as they move forward, but also communicates over long distances using high data rates. Further, the MCMF architecture ensures that the connection between the vehicles and the RSU remains open for considerably long time, even after the high-speed vehicle is out of the RSU range. Additionally, a novel ACRR protocol is proposed wherein the radio resource usage is increased by reusing the radio resource over every alternate cell. The MCMF/ACRR combination offers two main advantages—a near two-fold increase in the average throughput and a two-fold decrease in delay in the transmission of messages from the vehicle to RSU, as compared to the state-of-the-art AODV+ based multihop communication mechanism. The detailed mathematical analysis gives the average obtainable throughput of MCMF based ACRR protocol and also provides the lower and realistic upper-bound. Importantly, the lower bound of the achievable throughput itself is higher than that obtained using the AODV+/MCMF protocol and the single-hop architecture. This is a very significant result and demonstrates the superiority of both the ACRR protocol and the MCMF architecture in transmitting real-time high data rate information in the fast moving vehicular networks. Notably, the MCMF protocol could not only be deployed in the real-world vehicular network only, but also be incorporated as an update into the recently developed IEEE 802.11p/WAVE vehicular network standard.

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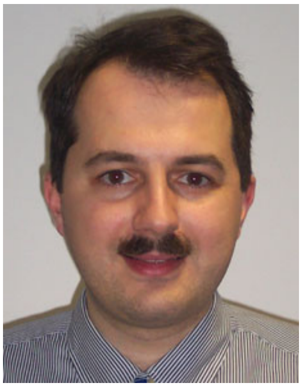

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